Towards a sustainable PV waste policy: Exploring the management practices of end-of-life solar photovoltaic modules in Australia

By

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List of Abbreviations

GIS	Geographical Information System
LCA	Life Cycle Assessment
MPS	Mandatory Product Stewardship
VPS	Voluntary Product Stewardship
EPR	Extended Producer Responsibility
PV	Photovoltaic
WEEE	Waste Electrical and Electronic Equipment
EoL	End-of-life
MEET	Methodology for calculating transport emission and energy consumption
RL	Reverse Logistics
GHG	Greenhouse Gas Emissions
PM	Particulate matter
CO	Carbon monoxide
CO_2	Carbon dioxide
NO_x	Nitrogen Oxides
OECD	Organisation for economic co-operation and development
SA	South Australia
APVI	Australian photovoltaic institute
NDS	Network dataset
NA	Network analysist
VRP	Vehicle routing problem
DTI	Department for Infrastructure and Transport
LRET	Large -scale Renewable Energy Target

MSW	Municipal solid waste
c-Si	Crystalline silicon
a-Si	Amorphous silicon
EU	European Union
GWP	Global warming potential
AD	Abiotic depletion
ODP	Ozone layer depletion
HNO_3	Nitric acid
LCIA	Life cycle impact assessment
LCI	Life cycle Inventory
IPCC	Intergovernmental panel on climate change
FRELP	Full recovery of end-of-life photovoltaic process
FU	Functional unit
CdTe	Cadmium telluride
CIGS	Copper indium gallium di-selenide
IEA	International energy agency
GaAs	Gallium arsenide
OPV	Organic solar cells
PSC	Perovskite solar cells
DSSC	Dye sensitized solar cell

Abstract

Solar photovoltaic (PV) systems are effective measures to reduce the greenhouse gas emissions. However, the large exploitation of solar PV modules, leads to undesirable waste accumulation, affecting the environment. Solar PV waste management research is an emerging field that has received more attention recently, affected by the increase volume of solar PV disposals. However, only a few studies have examined the current practices in solar photovoltaic waste management. In Australia, because of social and economic factors (such as the replacement of small-scale PV systems come with new rebates), residential solar systems are decommissioned earlier than expected before reaching their end-of-life (EoL). 70% of the market share of PV systems are predominately dominated by the residential market in Australia as of 2020. The average practical lifetime of PV modules instead of 20-30 years is 15-20 years in Australia. Therefore, the volume of EoL PV from the residential sector entering the waste stream in the coming decade will be higher than previously predicted.

This study aims to assess the environmental impacts of waste from rooftop solar photovoltaic panels in Australia to inform sustainable policies. To achieve the aim of the research, the following objectives are investigated: 1) exploring the current practices of managing end-of-life rooftop solar photovoltaic panels in Australia; 2) developing an optimised system approach in dealing with solar photovoltaic waste in Australia; and 3) assessing the environmental impacts of end-of-life rooftop solar photovoltaic panels in Australia within the developed assessment framework.

To achieve the research objectives, several methods are adopted to analyse the primary and secondary data for this research. A modified Fuzzy Delphi Method (FDM) is adopted in gathering data through interviews and questionnaires from experts in the field. The results show that, crystalline silicon panels were the most common panels on the Australian market and the ones that are being installed frequently. On policies, although the Australian government has banned PV waste from going to landfill since 2014, there were no regulations or action plans to manage PV waste. The absence of policies and regulations results in unregulated movement and tracking of solar PV waste in and out of Australia as well as within and across the states. The extent of the PV recovery and recycling warrants further investigation. Moreover, infrastructure and logistics has been a significant problem because of the geographical spread of the country and how it affects transportation and the supply chain. Findings led to the

establishment of a conceptual framework for the current treatment of solar PV waste in Australia.

Furthermore, a Weibull distribution model is employed to forecast the PV waste in the next three decades in South Australia. The study further estimates the pollutant emission associated with the collection and transportation of the waste for recycling and recovery. Results indicate that, there will be 109,007 tons of PV waste generated in urban and suburban context in South Australia by 2050. Among the three routing scenarios generated, the third scenario with optimised transfer stations and an additional recycling facility showed more than 34% reduction in pollutant emission.

This study evaluates the environmental impacts of three policy options for mono and multi crystalline silicon (c-Si) solar panel waste modules. The impact of transport distance from transfer stations to the recycling centre is also assessed. The life cycle assessment revealed that, -1E+06 kgCO_2eq and -2E+06 kgCO_2eq are associated with the mandatory product stewardship scenarios under global warming potential for mono and multi c-Si solar modules respectively. However, the non-existence of a product stewardship will produce a global warming impact of 1E+05 kgCO_2eq for both modules. The global warming effects revealed that, collecting and recycling most of the multi c-Si panels were not effective (-365 kg CO_2-eq, -698.4 kg CO_2-eq, -1032 kg CO_2-eq) compared to keeping them away from the landfills and fully recycling (-2E+06 kg CO_2-eq) them. It was also highlighted that, the highest environmental impact regarding the transport distances was the scenario of one recycling centre serving over 107 transfer stations with a global warming potential of 1E+06 kgCO_2eq.

In conclusion, this study contributes to the management of the supply market of solar PV technologies, using Australia as a case study. The recommendations derived from the study include: creating collection centres for EoL PV modules in South Australia, developing a logistic network to for the collection of EoL PV modules, creating and enhancing the PV recycling market for recovered materials, issuing a regulatory landfill ban for EoL solar PV module in South Australia, developing a mandatory product stewardship for PV waste in Australia, promoting and providing financial incentives to current and future infrastructure for PV recycling, minimising the exportation of PV waste overseas and interstate, encouraging industry led research on new innovations to improve the recovery of different PV technology families, developing sustainable measures to cut emissions for recycling through research and development in South Australia, and building the capacity and promoting awareness on the benefits of PV recycling in South Australia.

HDR Thesis Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

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Chapter 1. Introduction

1.1 Introductory background

According to a report by the United Nations (2015), urban areas are populated by over half of the population (54%) in the world with a projection increase by 66% in some few years (2050) to come. This move brings a lot of important development in the area of social and economic transformation. However, it is associated with problems like environmental stress and challenges with sustainable development such as greater impermeable coverage, reduction of green space, emission of noise and air pollution (Agudelo-Castañeda et al., 2017; Fdez-Ortiz de Vallejuelo et al., 2017; Tixier et al., 2011; United Nations, 2014). Urban growth significantly affects surface waters through the emission of a range of pollutants as well as increasing threats and decreasing the quality of human and environmental health (Ancion et al., 2010). Population increase, thriving construction sectors, rapid urban growth, and the escalation of the living standard of communities has extremely enhanced the waste generation in urban areas (Duan et al., 2019). The growth in population brings significant housing and energy demands leading to the creation of huge amounts of construction and demolition (C&D) waste of which residential solar photovoltaic (PV) modules for part in some countries. An estimated seven to ten billion metric tonnes of waste are produced yearly in the world, 8% of these wastes are utilities, 24% comes from municipal solid waste (MSW), 32% are from commercial and industrial waste with the huge part of the waste (36%) coming from the construction sector (UNEP & ISWA, 2015).

The need to satisfy green energy demands around the world has seen a high uptake of solar photovoltaic technologies. This need is much evident in the current drifts into PV installations. A report from the International Energy Agency indicated that, there has been a fifty percent growth in the installation of solar panels from 2015 to 2016, approximately 76GW increase. The current cumulative global PV installation capacity is around 580 GW (IEA-PVPS, 2021). Moreover, Australia holds the highest PV power per capita worldwide (IEA-PVPS, 2022b; IRENA, 2019; Majewski et al., 2021), and installations are expected to increasingly grow in the coming years.

By 2050, the volume of end-of-life (EoL) PV panels is expected to reach 60 million tons globally (Monier & Hestin, 2011; Xu et al., 2018). The significance to investigate the EoL of these PV systems is being heightened on the premise that their expected life is between 20 to 30 years and most of the panels have already been installed years back (Vellini et al., 2017). In some countries, rooftop solar installations are exempted from the producer take-back options. The installers are usually third-party companies who purchase their panels from different manufacturers. The authors and others captured that there is no interest in collecting these EoL PV panels for recycling due to little or no economic motivation. This is a clear indication that, these solar modules are likely to add up to municipal solid waste (MSW) or construction and demolition (C&D) waste stream in the absence of policy intervention (Goe & Gaustad, 2016a).

In Australia, because of social and economic factors (such as the replacement of small-scale PV systems come with new rebates) residential solar systems are decommissioned earlier than expected before reaching their EoL. This reason is, 70% of the market share of PV systems are predominately dominated by the residential market in Australia as of 2020. The average practical lifetime of PV modules instead of 20-30 years is 15-20 years in Australia. Therefore, the volume of EoL PV from the residential sector that will enter the waste stream in the coming decade will be higher than previously predicted (IEA-PVPS, 2022a).

The increasing installation of solar panels has raised concerns on how their EoL should be managed. Therefore, there is the need to investigate the impact of the waste from solar PV panels.

1.2 Statement of the Problem

1.2.1 Studies on solar photovoltaic technologies

The change from traditional fossil fuels to the use of renewable energy-based economies has lead to the emergence of photovoltaic technology as a main contributor. The PV system can be referred to as a technological option to convert solar radiation into electricity. In the early times of 1980, the technology was already being applied, with the first ever substantial photovoltaic power being generated in the early 1990s (Tao & Yu, 2015). Over the past decades, the PV market has seen the dominance of Si-crystalline (mono or poly) panels, which are also the most used PV technology. In the quest to reduce the cost of producing these panels, other photovoltaic technologies have been developed as substitutes. They include Hybrid and organic cells, CdTe and CIGS thin films and Siamorphous. Nevertheless, Si-crystalline (mono or poly) panels, remains the most profitable (SolarPower Europe, 2017; Padoan et al. 2019). The usage of toxic elements (Cd in CdTe) and/or rare-critical elements in the production of these PV technologies and alternatives to Si-crystalline panels are the main limitations to their use extensively. As a result of this, the market shares of these technologies have been captured as Si-polycrystalline having 51%, Si-mono having 41%, with CdTe and CIGS having 5% and 2% respectively (IRENA, 2019).

The polycrystalline/multicrystalline modules contain aggregated atoms arranged randomly in small monocrystalline grains. The monocrystalline modules, however, contains a single direction-oriented atoms of high homogeneity structure achieved through the Czocharalski method which is a laborious production process (Padoan et al., 2019). The most efficient, cheapest, and easiest cells produced and readily utilised are the silicon-based cells. With constituent materials like lead, tin, silver, plastic, silicon, glass and aluminium, the silicon technology is highly recyclable to recover the materials mentioned (Daljit Singh et al., 2021).

The thin film technology contains similar components with other substances like cadmium telluride or gallium that are cost intensive and difficult when it comes to the process of recycling the constituent materials. There are toxic substances in both technologies. For instance, trace amounts of tin and lead in the silicon modules and gallium and cadmium in the thin film modules that may cause harmful health and environmental effects. These include depression, immune system malfunction, hyperactivity and impulsive behaviour, aggression, nervous system disruption, effects on the aquatic ecosystem, and disturbance to the soil (Mahmoudi et al., 2020) when the modules are carelessly disposed.

1.2.2 Treatment of EoL solar photovoltaics

In the coming years, as solar panels reach their EoL stage, major issues will emanate from the solar panel waste created. The Japanese Environment Ministry realized in 2040 there will be a swift increase in the production of these panels from 10,000 to 800,000 tonnes, however, there are no measures to safely dispose these solar panel waste (Chowdhury et al., 2020; Husain et al., 2022). In the same vein, China has no plan for the effective disposal of old solar panel though they produce the largest amount of solar PV waste almost as twice as the United States. Roughly, 20 million tonnes of waste are likely to be produced in China by 2050 that is about 2000 times the weight of the Eiffel Tower (Cai, 2022; Xu et al., 2018).

The first country among the European Union to formally approve the proposal by the European Union’s (EU’s) Waste Electrical and Electronic Equipment (WEEE) Directive on the processing of the photovoltaic constituents was the United Kingdom. It was stipulated in the regulation that all the PV panels either locally produced or imported into the UK should be registered to the conformity plan and the producers are required to state all key information on the panels like the number produced and the amount imported when applicable. A revision of the electrical and electronic equipment regulations was conducted by Germany. This revision required the importers and producers to make formal registration of their product and take full responsibility of the end-of-life treatment where falters are subject to a huge fine (Monier & Hestin, 2011; WEEE Directive, 2012; Xu et al., 2018).

Outside the EU market, very few other countries have made this initiative of regulating waste production from solar panels. The California state in America having obtained a large solar market has developed a proposal for the supervisions and controlling of waste solar equipment parts. Through the intense promotion of recycling, the Department of Toxic Substances Control (DTSC) seeks to reduce the landfill disposal of the harmful parts of the waste panels. A recycling project was suggested in 2010, towards the treatment of solar panels as dangerous waste. China, in recent times, has gained recognition of being a world leader in the installation of PV systems, yet policies and regulations on management of waste is absent (Ding et al., 2016; Zhao, 2012).

1.2.3 Environmental assessment on EoL solar PV systems

The 25 years life expectancy of the solar PV is likely to cause the production of waste to lag behind the installations of the Solar PV modules. As the percentage of installation increases, the issues of future disposal also increase. 1MW solar PV system could produce 90 tonnes of used PV modules and may have to be landfilled (Kannan et al., 2006). The landfilling of solar panels may pose serious environmental and health risks if they are leached to the ground and water (Mahmoudi et al., 2018; Xu et al., 2018).

A number of studies have been conducted on the environmental impacts of the EoL solar panels on the environment and suggested various approaches to the treatment of these panels (Curtis et al., 2021; Goe et al., 2015; Mahmoudi et al., 2020; Padoan et al., 2019; Paiano, 2015). However, there remain the issue of localising these assessments to better aid the development of effective policies and recycling initiatives. Even in developed countries, the management of PV panel wastes is not effective under most of the industry lead EoL cycle and recycling programs (Bilimoria & Defrenne, 2013; Klugmann-Radziemska, 2013). This presents a huge problem as effective recycling technologies will lead to an efficient circular economy.

Therefore, a proactive approach should be employed to monitor the quantity and quality flow of the solar PV waste stream through long term forecasting and monitoring. This is a necessary first step to develop awareness of the kind of technologies on the market and the potential volume to be treated in the future. Discarded modules should be closely monitored from the waste source throughout its treatment process (Mahmoudi et al., 2019). The current progress of the PV waste stream needs to be examined locally to make an informed decision on which treatment or policy pathway will be environmentally beneficial or have less impact on the environment at a national and local level.

1.3 Gaps in knowledge

Lack of primary data as input for life cycle analysis on rooftop solar panels in Australia

Latunussa et al. (2016) in their research revealed that, Life Cycle Assessment (LCA) studies conducted on solar PV panels mostly exclude the EoL stages (Gerbinet et al., 2014) and this is as a result of the lack of primary data as input for life cycle inventory. A recent attempt by Mahmoudi et al. (2019) to forecast the flow of PV waste in Australia saw the use of secondary data and methods from Domínguez and Geyer (2017) who also collected the data from the International Renewable Energy Agency (IRENA) report using the market share of different systems for their forecasting (Kim & Park, 2018). Their research revealed the increase projection of waste from solar panels in the coming years. However, the lack of primary data has made it difficult to assess the environmental impacts associate with EoL PV panels in Australia and locally. Several LCA studies on PV waste assume most of the data as input for the assessment (Ansanelli et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016; Mahmoudi et al.,

2020) especially the transport distance of the PV waste source to the recycling plant which is the highest emission factor in an LCA analysis when it comes to EoL solar panels. There is urgent need to identify the current practice of PV waste management in Australia to effectively map out the appropriate treatment pathway to aid in gathering essential primary data for LCA analysis.

Little or no studies on the environmental impact of rooftop solar waste in Australia

Solar PV panels are made with hazardous substances which may be released into the atmosphere or leach into the ground if not properly disposed (Goe & Gaustad, 2016b; Mahmoudi et al., 2018; Savvilotidou et al., 2017) and without a proper assessment of their impacts, these modules may cause serious harm to the environment and humans. According to Tsoutsos et al. (2005), human health impacts is one of the important impact categories when it comes to assessing the EoL of solar PV panels and these impacts may depend on optimal routes for the waste or geo-spatial dependence (Goe & Gaustad, 2016b).

This iterates the need for an optimised reverse logistic network within a spatial environment that creates an effective estimate on transport distances for a local or region in this case South Australia (SA), as primary data to assess environmental impacts of EoL rooftop solar panels. Sica et al. (2018) mentions the importance of the EoL stage of PV panels as these materials might be reused or incinerated and lost or could cause environmental effects when disposed. Studies that look into rooftop solar in Australia are limited to the thermal performance and strategies to increase the penetration of rooftop solar (Buckman et al., 2014; Burtt & Dargusch, 2015; Deeba et al., 2016; Mountain & Szuster, 2015; Nicholls et al., 2015; Ratnam et al., 2017; Zahedi, 2009).

Australia remains the highest consumers or users of rooftop solar panels in the world. However, there is lack of studies tailored regionally to the environmental impacts of the panels once they reach their EoL. Previous studies (Mahmoudi et al., 2020; Salim et al., 2019) have examined the impacts nationally and the drivers and barriers of EoL solar panels but have not strategically estimated the environmental impacts using primary data from a regional case study. There is therefore the need to research into the impacts of rooftop solar panels regionally especially in South Australia as it remains the state with a solar PV manufacturing plant and the first PV waste recyclers.

Currently no policy governing the disposal of solar PV panels in Australia.

The European Union mandates the producers of solar PV panels to appropriately collect, recycle, reuse or dispose of solar PV waste through the Waste Electrical and Electronic Equipment (WEEE) Directive introduced in 2012 (Directive 2012/19/EU). Apart from the EU, other countries are attempting to follow suit with Australia looking to add solar panels to the Product Stewardship Act (Australian Government, 2022). According to the Australian Department of the Environment and Energy, “In 10 years’ time Australia should have a Circular Economy Plan well underway with ambitious mandatory waste reduction targets set for identified problematic wastes” (Australian Government, 2019). Among the problematic waste is the EoL solar PV panels. There is currently no policy guiding the management of EoL solar panels in Australia. According to researchers (Bilimoria & Defrenne, 2013; Klugmann-Radziemska, 2013; Xu et al., 2018), not enough policies are being developed in handling solar PV waste. However, with the health risks associated with the improper disposal of EoL solar PV panels and its waste growth in the future, there is the need to introduce policies and regulations.

1.4 Research questions

The following questions are posed in relation to the research:

1. *What is the current waste management practice(s) in dealing with rooftop solar photovoltaic panels in Australia?*

This question seeks to explore the material composition across the various technologies of solar photovoltaics in Australia and determine the alternative strategies and treatment pathways of EoL photovoltaic panels in Australia. Finding answers to this question will help develop guidelines that are necessary for the sustainable management of EoL solar photovoltaics in Australia.

2. *What are the significant factors that influence the treatment of end-of-life rooftop solar photovoltaic panels in Australia?*

This question will tackle the current volume and distribution of solar photovoltaic waste in South Australia. It will also probe into the logistics and infrastructure needs affecting the management of solar photovoltaic waste in SA. The answers to how policy and transport influence the management of solar photovoltaic waste in South Australia will be established.

3. *How can the information gathered from the assessment inform policies on the management of waste from rooftop solar photovoltaic panels in Australia?*

The last question looks at the environmental impacts associated with policy and regulatory options in South Australia. Moreover, it tackles the environmental impacts associated with transport through recycling of EoL solar photovoltaic panels. This will aid in suggesting sustainable policy options for the management of solar photovoltaic waste in South Australia.

1.5 Aims and objectives

1.5.1 Aim

The aim of the study is to assess the environmental impacts of waste from rooftop solar photovoltaic panels in Australia to inform sustainable policies.

1.5.2 Objectives

To achieve the aim of the research, the following objectives are devised:

Objective 1. *To explore the current practices of managing end-of-life rooftop solar photovoltaic panels in Australia.*

The study identifies the various technologies and composition of solar photovoltaic panels in Australia. The research then examines the alternative strategies and initiatives of EoL treatment pathways for solar photovoltaic panels in Australia. An assessment framework is developed for managing EoL solar photovoltaic panels in Australia, which is also adopted for the impact assessment.

Objective 2. *To develop an optimised system approach in dealing with solar photovoltaic waste in Australia.*

This objective quantifies the amount of waste generated from the decommissioning of rooftop solar photovoltaic panels in South Australia. It investigates the influence of reverse logistics and infrastructure needs on the management of solar photovoltaic waste in South Australia. An optimised system network for the collection and transport of EoL rooftop solar photovoltaic panels is developed for the recycling and recovery in South Australia.

Objective 3. *To assess the environmental impacts of end-of-life rooftop solar photovoltaic panels in Australia within the developed assessment framework.*

The last objective compares the environmental impacts of different policy options in the management of EoL solar photovoltaic panels in South Australia. The study then investigates the environmental influence of transport on the recycling of EoL solar photovoltaic panels. The last was to provide policy suggestions for the management of solar photovoltaic waste in Australia.

1.6 Significance of the research

This research contributes significantly to the area of academia, methodology and application within the EoL solar PV research field. The multidisciplinary nature of the research comes with many benefits to the built environment, engineering, and public health fields of research as well as its associated benefits to the government, industry and the public.

First of all, in Australia, other studies have investigated the generation of PV waste and its impact assessment, however, they did not incorporate the local factors that contributes to the results of the impacts especially the transport distance and the influence of current and future policy in the management of the PV waste stream. The significance of the studies lies with the innovative approach in developing a reverse logistic network for the management of PV waste from transfer stations to recycling centres in SA. The methodology offers an innovative way for researchers to develop their own contextual logistic network for the management of PV waste in other states in the country. The study also provides primary inventory data for life cycle assessment. The transported distance estimated offers real inventory data for the calculation of environmental impacts from recycling processes, which is used in LCA for the first time across the world.

Secondly, the study provides practical policy suggestions for government departments on the best policy pathway for the treatment of solar PV waste in Australia. It also generates a forecast in the next 30 years how the solar PV waste stream will behave in SA to aid in the development of a waste management plan for the state and the country. The data provided for the environmental impact assessment can aid the state and local governments, and other stakeholders to forecast other impacts such as economic feasibility and social impacts that comes with choosing any of the policy options. The information provided serves as a knowledge database for recyclers to plan their collection routes to minimise environmental emissions. It provides manufactures and suppliers information on how best to manage their installations and whether future operations like recycling can boost their sales, and how the enacted policies may affect them when it comes into force.

Lastly, on a national scale, the results of this study can serve as a guide for policy makers to process the introduction of a product stewardship scheme for Australia. This research is the first of its kind, when it comes to the development of an optimised system network for a particular locality using postcode data and GIS. Several studies across the globe when conducting LCA assumes specific distances from the waste source to the recycling centre. This study bridges that gap by using an estimated regional transport distance in the LCA simulation within the solar PV waste recycling processes.

1.7 Thesis structure

This thesis is divided into eight chapters. The ***Chapter 1*** (*Introduction*) explains the introductory background of the research, the problem statement, gaps in research, research questions, aim and objectives, and the significance of the research. ***Chapter 2*** (*Literature review*) presents the literature on EoL solar photovoltaics. The chapter is in manuscript format and presented as published work. ***Chapter 3*** (*Methodology*) describes the various methods employed in achieving the objectives of the research. ***Chapter 4*** (*Results: part 1*) presents the details on the current management practices of EoL solar photovoltaic panels in Australia. The chapter is presented in a manuscript format that is under revision. ***Chapter 5*** (*Results: part 2*) provides the details on the optimised logistic network for managing EoL PV panels in South Australia. This chapter is presented as a published paper. ***Chapter 6*** (*Results: part 3*) presents the environmental impact assessment of solar PV waste treatment pathways in South Australia. This chapter is presented in a manuscript format that is under review. ***Chapter 7*** (*Discussion*) elaborates on the previous chapters and makes comparative arguments with previous and current literature in a profound discussion**. *Chapter 8*** (*Conclusion*) gives a conclusion on the thesis highlighting the findings of the objectives and the contribution towards the body of knowledge and industry.

Chapter 2. Literature review

2.1 Introduction

The large exploitation of solar PV modules, leads to undesirable waste accumulation, affecting the environment. Solar PV waste management research is an emerging field that has received more attention recently, affected by the increase volume of solar PV disposal However, only a few studies have reviewed the current trends in solar photovoltaic waste management. This chapter reviews the emerging trends in solar photovoltaic waste management. Performance and efficiency of polymer solar cells have been the centre of recent research due to its light weight, flexibility, environmentally harmless materials, and lower cost over the silicon based solar cells. However, it will be years before they are ready for commercialization for specific applications. The silicon-based modules are the most installed to date and will be coming to their EoL very soon. Moreover, little attention is given to areas like recycling, recovery, policies, and regulations on solar PV module waste management.

2.2 List of manuscripts

This part of the research has been produced as a journal article, published in *Solar Energy*:

Oteng, D., Zuo, J., & Sharifi, E. (2021). A scientometric review of trends in solar photovoltaic waste management research. *Solar Energy*, 224, 545-562. DOI: https://doi.org/10.1016/j.solener.2021.06.036.

The paper is presented here in a reformatted version for consistency of the thesis presentation. The accepted manuscript can be found in Appendix A.

Statement of Authorship

Title of Paper	A scientometric review of trends in solar photovoltaic waste management research
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Oteng, D., Zuo, J., & Sharifi, E. (2021). A scientometric review of trends in solar photovoltaic waste management research. *Solar Energy*, *224*, 545-562. https://doi.org/10.1016/j.solener.2021.06.036

Principal Author

Name of Principal Author (Candidate)	Daniel Oteng		
Contribution to the Paper	Conceptualization, Methodology, Data curation; Writing - original draft; Formal analysis		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	02/11/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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2.3 A scientometric review of trends in solar photovoltaic waste management research

Abstract

Solar photovoltaic (PV) systems are effective measures to reduce the greenhouse gas emissions related to the generation of power. However, the large exploitation of solar PV modules, leads to undesirable waste accumulation, impacting the environment. Solar PV waste management research is an emerging field which has received more attention recently, affected by the increase volume of solar PV disposal However, only a few studies have reviewed the current trends in solar photovoltaic waste management. This study aims to review the emerging trends in solar photovoltaic waste management research from 1974 to 2019 using the scientometric review techniques. A total record of 4683 articles were retrieved from the Web of Science database on solar PV waste. The co-word, co-citation and co-author analysis of the retrieved articles were conducted to determine the emerging trends in the PV waste management research. The results revealed that, with a gradual growth in the PV waste management research performance and efficiency of polymer solar cells have been the centre of recent research due to its light weight, flexibility, environmentally harmless materials, and lower cost over the silicon based solar cells, however, it will be years before they are ready for commercialization for specific applications. Thus, the silicon-based modules are the most installed to date and will be coming to their end-of-life very soon. The results also show that, little attention was given to areas like recycling, recovery, policies, and regulations on solar PV module waste management. Future research should focus on assessing the recycling potential and emissions from current solar PV modules and the easily remanufacture, recovery and reuse of future solar PV modules.

1. Introduction

Photovoltaics is a renewable source of energy that converts solar radiation to electricity, which provides a perfect alternative to traditional fossil fuels as the world transitions to a renewable energy-based economy. The application of this technology has been in existence since the 1980s, but the 1990s has been recorded as the year of the first appreciable application of power from solar photovoltaics (Padoan et al., 2019; Tao and Yu, 2015). Solar energy is non-polluting, efficient, reliable and safe. There is a global interest recently in solar energy particularly PV technology. This has seen the use of solar PV modules climb sharply because of government's effort to achieve clean energy globally. PV technology is to become one of the main energy sources worldwide because of its expectation to significantly produce a portion of the world's energy consumption (Xu et al., 2018).

The awareness of the effects of greenhouse gas emissions has trigged an upsurge in the need for clean energy. The need is much evident in the current drifts into photovoltaic installation. The International Energy Agency in their 2021 preliminary market report, revealed that the global market for PV grew significantly despite the COVID-19 pandemic. This shows an installation of at least 139,4 GWdc of installed and commissioned PV systems worldwide last year. They further reported that, the relative global capacity has cumulatively reached 760,4 GWdc at the end of 2020 (IEA-PVPS, 2021). The use of Photovoltaic power generation can be considered a favourable technology because it can be used at any location to produce clean energy (emission free) during the day and night times if the power system has some storage technology incorporated in it. The implementation of the PV technology is being promoted by some governments from a worldwide perspective. These governments incorporate the use of incentives and target setting in making PV technology occupy a significant proportion of their energy needs (IEA-PVPS, 2017).

The application of PV system for solar energy becomes a viable choice for power production to decrease greenhouse gas (GHG) emission and life cycle energy use. Studies have identified that an abuse of this could however lead to unwanted environmental impacts in relation to disposal of waste and material availability (Fthenakis, 2004; Fthenakis and Moskowitz, 2000; Kannan et al., 2006; Nieuwlaar et al., 1996; Phylipsen, 1995). The exponential increase in the PV panel waste is anticipated to reach over 60 to 70 million tonnes by 2050 (Ardente et al., 2019; IRENA and IEA-PVPS, 2016). Moreover, PV modules contain dangerous materials that poses serious human health risk as well as risk to the environment (Mahmoudi et al., 2018). These dangerous materials can be found in PV modules such as Copper Indium Gallium Selenide (CIGS) which contains Cadmium (Cd), Lead (Pb) and Selenide (Se); Cadmium Telluride (CdTe) which contains Cd and Pb; and Crystalline Silicon (c-Si) which contains Pb (IRENA, 2016; Bang et al., 2018; Podoan et al., 2019; Mahmoudi et al., 2021) Workers who are exposed to these harmful waste materials and gases such as poly/brominated flame retardants, heavy metals, and Chlorofluorocarbons (ozone depleting carbons) are prone to severe health impacts, where some wider population may be affected by the exposures as well (Fiandra et al., 2019). The production of semiconductors springs up the most heath concerns in solar panel use because it contains potentially dangerous materials (Moss et al., 2014). Moreover, hazardous wastes are generated by the panels after their useful life which is also another environmental problem. Due to their life expectancy of 25 years, the reuse and recycling of these panels was not of much concern at the development stages, but, presently, an appreciable number of these already installed solar panels are entering their end-of-life stage. Therefore, an effective management of these retiring panels are now becoming an environmental issue of much concern (Aman et al., 2015; Xu et al., 2018).

1.1. Knowledge gap and research objectives

Photovoltaics is a broad research area because of its multidisciplinary application in various research fields. However, previous reviews on photovoltaics has leaned towards general application, capacity building and recycling. The waste management and end-of-life aspect is an emerging field and has received little attention when it comes to reviews, a gap this research tends to bridge. Solar panel waste recycling status by Xu et al. (2018) discussed the processes of the retrieval and dismantling of waste solar panels with an in-depth discussion of various recycling techniques and methods. Another review by Sica et al. (2018) addressed the end-of-life management of PV modules focusing on technology, life cycle, production, environmental issues, and their end-of-life explained into details. The study ended with suggestions and future directions on how the PV industry is becoming a big player in circular economy and how it is being shaped through the lens of natural systems in providing services and goods. Both studies adopted a qualitative review of the literature without necessary going through database searches.

Similarly, a review by Salim et al. (2019a) highlighted drivers, barriers and enablers of battery energy storage and photovoltaic systems when it comes to their end-of-life. They identified some drivers clustered under economic, social, and environmental. The barriers were also grouped under policy and economic, recycling infrastructure, environmental, market and social clusters. With the final which is the enablers falling under recycling technology and infrastructure, behavioural, policy and economic, market and social. A discussion of the current research trend was also highlighted, finally ending up with the development of a conceptual framework for solar energy systems when it comes to the circular supply chain. The study was limited to 2000 and 2018. In a recent systematic literature review carried out by Mahmoudi et al. (2019a), they discussed the trend analysis, bibliometric details and treatment procedures of end-of-life PV modules. Their review considered all published research available at Web of

Science (WoS), Scopus and Science direct by 2018. With both of them using the WoS database in addition to Scopus and Science direct respectively.

Moreover, Salim et al., (2019a) and Mahmoudi et al., (2019a) analysed 817 and 70 journal papers respectively as compared to the number of papers that is used in this study (4683 articles). Most importantly, waste and end-of-life solar PV panel management research is an emerging field and needs to be constantly reviewed as new articles emerge (Xu et al., 2018; Chowdhury et al., 2020; Mahmoudi et al., 2021). Furthermore, none of the previous studies on solar photovoltaics and waste have mapped out the co-author relationship and analysis linking authors and their institutions. Again, these studies have not further studied into details of co-citation, co-author, and co-word analysis. This research is relevant because, bibliometrics review using the aforementioned analysis is a valuable complement to traditional ways of reviewing literature, thus, it creates more understanding through the relationship that exists (Fonteyn et al., 2020) within the full structure of the solar PV waste research domain. It presents a broader perspective on solar PV through the collaborative ties that links various researchers within the domain, links and maps out similar research elements as well as identifying information flow and influential researchers within the field of solar photovoltaics research.

From the above, this study differentiates itself by bridging the gap in literature on solar PV waste research through scientometric analytical review. This study provides an in-depth understanding of the current research trend on solar photovoltaic waste research through all the years till now. It also identifies future research agenda and the gaps in literature. It aims to highlight the emerging trends of solar photovoltaic waste research through i) co-word analysis, ii) co-citation analysis, and iii) co-author analysis using the retrieved data from the WoS database.

This paper consists of five sections: The *first* section gives and introduction and the reason for the research as previously explained. The *second* section explores the methods that is adopted in analysing the study. The selection of the database, keywords, and tools as well as the scientometric techniques used are explained in this section. The *third* section describes the analysis and the results from the research. It discusses the co-word, co-citation, and co-author analysis of the study. The discussion of the results is elucidated in the *fourth* section of this paper. The *last* section finally lays down the conclusion.

2. Methodology

Data analysis in this paper is based on the science mapping methodology. According to Chen (2017), science mapping represents a "generic process" of domain analysis and visualisation. This process includes several components within a scientific literature that enables the exploration and interpretation of significant trends and patterns highlighted by visual and scientometric analytical indicators, metrics, and tools. Bibliometric or Science mapping is a spatial representation relating specialities, fields, disciplines and individual authors and documents to each other showing their relative locations and physical proximities (Cobo et al., 2011). Science mapping overlaps between scientometric, bibliometric and informatics in its analysis yet they are independent techniques on their own (Hood and Wilson, 2001). Studies based on science mapping typically applies either a scientometric or bibliometric analysis technique (Hosseini et al., 2018).

Scientometric analysis compared to bibliometrics delivers a broader approach when it comes to measuring and analysing bibliometric tools and data, to reveal potentially insightful trends and patterns whiles bibliometrics predominantly focuses on the literature per se (Hood and Wilson, 2001). Several studies employ different scientific methods when reviewing literature such as systematic literature reviews (Curtin et al., 2019; Wassie and Adaramola, 2019; Wu, H.Y. et al., 2019), bibliometric technique (Chen et al., 2017), scientometric analysis (Chen et al., 2014; Montoya et al., 2014; Shi and Liu, 2019), and content analysis (Herbes and Ramme, 2014) within areas like renewable energy, sustainability, construction, and diseases. This study therefore employs scientometric techniques in its analysis as it broadly covers bibliometric data, tools, and methods.

2.1. Database and keyword selection

The quality of a scientific review depends on the selection of appropriate databases and the methodology used. Retrieval of data from bibliometric sources such as Scopus, WoS, Medline, Science Direct and Google Scholar (Cobo et al., 2011; Mongeon and Paul-Hus, 2016), are relevant in collecting information within several scientific fields. However, results may vary depending on the database used as their coverage differs in each database when it comes to research disciplines (Mongeon and Paul-Hus, 2016). Clarivate Analytics uses the Web of Science citation database, consisting over 155 million records in 34,000 journals having over 1.7 billion cited references across several disciplines (Clarivate Analysis, 2020), and is mostly used by the scientific research community due to its quality (Niñerola et al., 2019). This study employs the WoS database because of its scientific robustness and comprehensiveness (Neto et al., 2016; Olawumi and Chan, 2018). The search is conducted within the Web of Science Core Collection (including Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Emerging Sources Citation Index (ESCI), Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH), Conference Proceedings Citation Index- Science (CPCI-S), and Arts & Humanities Citation Index (A&HCI)) database on 10th December, 2019. Many articles would have been under review or published after the database search which means publication number may increase at the end of the year. These articles are not analysed in this paper but may be cited in the discussion.

The keywords for this study are within the waste research studies conducted by several researchers on solar or photovoltaic cells. Therefore, these keywords were adopted (Mahmoudi et al., 2019a; Salim et al., 2019a; Shubbak, 2019; Sica et al., 2018) and modified (keywords from the waste hierarchy (Parto et al., 2007) formulated by Ad Lansink through expert opinions to suit the purpose of this study. A search criterion was then developed to select the required articles needed for the studies. Keywords such as *"solar panels" OR photovoltaic OR "photovoltaic cells" OR "pv panels" AND "End-of-life" OR waste OR recycl* OR reus* OR recover* OR dispos* OR treatment,* were combined with the Booleans (“AND” and “OR”) and used as the search query in the WoS database. These keywords needed to occur within the topic search of the Web of Science Core Collection.

An initial search produced 6520 records, among these were academic literature consisting of 4857 articles, 1724 proceedings papers, 274 reviews, 16 early access, 7 editorial materials, 7 meeting abstracts, 3 letters, 1 note, 1 book chapter, 1 retracted publication and 1 correction from 13 different languages. This search was then limited to articles which were written in English in all years. All the other documents were also excluded with the exception of the articles and reviews because of the comprehensiveness and reputability of these sources as “certified knowledge” (Olawumi and Chan, 2018). Thus, 4683 total records were retrieved for analyses. The records were then downloaded and imported into EndNote version X9 reference manager for analysis.

2.2. Tool selection

The selection of an appropriate visualisation tool for analysis is very critical when it comes to scientometric analysis. There are several existing science mapping tools such as VOSviewer (van Eck and Waltman, 2009), VantagePoint (Porter and Cunningham, 2004), Sci^2 Tool (Chen et al., 2012), Network Workbench Tool (Börner et al., 2010), Leydesdorff’s Software (Leydesdorff and Schank, 2008), IN-SPIRE (Wise, 1999), CoPalRed (Bailón-Moreno et al., 2005), CiteSpace II (Chen, 2006), Bibexcel (Persson et al., 2009), Gephi (Bastian et al., 2009) and HistCite (Garfield, 2004) for visualising and analysing temporal, dynamic and structural trends and patterns within a scientific literature. Moreover, analytical methods such as network, temporal (burst detection) and geospatial analysis are conducted using these software tools (Cobo et al., 2011). The various tools perform differently according to each of their abilities and strengths when it comes to bibliographic data analysis.

Thus, choosing an appropriate tool is critical when thoroughly analysing your data. A careful analysis of the various software established the need for the use of CiteSpace, Gephi and VOSviewer for this research. This is because Citespace facilitates the detection of abrupt changes and emerging trends within scientific literature (Chen et al., 2012), Gephi is used to explore and manipulate networks (Bastian et al., 2009) whiles VOSviewer explores, visualises, and produces bibliometric maps and networks (Van Eck and Waltman, 2018).

2.3.Scientometric techniques

Establishing a relationships and links between units such as authors, cited references, documents, and journals through co-word analysis, co-citation analysis, co-author analysis and bibliographic coupling are the analysis involved in scientometric techniques (Cobo et al., 2011). Processing the data retrieved required the use of three scientometric techniques for this study, and among them are 1) co-word analysis: involves keyword co-occurrence and clusters as well as burst detection of the top keywords, 2) co-citation analysis: deals with the co-cited author, documents and journal visualisation and relationships within downloaded papers from the WoS database, and 3) co-author analysis: compares the occurrences and linkages between authors, countries and institutions. Table A1 in appendix A shows the details and description of the techniques used.

3. Analysis and results

The 4683 retrieved articles were analysed using CiteSpace, Gephi and VOS viewer software to establish the emerging trends of solar photovoltaic waste research. According to Cobo et al. (2011), critical information can be extracted through network, temporal and geospatial analysis. The aforementioned analysis was performed using the software explained earlier. This section therefore explains the various analysis applied to the data retrieved from the database.

3.1. Publication distribution

Research on solar photovoltaics was first referenced as back as 1974 in the journal of applied physics (Fahrenbr.Al and Bube, 1974), where Fahrenbr and Bube researched on the effects of heat treatment on copper sulphide/cadmium sulphide (Cu_2S-CdS) heterojunction photovoltaic cells. Research concerning photovoltaics was also cited by (Lawrence et al., 1984; and Miyata et al., 1987) in 1984 and 1987. From these years, photovoltaic research has received a study interest since 1991. A look at fig 1 shows the growth of solar photovoltaic module waste research through the years till now. Particularly in 2014 where there was a sharp climb of about 438 documents within the year. This shows the attention solar photovoltaics (PVs) waste research is receiving and will continue to receive because of the retirement of old solar PV modules in the coming years. This upward increase and interest in this area of research has propelled several researchers (Salim et al., 2019b; Sica et al., 2018) to look into the end-of-life management of solar PVs. A significant record of 636 publications on solar photovoltaic waste module research occurred in 2018 only. This shows the gradual interest waste research is receiving recently and how best researchers can steer towards new innovation and creativity when it comes to solar photovoltaic modules.

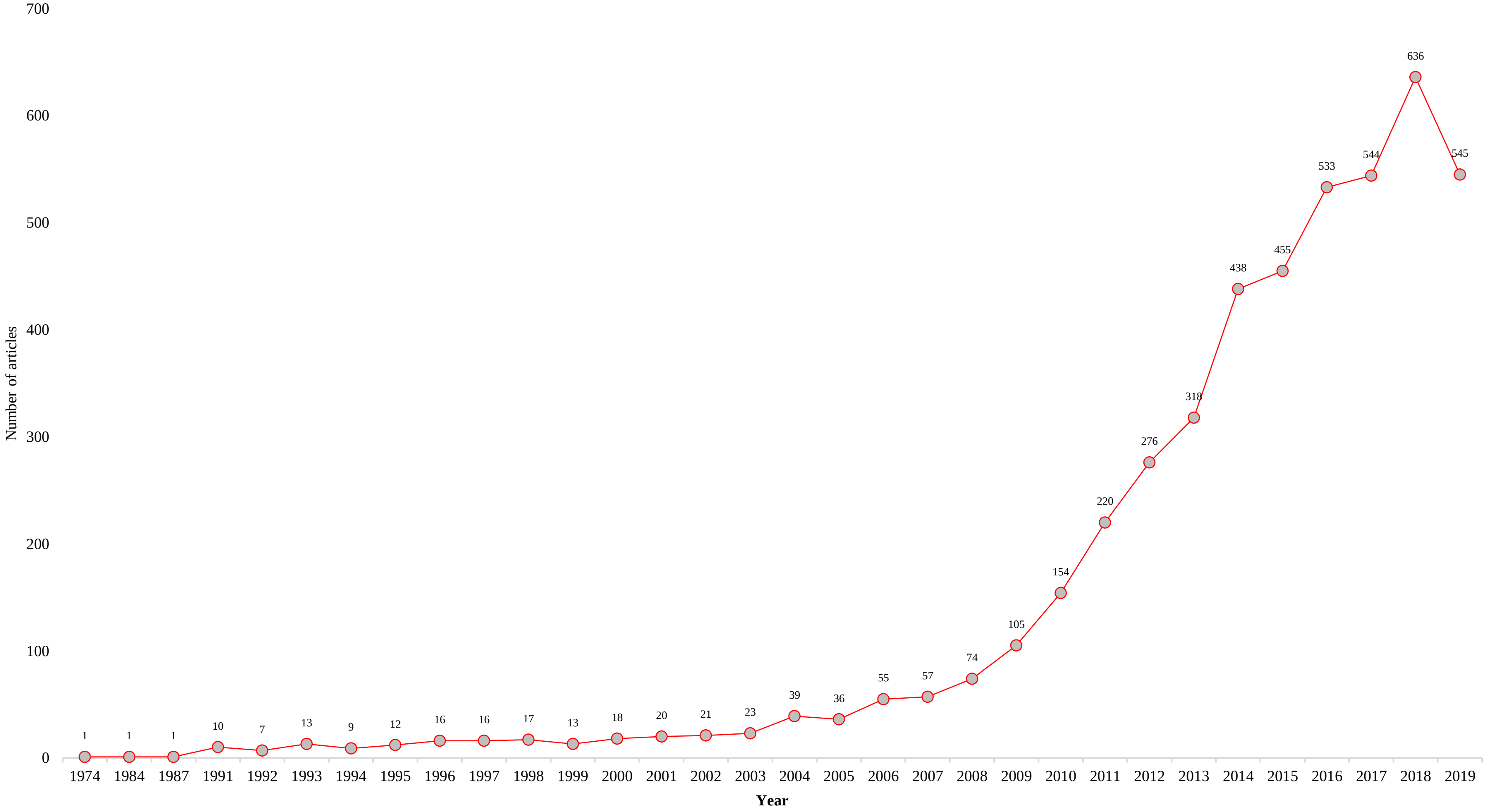


Fig. 1. Annual publication distribution of Solar PV waste research

3.2. Distribution of articles in journals

Among the articles retrieved, journals that produced 45 and more articles were selected making up the top 20 journals within the field. Table 1 illustrates the distribution of the publications within the top 20 journals selected. Their characteristics such as the number of articles produced, number cited, journal impact factor (JIF) and their Scimago Journal and Country Ranking (SJR) were accessed. Among the 20 journals, Solar Energy Materials and Solar Cells, ACS Applied Materials and Interfaces, Solar Energy, Journal of Materials Chemistry A and Journal of Physical Chemistry C produced more than 100 articles related to solar photovoltaics waste research.

Table 1
Characteristics of top 20 journals

S/N	Journal Name	No. of Articles	Citations	JIF	SJR	*JIF Ranking*
1	*Solar Energy Materials and Solar Cells*	204	6171	6.984	1.83	*10*
2	*ACS Applied Materials & Interfaces*	154	3405	8.758	2.57	*6*
3	*Solar Energy*	108	2142	4.608	1.54	*12*
4	*Journal of Materials Chemistry A*	104	2864	11.301	3.43	*4*
5	*Journal of Physical Chemistry C*	102	3964	4.189	1.48	*13*
6	*Organic Electronics*	90	1743	3.310	0.90	*16*
7	*Renewable & Sustainable Energy Reviews*	78	2756	12.110	3.63	*3*
8	*RSC Advances*	70	588	3.119	0.74	*17*
9	*Applied Physics Letters*	68	2832	3.597	1.34	*14*
10	*IEEE Journal of Photovoltaics*	67	885	3.052	1.00	*18*
11	*Applied Energy*	63	1585	8.848	3.61	*5*
12	*Journal of Applied Physics*	61	1784	2.286	0.73	*19*
13	*Journal of Cleaner Production*	61	754	7.246	1.89	*9*
14	*Renewable Energy*	59	1252	6.274	2.05	*11*
15	*Thin Solid Films*	58	1016	2.030	0.51	*20*
16	*Advanced Functional Materials*	57	7266	16.836	5.88	*2*
17	*Progress in Photovoltaics*	53	1359	7.690	1.86	*8*
18	*Energy Conversion and Management*	51	807	8.208	2.92	*7*
19	*Advanced Energy Materials*	49	1670	25.245	9.51	*1*
20	*Physical Chemistry Chemical Physics*	45	1002	3.430	1.14	*15*

InCites Journal Citation Report /Scimago Journal and Country Ranking (2019)

InCites Journal Citation Report from Clarivate analytics indicates that Advanced Energy Materials (25.245), Advanced Functional *Materials* (16.836), Renewable and Sustainable Energy Reviews (12.110), Journal of Materials Chemistry A (11.301) and Applied Energy

(8.848) are the top five journals with the highest impact factor in 2019 citation report with Advanced Functional Materials having the highest number of citations (7266) followed by Solar Energy Materials and Solar Cells (6171). The SJR was also compared with the JIF to reconcile the impacts these journals have on photovoltaic waste research. The results were similar when it comes to how the journals were ranked and the impact they had on photovoltaic research.

3.3. Co-word analysis

The analysis of the main concept and conceptual structure extracted from a research field is termed as co-word analysis (Cobo et al., 2011). The keywords extracted from the WoS database search through the title, abstract and keywords are analysed to obtain the term co-occurrences of the documents. This section explains the analysis of the network of co-occurring keywords and co-occurring subject categories.

3.3.1. Network of co-occurring keywords

The analyses of keywords are essential in determining key research areas (Shrivastava and Mahajan, 2016) across a field of study. Thus, keywords characterise the core research of a published paper and shows the boundaries within which a research area is depicted (Su and Lee, 2010). The network of a keyword provides a good picture of the knowledge area of research giving insight into the association and organisation of topics within a research domain. This is calculated on the basis of publications within which both these keywords appear together through the weight of their links (van Eck and Waltman, 2014). The network of co-occurring keywords was explored using the VOSviewer and CiteSpace software. Using all the keywords such as the author's keywords and keywords plus (indexed terms from journals) from the database, the relationship and patterns of the keywords were established. Fig. 2 shows a visualisation of the frequency or count of the keywords as well as the co-occurrence between them.

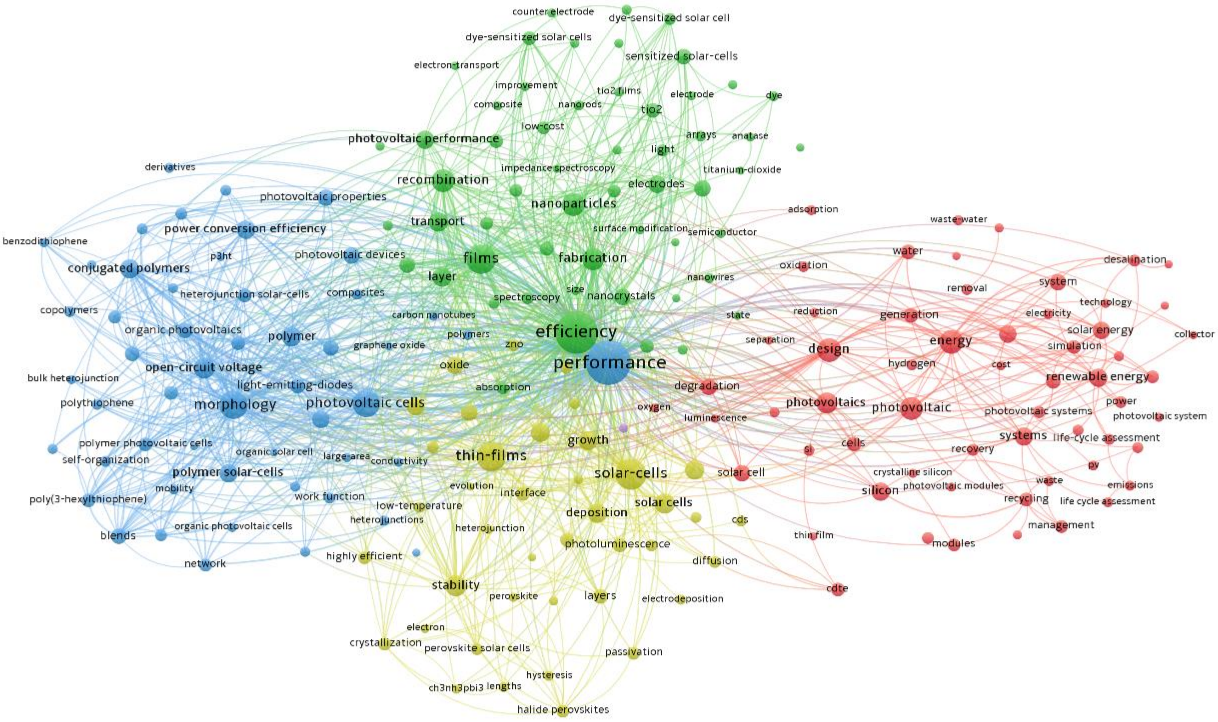


Fig. 2. Visualisation of co-occurring keywords

From a combination of over 14561 keywords analysed, 207 nodes surpassed the threshold of minimum thirty occurrences for the analysis in VOSviewer. The visualisation in Fig. 2 shows the keyword counts, where "performance" and "efficiency" received the highest frequency of 813 and 702 respectively. "solar cell" was the third highest with 647 counts. The others are "thin film" (470), film (418), morphology (332), photovoltaic cell (296), system (224), layer (243), polymer solar cell (225), energy (224), design (223), nanoparticle (218), photovoltaic (213), recombination (202), polymer (196), fabrication (194), open circuit voltage (168), conjugated polymer (159) and photovoltaics (158). Other keywords such as renewable energy, dye-sensitized solar cells, silicon, solar energy were also predominant. The visualisation clearly shows the trend of photovoltaic waste research, has leaned towards solar performance and efficiency for the past few years. Studies such as (Li, F. et al., 2012; Shen et al., 2013) looks at enhancing the performance of solar cells which could reduce the amount manufactured in volume needed for residential and commercial installation therefore reducing the amount of waste produced at the end-of-life of the PV panel. Moreover, there is gradual shift into environmental sustainability as old solar cells come to the end of their service life. There is therefore research into new ideas on how best these solar cells may become environmentally friendly whiles producing less waste.

3.3.1.1. Keyword clusters

Analysing keywords in clusters helps establishes emerging trends in literature. Clustering group keywords together establishing a link within the same field of research. CiteSpace supports the selection of cluster labels based on Latent Semantic Indexing (LSI), Log-Likelihood Ratio Test (LLR) and Mutual Information (MI). Moreover, thematic labels of each cluster include terms selected by either LLR which highlights the unique themes or LSI which identifies common themes (Chen and Song, 2019). These two selections can indicate different themes or turn similar. This study therefore uses the LLR in analysing the keywords. In giving a sound interpretation of the results, the silhouette and modularity has to be taken into consideration (Chen, 2016). The average homogeneity of the clusters, thus, the clustering configurations quality is measured using the silhouette value (Chen et al., 2010). The modularity, however, measures the degree with which a group of nodes in a network can be divided such that they are closer and tighter within the same group than in another different group (Chen et al., 2012). The modularity and silhouette representing the results of this analysis are Q = 0.330 and 0.587 respectively. The details of the twenty highest LLR labels are presented in the appendix table A2. The clusters are solar cell, dye-sensitized solar cell which appeared twice, Cadmium telluride (CdTe) solar cell and single-walled carbon nanotube. Table 2 gives the details of the characteristics of the clusters.

Cluster #0 is the largest cluster with 64 members and a silhouette value of 0.78 and is labelled “solar cell” by LLR. Other alternative labels are polythiophene and polymer nanoparticle. The most active citer in cluster #0 is Xi et al. (Xi et al., 2010), who did experimental research on improving the performance of organic solar cells. This cluster indicates the considerable research that has gone into organic solar cells in recent years and how researchers are still finding ways to make organic solar cells more efficient and productive. Organic solar cells in comparison with other types of solar PV modules, organic solar cells create a number of possible applications because they are potentially environmentally friendly, variable in colour, lightweight, flexible and cheap. Unfortunately, there are a lot of research being conducted on organic cells before they are ready for commercialization (Yin et al., 2020). Cluster #1 is the second largest cluster with 52 members and a silhouette value of 0.696 and is labelled "dye-sensitized solar cell (DSSC)" by LLR. The silhouette value of the five clusters are all above 0. 65, indicating a robust and meaningful results.

Table 2
Keywords cluster characteristics

Cluster ID	Size	Silhouette	Mean (Year)	Cluster Label (LLR)	Other Labels	Articles
0	64	0.780	2007	solar cell	polythiophene, polymer nanoparticle	(Nelson et al., 2009; Po et al., 2010; Yang et al., 2011)
1	52	0.696	2007	dye-sensitized solar cell	organic sensitizer, phenylenevinylene copolymer	(Wang et al., 2013; Yu et al., 2011; Zhao et al., 2010)
2	45	0.760	2009	dye-sensitized solar cell	solar cells, photovoltaic modules, crystalline silicon,	(Friedel et al., 2009; McDonald and Pearce, 2010; Yoon et al., 2010)
3	38	0.765	2003	CdTe solar cell	solar cells electrodeposition, chalcopyrite thin film	(Heath et al., 2004; Lincot et al., 2004;

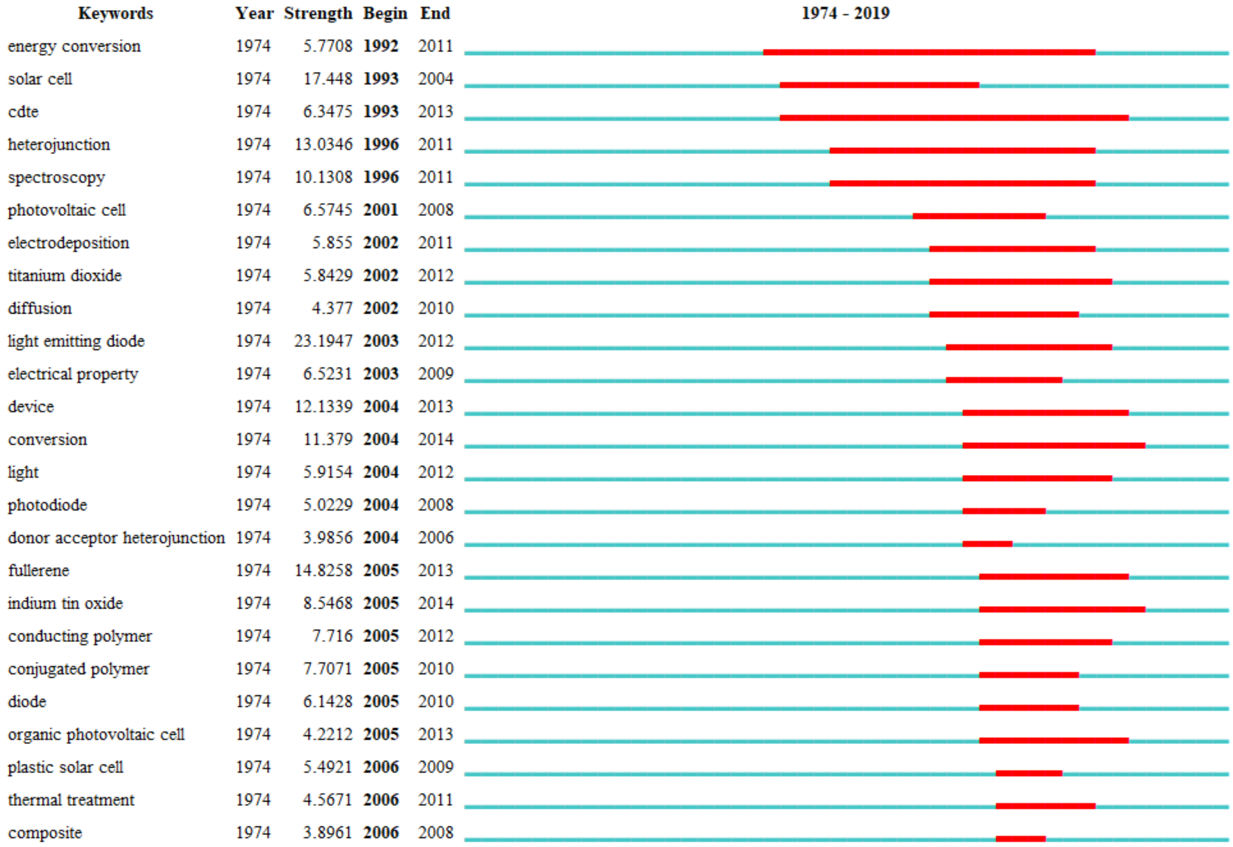
4	12	0.866	2005	single-walled carbon nanotube	solar cells, open circuit voltage, enhancement	Lupan et al., 2010) (Mistry et al., 2011; Stevens et al., 2009; Szeifert et al., 2009)

The alternative names are organic sensitizer and phenylenevinylene copolymer. The most active citer in the cluster is Yang et al. (Yang et al., 2013), followed by cluster #2 with 45 members and a silhouette value of 0.760 that is labelled “dye-sensitized solar cell” by LLR. Alternative names are solar cells, photovoltaic modules and crystalline silicon. Cluster #3 is the fourth cluster with 38 members and a silhouette value of 0.765 and is labelled “CdTe solar cell” by LLR. Alternative names are solar cells electrodeposition and chalcopyrite thin film. Cluster #4 has the least members (12) and a silhouette value of 0.866 and is labelled “single-walled carbon nanotube” by LLR the alternative labels are solar cells, open circuit voltage and enhancement. Dye-sensitized solar cells have been under extensive studies due to its ease of production, low toxicity and low cost since the early 2000s (Sharma et al., 2018). Cluster #1 and #2 clearly shows the efforts of researchers that has gone into the studies on dye-sensitized solar cells. The occurrence of mean year of both clusters between 2007 and 2009 depicts that, over the decade a lot of attention has gone into the performance and efficiency of DSSC. The mean years of all the clusters shows that, they have been formed relatively around old documents as the mean year ranges from 2003 to 2007.

3.3.1.2. Citation bursts and betweenness centrality

The rate of change throughout a field is measured by its burstness. Through a period of time, a sudden change in the frequency of an entity at a specific time shows its burstness. Burstness can be analysed through the use of CiteSpace. When a node shows a strong burst (showed by the red colour), it signifies the attention the work has received within a short period of time

(Chen, 2016). The burstness of the keywords were measured within year groups. The keyword with the strongest burst (23.195) is "light emitting diode" which receive a lot of attention within the 2003 to 2012-year period. This is followed by "solar cell" with a strength of 17.448 through the years of 1993 to 2004. It was realised that within the year 2006 to 2009 the keyword "plastic solar cell" was very prominent with a burst strength of 5.492. This shows the attention given to research on new technologies as alternatives, in achieving efficient improvements and more stable performance in its operation.



Keywords	Year	Strength	Begin	End	1974 - 2019
energy conversion	1974	5.7708	**1992**	2011	
solar cell	1974	17.448	**1993**	2004	
cdte	1974	6.3475	**1993**	2013	
heterojunction	1974	13.0346	**1996**	2011	
spectroscopy	1974	10.1308	**1996**	2011	
photovoltaic cell	1974	6.5745	**2001**	2008	
electrodeposition	1974	5.855	**2002**	2011	
titanium dioxide	1974	5.8429	**2002**	2012	
diffusion	1974	4.377	**2002**	2010	
light emitting diode	1974	23.1947	**2003**	2012	
electrical property	1974	6.5231	**2003**	2009	
device	1974	12.1339	**2004**	2013	
conversion	1974	11.379	**2004**	2014	
light	1974	5.9154	**2004**	2012	
photodiode	1974	5.0229	**2004**	2008	
donor acceptor heterojunction	1974	3.9856	**2004**	2006	
fullerene	1974	14.8258	**2005**	2013	
indium tin oxide	1974	8.5468	**2005**	2014	
conducting polymer	1974	7.716	**2005**	2012	
conjugated polymer	1974	7.7071	**2005**	2010	
diode	1974	6.1428	**2005**	2010	
organic photovoltaic cell	1974	4.2212	**2005**	2013	
plastic solar cell	1974	5.4921	**2006**	2009	
thermal treatment	1974	4.5671	**2006**	2011	
composite	1974	3.8961	**2006**	2008	

Fig. 3. Top 25 keywords with the strongest citation burst

The betweenness centrality of the keywords indicates the transformative potential of a contribution or the importance of that node in the network (Chen et al., 2012). Looking back at Fig 2., the following shows the betweenness centrality of the keywords with Performance (0.12) having the highest value, and the second being efficiency (0.10), and the others are solar cell (0.19), thin film (0.08), film (0.06), morphology (0.06), photovoltaic cell (0.08), system

(0.08), layer (0.02), polymer solar cell (0.03), energy (0.10), design (0.03), nanoparticle (0.05), photovoltaic (0.06), recombination (0.04), polymer (0.04), fabrication (0.06), open circuit voltage (0.02), conjugated polymer (0.06) and photovoltaics (0.05). Performance and efficiency as explained previously has been an important part of photovoltaic research and will continue to be, because of the quest to find better and more efficient solar photovoltaics to prevent harmful waste to humans and the environment.

3.3.2. Network of co-occurring subject categories

The subject category came up with a modularity of Q = 0.4676 and silhouette of 0.8723. Among the research subject categories discovered were Materials Science; Materials Science, Multidisciplinary; Physics; Physics, Applied; Chemistry; Energy and Fuels; Science and Technology; Engineering; Chemistry, Physical; Nanoscience and Nanotechnology; Chemistry, Multidisciplinary; Physics, Condensed Matter; Engineering, Electrical and Electronic; Green and Sustainable Science & Technology; Environmental Sciences and Ecology; Environmental Sciences; Engineering, Chemical; Engineering, Environmental; Electrochemistry; Materials Science, Coatings and Films; Polymer Science; Thermodynamics; Optics; Physics, Atomic, Molecular and Chemical; Water Resources; Mechanics; Multidisciplinary Sciences; Metallurgy and Metallurgical Engineering; Environmental Studies; Engineering, Mechanical; Construction and Building Technology; Physics, Multidisciplinary; Engineering, Civil; and Instruments and Instrumentation.

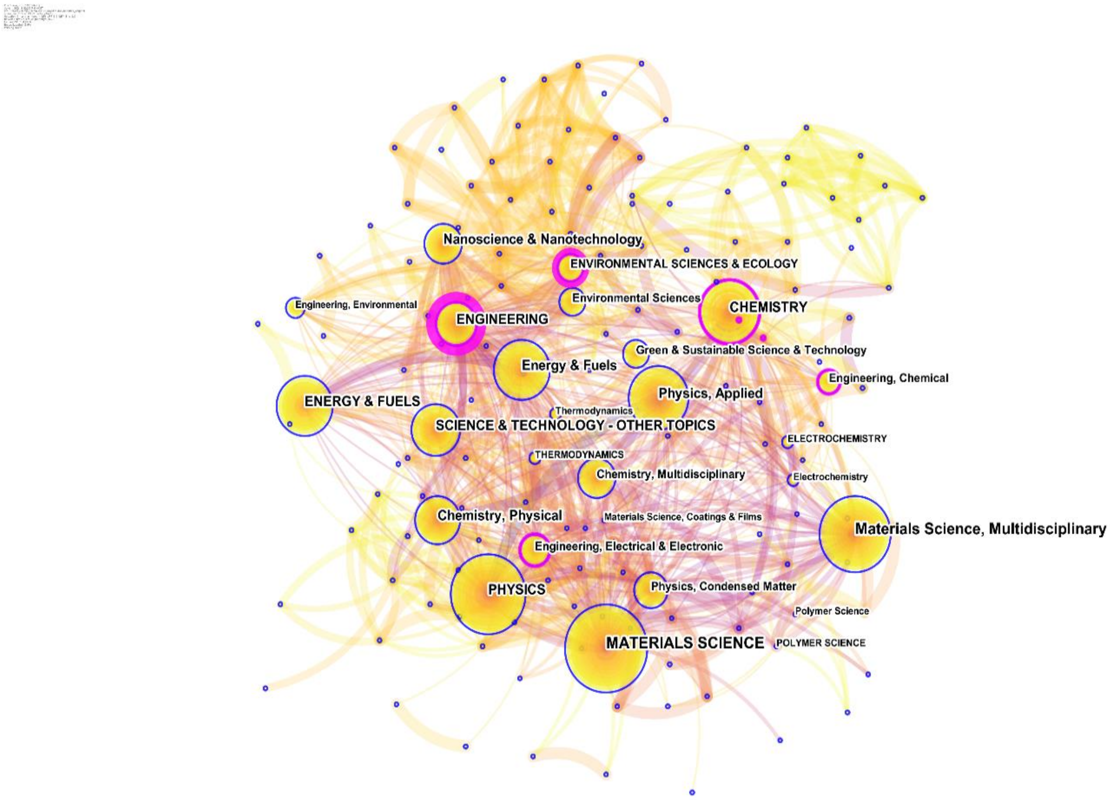


Fig. 4. An overview of the subject category co-occurring network

The highest citation count is related to Materials Science, with 2178 citation followed by Materials Science Multidisciplinary with 2028, Physics with 1671, Physics Applied with1408, Chemistry with 1342, Energy & Fuels with 1274, Science & Technology (2000) with 1095, Engineering with 895, Chemistry, Physical with 892 and Nanoscience and Nanotechnology with 698 citation counts. The field of material science has received a major boost in terms of citation as well as physics and chemistry as these research areas lead the studies on solar photovoltaics waste management research. Thus, the emergence and production of new materials for solar panels that are more efficient and effective are constantly researched to better perform when it comes to carbon emissions during production and after its end-of-life. Their recycling and recovery capabilities are also significant areas of research.

3.3.2.1. Citation bursts and betweenness centrality

The highest ranked item by bursts is Physics (1991-2005), with burst score of 34.26. This explains the attention physics as a subject area has received in the area of solar photovoltaics from 1991 to 2005. The second one is Physics, Applied (1992-2005), with bursts of 31.83. It can be realised that, applied physics also receive the same attention around the same year as physics, this shows the collaborative work between these two disciplines on the work of solar photovoltaic waste research. The third is Polymer Science (2005-2013), with bursts of 11.05. The 4th is Physics, Multidisciplinary (2006-2012), with bursts of 7.02. The 5th is Materials Science, Coatings and Films (1991-2010), with bursts of 6.00. The 6th is Physics, Condensed Matter (2006-2008), with bursts of 5.18. The 7th is Energy and Fuels (2001-2002), with bursts of 4.87. The 8th is Engineering, Electrical & Electronic (1999-2001), with bursts of 4.87.

The pink ring around the nodes depict the centrality of each node. The bigger the ring the higher the centrality which shows the importance of that node to the group. The highest ranked item by centrality is Engineering, with centrality score of 0.52, followed by Energy and Fuels, Chemistry, Environmental Studies and Materials Science with respective centrality values of 0.26, 0.18 and 0.14. Science and Technology, Environmental Sciences and Ecology and Engineering, Chemical had a similar centrality value of 0.11; Biotechnology and Applied Microbiology, had centrality value of 0.10 and Engineering, Electrical and Electronic had centrality value of 0.09.

3.4 Co-citation analysis

Co-citation explains the citation of two scholarly items such as journals, references, documents and/or authors by the same article (Olawumi and Chan, 2018; Wu, J. et al., 2019). The intellectual structure within a scientific field can be analysed via co-citation (Cobo et al., 2011). The VOSviewer, Gephi and CiteSpace software was used to analyse the co-citation networks of the authors, documents and journals as explained in this section.

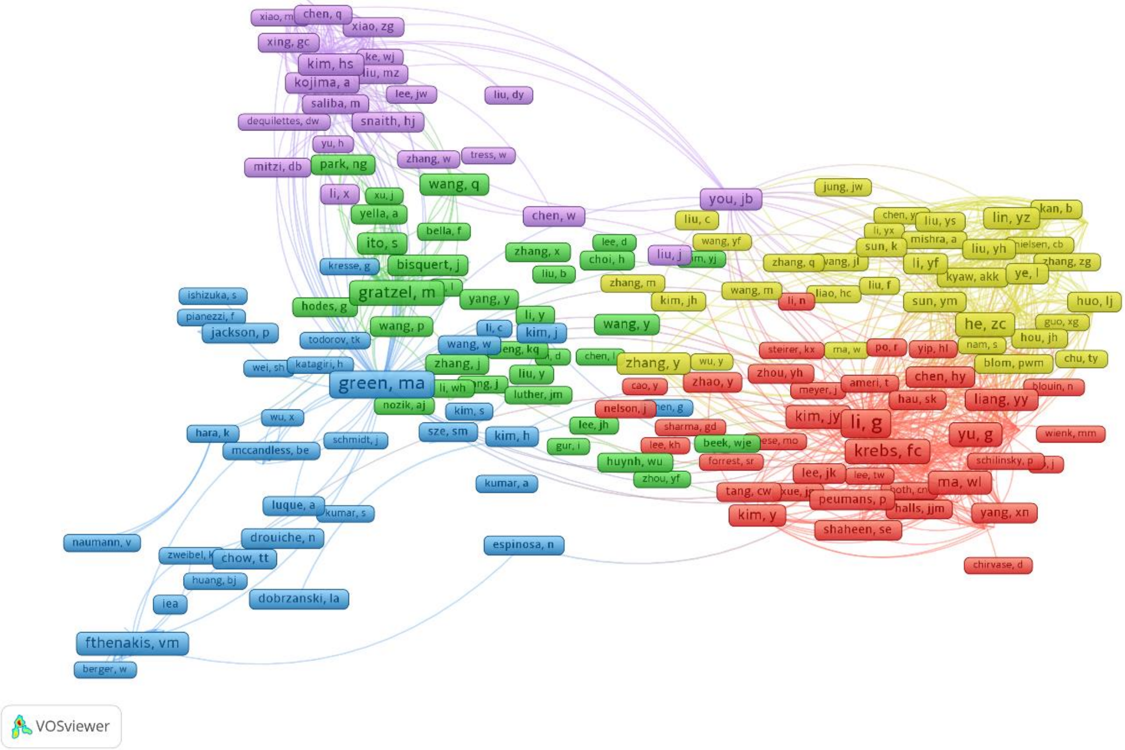


Fig. 5. Author co-citation visualisation network

3.4.1 *Author co-citation network*

Author co-citation explores the frequently cited authors in a research field (McCain, 1991). Author co-citation network is visualised with the aid of the VOSviewer software. The colours in Fig. 5 shows the pattern and network of authors who are indirectly cited together whether collaboratively or individually.

The highest ranked author is Li et al. (Li et al., 2006), with citation counts of 631, followed by Green and Wenham (Green and Wenham, 1994) with 563, Krebs et al. (Krebs et al., 2005) 430, Brabec et al. (Brabec, 2003) with 380, Gratzel (Grätzel, 2004) with 356, Yu (Yu et al., 2003) with 337, He et al. (He et al., 2012) with 323, Fthenakis and Wang (Fthenakis and Wang, 2006) with 285, Ma et al. (Ma et al., 2005) with 257, and Kim et al. (Kim et al., 2005) with 246 citation counts. The most cited paper, Li et al. (Li et al., 2006), looks at efficient inverted polymer solar cells. The second most cited paper by Green and Wenham (Green and Wenham, 1994) explored novel parallel multijunction solar-cells.

3.4.1.1. Citation bursts and betweenness centrality

The highest ranked item by bursts is Ma et al. (Ma et al., 2005) with bursts of 43.83, followed by Kojima et al. (Kojima et al., 2015) with bursts score of 42.41, Yang et al. (Yang et al., 2015) with 39.50, You et al. (You et al., 2013) with 35.21, Padinger et al. (Padinger et al., 2003) with 34.00, Zhang et al. (Zhang et al., 2016) with 33.79, Jeon et al. (Jeon et al., 2014) with 33.60, Kim et al. (Kim et al., 2005) with 33.33, Shaheen and Ginley (Shaheen and Ginley, 2004) with 32.98, and Zhao et al. (Zhao et al., 2017) with 32.97 bursts scores.

3.4.2 Document co-citation network

CiteSpace recorded a modularity of 0.6947 and a Silhouette of 0.4812 during the mapping of the document co-citation network. The highest ranked item by citation counts is Li et al. (Li et al., 2005) in Cluster #1, with citation counts of 185, followed by Ma et al. (Ma et al., 2005) in Cluster #1 with 162 citation counts, Burschka et al. (Burschka et al., 2013) in Cluster #2 with 148, Lee et al. (Lee et al., 2012) in Cluster #2 with 129, He et al. (He et al., 2012) in Cluster #0 with 120, Liu et al. (Liu et al., 2014) in Cluster #2 with 116, Li et al. (Li, G. et al., 2012) in Cluster #4 with 113, Jeon et al. (Jeon et al., 2014) in Cluster #2 with 112, Stranks et al. (Stranks et al., 2013) in Cluster #2 with 111, and Li (Li, 2012) in Cluster #0 with 104 citation counts.

Cluster #0 is the largest cluster with 83 members and a silhouette value of 0.761 and is labelled “efficient polymer” by LLR. Xin et al. (Xin et al., 2010) is the most active citer to cluster #0 with his work on “polymer nanowire/fullerene bulk heterojunction solar cells: how nanostructure determines photovoltaic properties”. Cluster #1 (the second largest) has 80 members and a silhouette value of 0.764 and is labelled “fullerene bulk heterojunction” by LLR. The most active citer to the cluster is Liu et al. (Liu et al., 2010) on their paper “the mechanisms for introduction of n-dodecylthiol to modify the P3HT/PCBM morphology". Cluster #3 is the third largest cluster with 45 members and a silhouette value of 0.85 and is labelled "device architecture" by LLR. The most active citer to the cluster is Kwong et al. (Kwong et al., 2004) on "CuPc/c-60 solar cells-influence of the indium tin oxide substrate and device architecture on the solar cell performance".

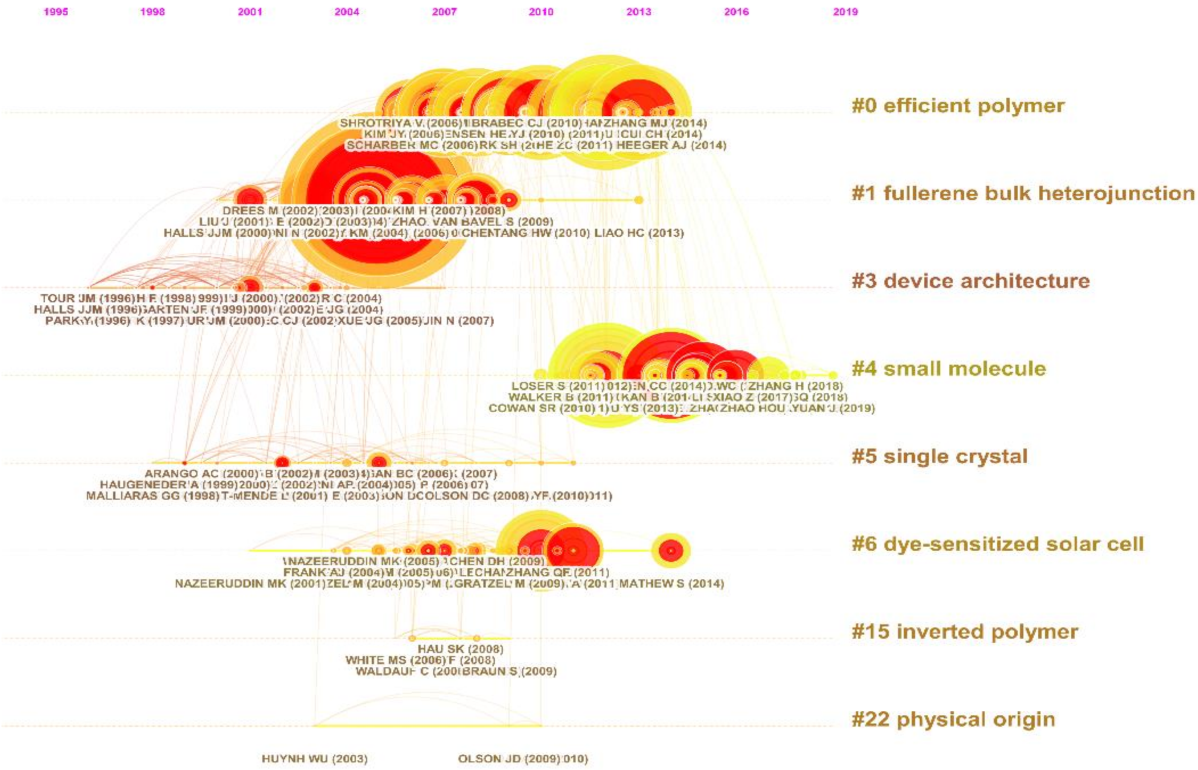


Fig. 6. Network of document co-citations

Cluster #0 and #1: The first and second clusters (#0 and #1) focus on the polymer solar cells performance especially the fullerene bulk heterojunction solar cells. The search for a more efficient and low-cost solar cells is trending in the photovoltaic waste research field as old panels reach their end-of-life and the need to create less harmful and environmentally friendly solar cells. Research such as that of Xin et al. (Xin et al., 2010), experimented on bulk heterojunction solar cells through the use of solvent and thermal annealing to vary the morphology of fullerene composites. The work of Po et al. (Po et al., 2010), delved into the current approaches and achievement in polymer solar cells. They realised that the cost, durability, and efficiency are the critical elements to pivot the success of polymer solar cells. Other researchers (Canli et al., 2010; Hains et al., 2010; Liu et al., 2010; Tang et al., 2010) have also examined different treatment and properties of polymer solar cells to make it more efficient and low cost. A look at the five strongest citation burst (*see fig. 7*) reveals that the emerging trend on photovoltaic modules waste management research has been centred on polymer solar cells (Coakley and McGehee, 2004; Li et al., 2005; Padinger et al., 2003; Shaheen et al., 2001; Yang et al., 2005) from the year 2004 to 2013. But a critical look at the research on photovoltaic waste has been a gradual process through the years. Even thou most of the earlier research is centred on polymer solar cells as the alternative to the old PV technologies because of the less harmful effect on the environment, its effectiveness and efficiency is still an ongoing study. That means, many of the silicon and cadmium based solar panels will be installed by the time other new technologies hit the market. There is therefore the need to intensify the research on how to properly manage the waste from the old PV technologies.

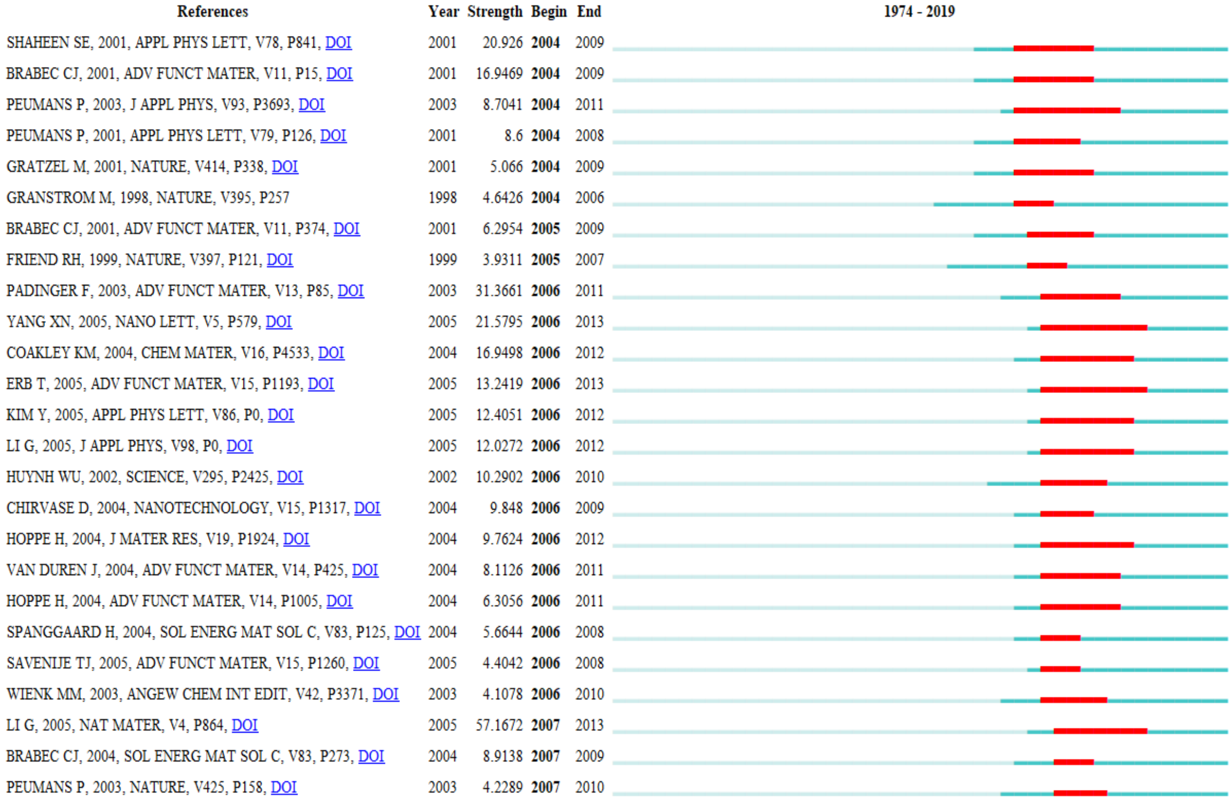
Cluster #3, #4 and #5: These three clusters examine the characteristics and properties of polymer solar cells. The article with the highest coverage in the fourth cluster (#3) which is Kwong et al. (Kwong et al., 2004) investigated the performance of organic solar cells through the application of different indium tin oxide surface treatment and device architecture. The performance of the organic solar cell, they realised will be greatly improved through the use of a three-layer architecture having a co-deposited mixed layer. Exploration and application of multi-layer photodetectors (Xue and Forrest, 2004), oligo derivatives (Nierengarten, 2004; Nierengarten et al., 2004), and nanoscale morphology (Hoppe et al., 2004) to organic solar cells are some of the of the characteristics and properties that several researchers are studying to improve the performance and efficiency of organic solar cells. This cluster (#4) describes the improvement made within the small molecule based organic solar cells. Patil et al. (Patil et al., 2016) and Wang et al. (Wang et al., 2015) are some of the most referenced researchers on small molecule based organic solar cells. Their studies investigate the improvement of small molecule based organic solar cells through experimental tests. The sixth cluster (#5) demonstrates how solar cells perform through different treatments (Olson et al., 2007; Uhlrich et al., 2009a; Uhlrich et al., 2009b). The three clusters explained in this paragraph also looks at polymer solar cells. the trend in a past couple of years has been centred on polymer solar cells, its characteristics and advantages compare to the silicon based solar cells. Their characteristics such as its lightweight, low cost and its low impact to the environment has made it the alternative solar technology compared to the old technologies.

Cluster #6, #15 and #22: The last three clusters examine sensitized, inverted and hybrid solar cells. As research progresses, experts are finding new ways and methods to improve the performance and efficiency of solar cells as well as make them environmentally friendly. An increase in the performance and efficiency of photovoltaics has been recorded through the use of quantum dot sensitized solar cells (Jin et al., 2012; Pan et al., 2012). The same case is recorded in inverted polymer solar cells through the modification of its cells (Cho et al., 2011; Sun et al., 2011). The last cluster (#22) discusses the improvement and treatment of hybrid solar cells. The studies conducted by Zhou et al. (Zhou et al., 2011) describes the enhancement of hybrid solar cells through acid treatment. The last batch of clusters also look at different PV technologies that might serve as an alternative to the current installed ones. It is important to establish new innovations that are environmentally friendly and can help with reducing waste from solar PV technologies.

3.4.1.1. Citation bursts and betweenness centrality.

The highest ranked item by bursts is Li et al. (Li et al., 2005) in Cluster #1, with bursts score of 57.17 followed by Ma et al. (Ma et al., 2005) in Cluster #1 with 48.98 bursts, Padinger and Rittberger (Padinger et al., 2003) in Cluster #1 with 31.37, Kojima et al. (Kojima et al., 2009) in Cluster #2 with 29.58, He et al. (He et al., 2012) in Cluster #0 with 28.36, You et al. (You et al., 2013) in Cluster #0 with 27.85, Yang et al. (Yang et al., 2015) in Cluster #2 with 26.49, Jeon et al. (Jeon et al., 2014) in Cluster #2 with 26.29, Liu et al. (Liu et al., 2014) in Cluster #4 with 24.08, and Burschka et al. (Burschka et al., 2013) in Cluster #2 with 23.10 bursts scores.

The burst within the years as visualised in Fig. 7, shows the citation burst (showed by the red colour) of the references as sorted by years. The beginning year 2004, 2005, 2006 and 2007 showed (indicated by the deep blue colour) the most strength in its burstness. From the years of 2004 to 2011, Shaheen et al. (Shaheen et al., 2001), recorded the highest burst strength of 20.93. The year 2005 to 2009 saw the highest burst strength of 6.30 from Brabec et al. (Brabec et al., 2001). With a burst strength of 31.37, 21.58 and 16.95 the references Padinger et al. (Padinger et al., 2003), Yang et al. (Yang et al., 2005) and Coakley (Coakley and McGehee, 2004) respectively received one of the highest strengths in the year period 2006 to 2013. Li et al. (Li et al., 2005), received the highest burst within all the year groups with a burst of 57.17. in its year group from 2007 to 2010. The research on the articles that received the highest burst were on polymer solar cells. For the past decade, attention of researchers has shifted towards the performance and efficiency of polymer solar cells. This is because of the quest to fight the harmful impact of waste from old solar panels and to easily produce new and low-cost solar panels.



References	Year	Strength	Begin	End	1974 - 2019
SHAHEEN SE, 2001, APPL PHYS LETT, V78, P841, DOI	2001	20.926	**2004**	2009	
BRABEC CJ, 2001, ADV FUNCT MATER, V11, P15, DOI	2001	16.9469	**2004**	2009	
PEUMANS P, 2003, J APPL PHYS, V93, P3693, DOI	2003	8.7041	**2004**	2011	
PEUMANS P, 2001, APPL PHYS LETT, V79, P126, DOI	2001	8.6	**2004**	2008	
GRATZEL M, 2001, NATURE, V414, P338, DOI	2001	5.066	**2004**	2009	
GRANSTROM M, 1998, NATURE, V395, P257	1998	4.6426	**2004**	2006	
BRABEC CJ, 2001, ADV FUNCT MATER, V11, P374, DOI	2001	6.2954	**2005**	2009	
FRIEND RH, 1999, NATURE, V397, P121, DOI	1999	3.9311	**2005**	2007	
PADINGER F, 2003, ADV FUNCT MATER, V13, P85, DOI	2003	31.3661	**2006**	2011	
YANG XN, 2005, NANO LETT, V5, P579, DOI	2005	21.5795	**2006**	2013	
COAKLEY KM, 2004, CHEM MATER, V16, P4533, DOI	2004	16.9498	**2006**	2012	
ERB T, 2005, ADV FUNCT MATER, V15, P1193, DOI	2005	13.2419	**2006**	2013	
KIM Y, 2005, APPL PHYS LETT, V86, P0, DOI	2005	12.4051	**2006**	2012	
LI G, 2005, J APPL PHYS, V98, P0, DOI	2005	12.0272	**2006**	2012	
HUYNH WU, 2002, SCIENCE, V295, P2425, DOI	2002	10.2902	**2006**	2010	
CHIRVASE D, 2004, NANOTECHNOLOGY, V15, P1317, DOI	2004	9.848	**2006**	2009	
HOPPE H, 2004, J MATER RES, V19, P1924, DOI	2004	9.7624	**2006**	2012	
VAN DUREN J, 2004, ADV FUNCT MATER, V14, P425, DOI	2004	8.1126	**2006**	2011	
HOPPE H, 2004, ADV FUNCT MATER, V14, P1005, DOI	2004	6.3056	**2006**	2011	
SPANGGAARD H, 2004, SOL ENERG MAT SOL C, V83, P125, DOI	2004	5.6644	**2006**	2008	
SAVENIJE TJ, 2005, ADV FUNCT MATER, V15, P1260, DOI	2005	4.4042	**2006**	2008	
WIENK MM, 2003, ANGEW CHEM INT EDIT, V42, P3371, DOI	2003	4.1078	**2006**	2010	
LI G, 2005, NAT MATER, V4, P864, DOI	2005	57.1672	**2007**	2013	
BRABEC CJ, 2004, SOL ENERG MAT SOL C, V83, P273, DOI	2004	8.9138	**2007**	2009	
PEUMANS P, 2003, NATURE, V425, P158, DOI	2003	4.2289	**2007**	2010	

Fig. 7. Top 25 references with the strongest citation burst

3.4.3 Journal co-citation network

According to McCain (McCain, 1991), journal co-citation networks establish frequently co-cited journals. This shows the network of documents that are mostly cited in these journals. The CiteSpace and Gephi software were used in analysing and visualising the networks between the journals. The journal co-citation network has 216 nodes, the journals with the most cited papers are discussed. Table 1 as explained earlier describes the number of articles that were published in some of these journals and their characteristics. Fig. 8 shows the connection and links between the journals. The bigger and deeper the colour of the node and edges the higher and stronger the frequency and connection between the citation of the journals.

The highest ranked item by citation counts is "Solar Energy Materials and Solar Cells" with 2091 citations followed by "Applied Physics Letters" with 2029, Advance Materials with 1938, "Journal of the American Chemical Society" with 1747, "Advanced Functional Materials" with 1452, "Science" with 1441, "Journal of Applied Physics" with 142, "Journal of Physical

Chemistry C" with 1363, "Nano Letters" with 1295, and "Energy and Environment Science" with 1292 citation counts. Table A3 in the appendix shows the details of twenty journal sources with the highest citation count. This result shows the significant contribution these journals have made in the area of photovoltaic waste research.

3.4.3.1. Citation bursts and betweenness centrality

The highest ranked item by bursts is "Nano Energy" with bursts of 102.83. The second one is "Synthetic Metals" with bursts of 80.43. The third is "Nature Energy" with bursts of 74.00. The 4th is "Chemical Physics Letters" with bursts of 65.44. The 5th is "Energy Policy" with bursts of 64.74. The 6th is "Scientific Reports" with bursts of 60.42. The 7th is "IEEE Journal of Photovoltaics" with bursts of 58.26. The 8th is "Journal of Materials Chemistry A" with bursts of 51.91. The 9th is "Nanotechnology" with bursts of 51.64. The 10th is "Journal of Materials Chemistry C" with bursts of 50.47.

The highest ranked item by centrality is "Applied Physics Letters" with centrality of 0.26. The second one is "Solar Energy Materials and Solar Cells" with centrality of 0.18. The third is "Journal of the Electrochemical Society" with centrality of 0.16. The 4th is "Solar Energy" with centrality of 0.10. The 5th is "Renewable Energy" with centrality of 0.10. The 6th is "Solar Cells" with centrality of 0.09. The 7th is "Journal of the American Chemical Society" with centrality of 0.09. The 8th is "Journal of Applied Physics" with centrality of 0.08. The 9th is "Japanese Journal of Applied Physics" with centrality of 0.08. The 10th is Physical Review B with centrality of 0.08.

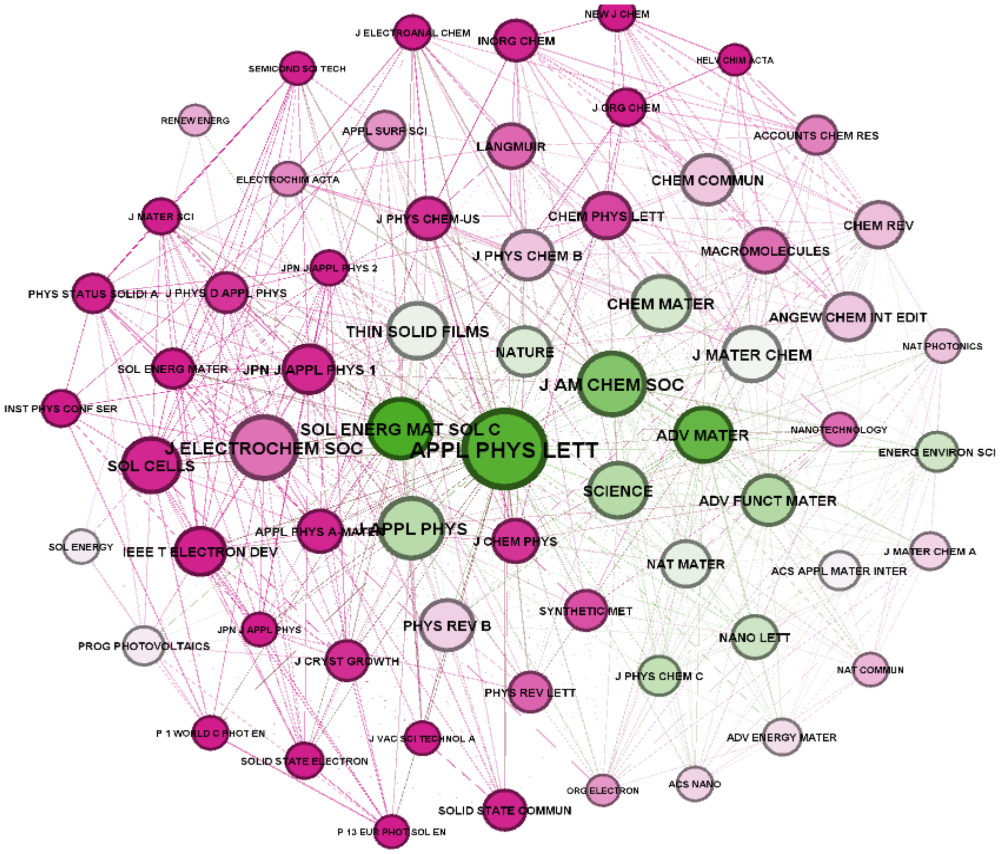


Fig. 8. Co-citation network of journal sources

3.5 Co-author analysis

Glänzel and Schubert (2005) argues that the lack of scientific collaboration or co-authorship is seen as lower research productivity within the scientific community. Thus, publications produced through collaboration serves as enough evidence as they receive more citations and are published in higher impact journals. This section explains the scientific collaboration between authors through their publication, countries and institutions using the VOSviewer, CiteSpace and Gephi software with an explanation of the publication distribution using mapchart.net. The sections therefore explain the co-authorship networks, network of countries/regions and the network of institutions/faculties.

3.5.1 Co-authorship network

The author-to-author publication network starts with researchers such as Li, Yongfang who has had about fifty-three collaborations, which is the highest, collaborating with authors like Zou, Yingping; Zhang, Zhi-guo (4th highest); Shen, Ping; Yuan, Jun; Sun, Chenkai; Cui, Chaohua; Brabec, Christoph J.; Liu, Feng; and Chen, Yiwang (2nd highest). Another prominent researcher Cao, Yong (3rd highest) has also made collaborations with several researchers among them are Kim, Jin Young (5th highest); Wang, Jian; Woo, Han Young; Wang, Jing; Russell, Thomas P. and Liu, Feng. The colours in Fig. 9 represents the research communities of the authors within the photovoltaic waste research field.

The top ten collaborators by the number of articles produced are Li, Yongfang (53) with 2085 citations; Chen, Yiwang (24) with 373 citations; Cao, Yong (22) with 702 citations; Zhang, Zhi-gou (21) with 279 citations; Kim, Jin Young (19) with 1914 citations; Chen, Lie (15) with 246 citations; Wu, Jihuai (15) with 250 citations; Brabec, Christoph J. (14) with 2185 citations; Yang, Renqiang (14) with 238 citations; and Na, Seok-in (14) with 635 citations.

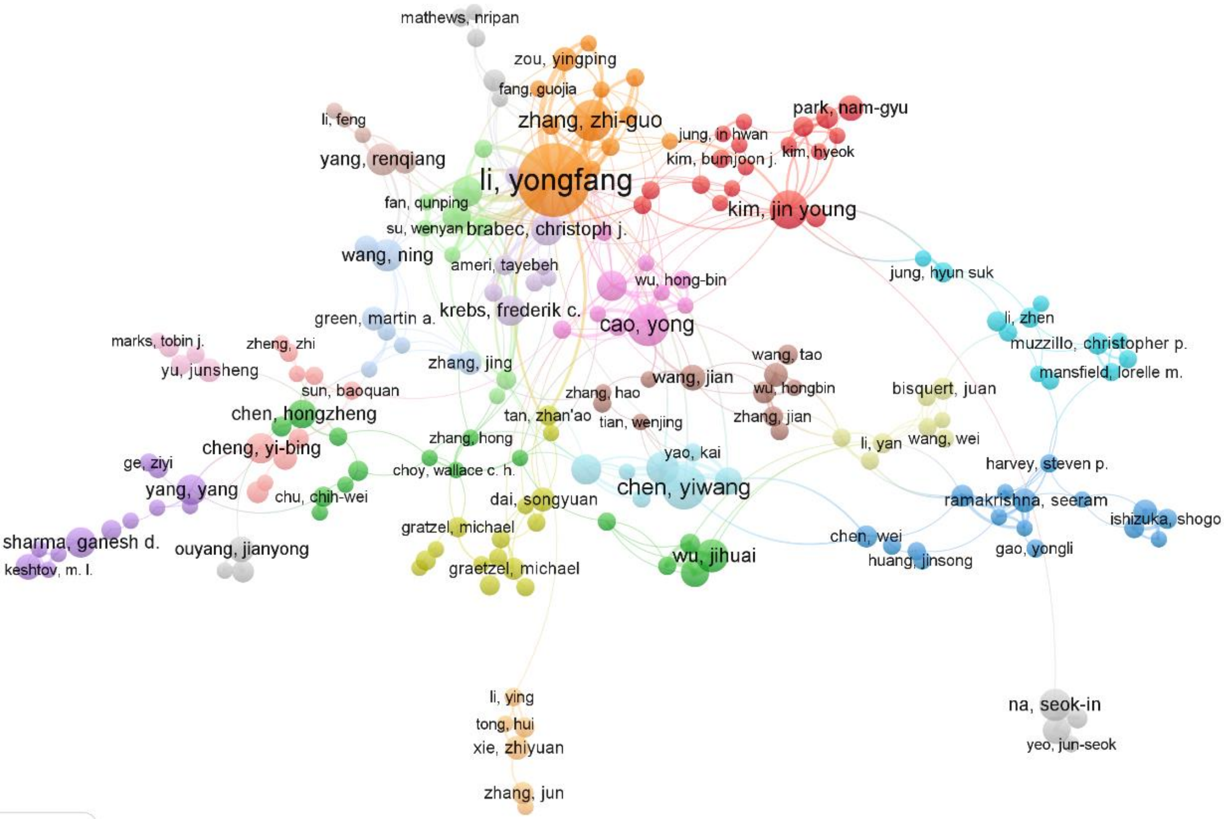


Fig. 9. Author collaboration network

3.5.2 Network of countries/regions

Fig 10 shows the distribution of the number of published research by country worldwide. Countries like USA., China, England, Germany, Japan, South Korea, India all had more than 200 published articles on photovoltaic waste research. Canada, Spain, France, Australia, Iran, Turkey, Malaysia, Netherlands, and Brazil were among the countries with about 51 to 200 documents. The rest of the countries including Algeria, Egypt, Russia, Poland, South Africa and the others shown on the map produced 50 articles or less. This establishes the seriousness and contribution of countries like the USA and China on the fight against photovoltaic waste through research and innovation.

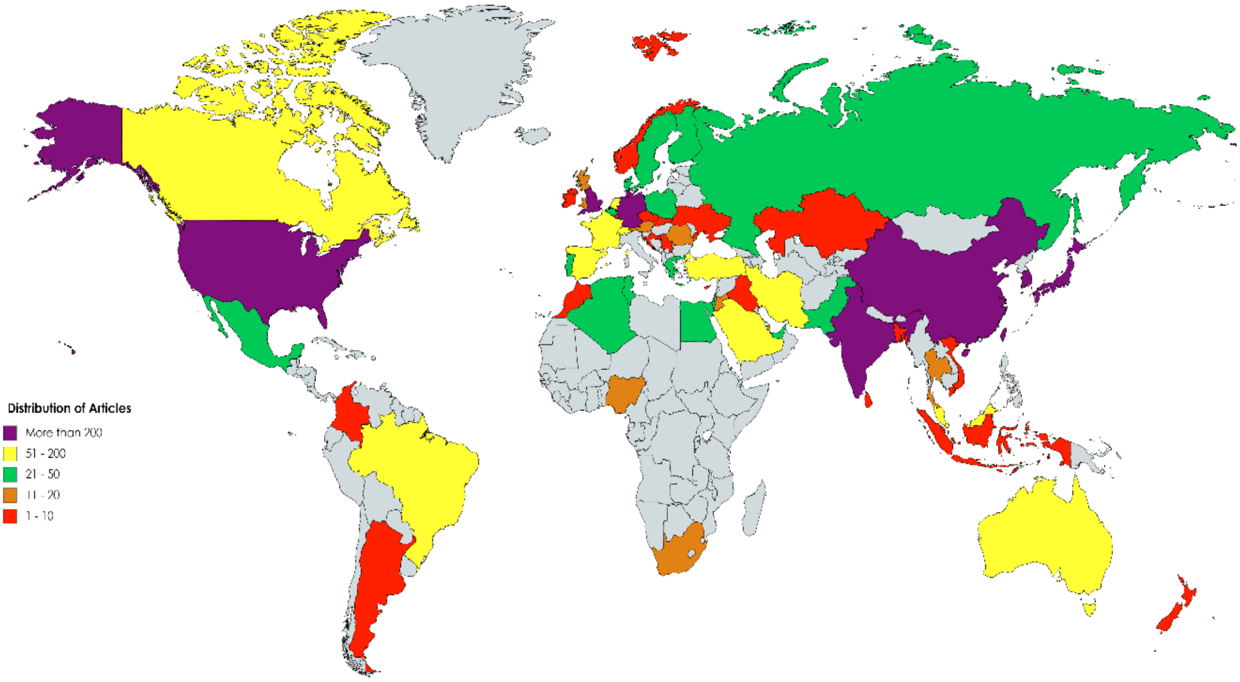


Fig. 10. Distribution of articles across countries

The highest ranked item by frequency is China with documents of 1150 and a citation count of 25571, followed by the USA with 819 documents and 36444 citation counts. Next is South Korea with 451 documents and 10768 citation counts, Japan with 280 documents and 7243 citation counts, India with 258 documents and 3035 citation counts, Germany with 240 documents and 7075 citation counts, Italy with 229 documents and 8859 citation counts, Taiwan with 222 documents and 4144 citation counts, England with 217 documents and 9086 citation counts, and France with 183 documents and 6621 citation counts. The details are documented as Table A4 in the appendix A section of this thesis.

3.5.2.1 Citation bursts and betweenness centrality

The highest ranked item by bursts is France with bursts of 21.71, followed by Japan with bursts of 20.63, the USA with bursts of 17.73, Singapore with bursts of 10.91, Germany with bursts of 8.25, Taiwan with bursts of 6.16, and Austria with bursts of 4.08. France showed a lot of productive research from 1996 through to 2008. Fig 12. Shows a lot of productive research being done across the globe. The links and collaborations between the countries are very strong and very productive. Table three shows the burstness and betweenness centrality of the countries through the years and at what point they have been productive.

Table 3
Burstness and centrality of collaborative countries

No.	Country	Burst	Centrality	Span
1	France	21.71	0.16	1996-2008
2	Japan	20.63	0.07	1998-2010
3	USA	17.73	0.29	1991-2009
4	Singapore	10.91	0.00	2011-2012
5	Germany	8.25	0.17	2000-2005
6	Taiwan	6.16	0.01	2008-2011
7	Austria	4.08	0.00	2011-2012

The highest ranked item by centrality is USA with centrality of 0.29, followed by England with centrality of 0.25, Germany with centrality of 0.17, France with centrality of 0.16, Spain with centrality of 0.13, China with centrality of 0.11, Australia with centrality of 0.08, Japan with centrality of 0.07, Saudi Arabia with centrality of 0.07, and India with centrality of 0.06.

3.5.3 Network of institutions/faculties

Collaboration between institutions is very important in the growth of research and development through the sharing of ideas and expertise within the same and different fields. Thus, collaborations between various researchers both in the same field and interdisciplinary has grown recently. This has seen various institutions collaborating with others due to similar interest in several research fields. To reveal these characteristics, CiteSpace was used to analyse the data retrieved from the WoS database. The results of the analysis revealed a modularity score of 0.663 and a mean silhouette of 0.2719.

The highest ranked item by citation count is Chinese Academy of Sciences with citation counts of 251, followed by National Renewable Energy Laboratory with citation count of 84, the University of the Chinese Academy of Sciences with a citation count of 52, Soochow University with citation counts of 50, Sungkyunkwan University with a citation counts of 48, National Taiwan University with a citation count of 43, North China Electric Power University with a citation count of 41, Nanyang Technology University with a citation count of 39, Zhejiang University with a citation counts of 37, and the National University of Singapore with a citation count of 35. Table A5 in the appendix shows the details of twenty institutions with the highest citation count.

3.5.3.1 Citation bursts and betweenness centrality

The highest ranked item by bursts is the South China University of Technology with bursts of 7.76. The second one is National University of Singapore with bursts of 6.98. The third is Nanyang Technology University with bursts of 5.08. The 4th is National Taiwan University with bursts of 4.96. The 5th is Industrial Technology Research Institute with bursts of 4.95. The 6th is University of California, Los Angeles with bursts of 4.89. The 7th is Pusan National University with bursts of 4.80. The 8th is the Beijing Jiaotong University with bursts of 4.56. The 9th is Massachusetts Institute of Technology (MIT) with bursts of 4.56. The 10th is the Delft University of Technology with bursts of 4.48.

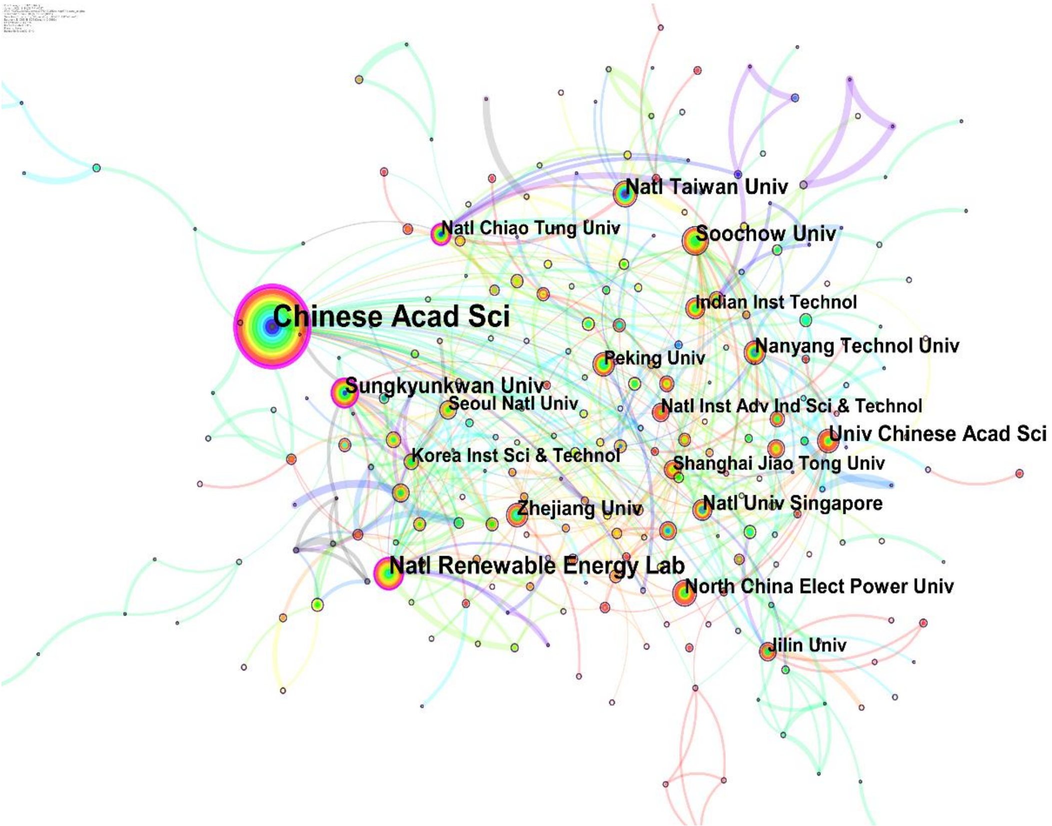


Fig. 11. Network of collaborations between institutions

The highest ranked item by centrality is the Chinese Academy of Sciences with centrality of 0.37. The second one is National Renewable Energy Laboratory with centrality of 0.17. The third is National Chiao Tung University with centrality of 0.13. The 4th is Sungkyunkwan University with centrality of 0.10. The 5th is Soochow University with centrality of 0.09. The 6th is National University of Singapore with centrality of 0.08. The 7th is Nanyang Technology University with centrality of 0.08. The 8th is Seoul National University with centrality of 0.06. The 9th is Yeungnam University with centrality of 0.06. The 10th is Ecole Polytechnique Federale de Lausanne with centrality of 0.06.

4 Discussion of emerging trends and future directions

Recently, the PV market has seen the dominance of Si-crystalline (mono or poly) panels, which has become the most used PV technology worldwide because of its high efficiency and low cost of production. Alternative technologies such as Hybrid and organic cells, CdTe and CIGS have been developed and others still under research. However, Si-crystalline (mono or poly) panels, remains the most profitable (Padoan et al., 2019). The usage of toxic elements (Cd in CdTe) and rare/critical substances in the production of these PV modules are the main concern to their use extensively. Furthermore, the waste generation from the PV module is being tagged as potentially harmful, similar to e-waste, and is liable to the European WEEE (Waste Electrical and Electronic Equipment) Directive (2012). This has generated a lot of debate around the policies and regulations, performance and efficiency, recovery and recycling and end-of-life assessment of solar PV module waste management. Drawing from the aforementioned analysis, the emerging trends and future directions are discussed under four themes.

4.1 Policies and Regulations

Several countries have been early promoters of solar energy. They have focused on providing financial and investment aid in supporting initial policies and regulations. The introduction of feed-in tariffs (FiTs) in Australia, United Kingdom, Portugal, Italy, Germany, France, Japan and other countries has caused an increase in the installation of solar PV panels in residential sector (Pereira da Silva et al., 2019). There are other policies by governments which also provided incentives for the increase in the use of solar PV worldwide, aiming to achieve intergovernmental sustainability targets. This has informed many to turn to renewable and sustainable energy sources. With photovoltaics as an important solar energy generator, world leaders developed interest in this particular source of energy and started initiating policies and regulations for its use. However, the current problem to this is the harm it can cause if not properly disposed at the end of its life. The attention generated by this treat has again brought governments together to search for a solution. Since policies and regulations keep changing when it comes to the solar PV industry, several countries have started developing new policies or modifying others to help in achieving the sustainability goals. According to this analysis, the results clearly show the less attention that is given to policies and regulations when it comes solar PV waste research over the years. The analysis draws researcher’s attention to the performance and efficiency of solar cells throughout the co-word and co-citation analysis. Nonetheless, recent research has emphasised the need to establish policies and standards for PV disposal (Nain and Kumar, 2020; Shubbak, 2019).

According to Xu et al., (2018) there should be an encouragement within government agencies in devising a recycling and safe disposal policy for solar PV module waste. This has informed several countries into developing policies that tackle solar PV waste the end-of-life management. The European Union (EU) on their Waste Electrical and Electronic Equipment (WEEE) Directive outlined guidelines for the collection, recycling and recovery of solar PV waste. Reinforcing the responsibility of producers is an efficient approach in managing waste from solar PV known as the extended producer responsibility (Fthenakis et al., 2020). Many countries are introducing regulatory frameworks to guide the management of PV module waste. The WEEE directive has been a big influence in areas like Japan, South Korea, China and California in the establishment of similar policies and regulations. There is more to be done because of the potential waste that will come into the system in the years to come. Countries which produces most of these wastes are yet to establish safe guidelines in regulating solar PV module waste. Polices and regulations are needed to guide the safe disposal of these waste as well as the proper recycling and recovery of old panels. The results emphasised on the use of new materials such as organic cells which are more efficient and cheaper. Regulations should be made in the use of sustainable materials and easy to recycle materials after their end-of-life.

4.2 Performance and Efficiency

Performance and efficiency have been the centre of research in photovoltaics for a very long time as the results suggests. This started with the development of the first-generation photovoltaics which were based mostly on silicon (i.e. solar cells which were either single-crystalline or multi-crystalline). The second generation focused more on thin-film modules and cells (i.e. amorphous silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS)). The third-generation technologies however in an innovative capacity integrates several organic, inorganic or hybrid-based solar cells. This has seen efficiency and technological development in the application of solar PV through technologies such as quantum dots solar cells (QDSCs), perovskite solar cells (PSCs), full organic PV solar cells (OPCs) and dye sensitized solar cells (DSSCs) (Parisi et al., 2020). This technological innovation and improvement have been seen throughout the years and in this analysis within the visualisation of the keyword clusters and citation bursts. The highest frequency within the keywords analysis was performance and efficiency. Solar PV performance has gone through several technological advancement and research through the use of different materials. Materials such as DSSCs was used a lot in these experiments. between 2003 and 2009, researchers studied the characteristics of DSSCs (Lupan et al., 2010; Xi et al., 2010; Yu et al., 2011), aiming to improve the performance and efficiency of these cells and also application of organic and hybrid solar cells. These research leads towards finding a more sustainable solar cell in the future. Researchers are encouraged to work on more sustainable an efficient solar cell to reduce the burden on waste from the end-of-life solar cell.

4.3 Recycling and Recovery

The rapid growth in the installation of solar PV systems and its generation capacity has necessitated the implementation of recovery and recycling strategies of end-of-life PV panels by 2040. This action is anticipated to result in carbon dioxide emission reduction and therefore, positively address environmental sustainability targets. Solar module recycling has been the focus when it comes to research and development in the US, Europe and Japan recently. Recycling types such the physical, thermal and chemical processes are the three types that are commonly applied to solar PV panels. Most importantly, the research focuses on the Si panels on how to recycle and recover the essential parts for remanufacture (Chowdhury et al., 2020). This has caused several researchers to patent their recycling procedures. There are other recycling processes such as the mechanical processes which has an advantage of being inexpensive but requires more elaborate treatment when recovering high value materials (Padoan et al., 2019). From Vargas and Chesney (2020), in 2018 a joint effort between PV Cycle France and Veolia lead to the installation of a recycling plant in France which was the first in Europe. The facility by 2022 is expected to recycle over 4,000 tons of solar PV waste.

The remanufacture of solar PV from recovered or recycled materials is gaining a lot of attention recently. The analysis of the keywords shows results of the clusters and citation burst mostly around the year 1992 to 2011, recycling and recovering was not covered by many researchers around these years. This is because, solar PV then and now are not concentrated neither by content nor geography, with many applications dominated by stand-alone residential installations as well as off-grid power systems application on industrial areas. The collection as well as the value of materials to be reclaimed are low (Fthenakis, 2000). However, the first-generation of the solar photovoltaic panels are coming to the end of their life. This has called for researchers to focus more on the end-of-life treatment and production of a safer and more efficient photovoltaic cells in the future. Over the years, researchers (Dominguez and Geyer, 2017; Salim et al., 2019a) have proven the harmful effect of waste from solar photovoltaics and the need to manage these wastes to help improve the environment. The research on environmental impact from solar photovoltaics have been conducted a lot with several recommendations on the need to properly manage the incoming influx of solar waste in the coming years. Options such as incineration, recycling, treatment and disposal has been some of the solutions up until now (Mahmoudi et al., 2019b; Shubbak, 2019). Recycling PV waste is beneficial to the environment and as well will become economically profitable with decreased initial investment cost as PV module waste flow rises (Faircloth et al., 2019). More research and development are needed in fighting negative impacts recycling processes have on the environment (Contreras Lisperguer et al., 2020). More so the economic and social aspects are very important in achieving sustainability.

4.4 End-of-Life Assessment

With emerging increase in the research and development of PV waste, there is still lack of data when it comes to waste from PV modules. There have been a lot of studies conducted by researchers to estimate the waste from PV panels in the years to come. This is to help with the forecasting of PV waste volumes necessary for designing a proactive strategy in treating and recycling waste (Dominguez and Geyer, 2019; Mahmoudi et al., 2019a). To do this, environmental and techno-economic analysis are needed to ascertain the impacts of the waste stream (Dominguez and Geyer, 2019) through assessment such risk and life cycle analysis. The results of these assessments inform governments and policy makers on the urgency of decreasing environmental impacts through the establishment of recycling and recovery facilities, especially with countries that do not have these facilities or regulations on PV waste but in highly use of PV technology (Contreras Lisperguer et al., 2020).

Many PV modules such as the silicon-based PVs are coming to their end-of-life in the near future, others like the CdTe PV modules as stated by Fthenakis et al., (2020) are not of an immediate concern because of their relatively low volume of installation and use. With their decommissioned time slated for 25 to 30 years, a considerable growth in CdTe PV waste is anticipated. However, to deal with the considerable amount of PV module waste in the near future (IRENA and IEA-PVPS, 2016), their end-of-life management must be understood today to prevent problems associated with sustainability in the coming years. There have been a lot of assessment on Solar PV waste ranging from Risk assessment, material flow analysis, circular economy, Chemical treatment, and life cycle analysis. A clear indication of the earlier results of the analysis reveals that, early research was based more on the performance and efficiency of solar panels instead of its waste prospects. The term end-of-life was recently introduced within the solar PV research field because of the projection of PV waste in the coming years and the need for us to reach the sustainability goals and help protect the environment. Also, the issue of leaching and contamination of PV waste within the solar research field needs more attention as this research and others (Nain and Kumar, 2020) have shown.

5 Conclusions

Emerging waste streams such as that from the solar technologies are now becoming a problem because of the growth and the need to satisfy the housing and energy demands as well as produce clean energy. This has caused a quick rise in the installation of PV panels across the world. Solar photovoltaic waste research is an emerging research area which has received more attention recently due to the health and environmental impacts associated with its disposal. This study reviewed the emerging trends and patterns of PV waste research over the years. The study revealed that, research on solar photovoltaics was first referenced as back as 1974 in the journal of applied physics, also the study has seen a gradual increase in the interest of solar photovoltaic waste research since 1974. Moreover, Advanced Energy Materials, Advanced Functional Materials, Journal of Materials Chemistry A, Renewable and Sustainable Energy Reviews and ACS Applied Materials and Interfaces were ranked as the top five journals with the highest impact factor per the 2019 incites citation report.

The co-word analysis established the keyword co-occurrence and clusters as well as the subject categories which revealed performance and efficiency as the most frequent keywords, and this is because there is a considerable effort going into research on the performance and efficiency of alternative PV technologies to replace the old ones. A good mention is the polymer solar cell. The keyword clusters however produced five clusters and they are solar cell, dye-sensitized solar cell which appeared twice, Cadmium telluride (CdTe) solar cell and single-walled carbon nanotube. The co-citation analysis discussed the author co-citation, document co-citation and the journal co-citation networks. The discussion revealed the attention that has been given to polymer solar cells within the past few years as researchers continue to search for a more efficient and strong performing material to alternatively replace the old technologies. It was realised in the discussion that, waste research towards the end-of-life solar panels started within the decade and continues to grow. The collaborative efforts of the authors were also discussed with the USA and China proving to be the most collaborative countries as well as researchers on solar PV waste research. The results posit that, little attention was given to reuse, recovery and recycling of solar PV modules throughout the years and with the previous installations coming to their end-of-life, interest in its management has been one of the hot topics recently.

With most of the earlier research concentrating on the performance and efficiency of polymer solar cells, future research should aim at finding solar cells that are easily recycled or recovered after its end-of-life. Moreover, the commercialisation of organic solar cells should be prioritised because of its environmental benefits. Current research on PV module waste, needs improvement because of the slow development of policies and regulations in countries with a high number of solar PV installations. Moreover, assessments (risk and life cycle analysis) should be conducted on waste disposal strategies and recycling technologies to meet the requirements of the old and new PV modules. Finally, future research should focus on assessing the emissions of current solar PV modules and the easily remanufacture, recovery and reuse of future solar PV modules.

Chapter 3. Research methodology

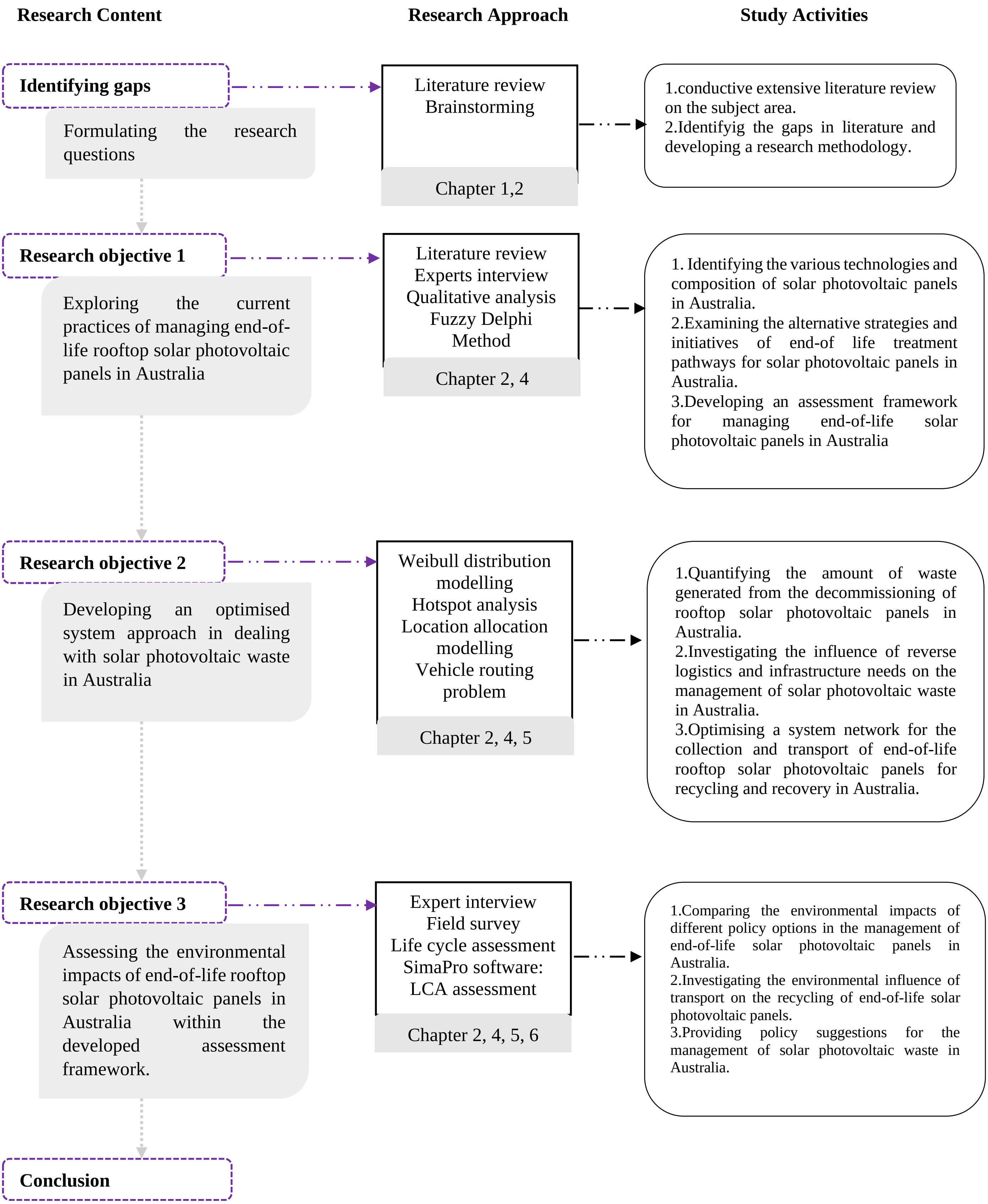
3.1 Introduction

This chapter explains the various methods employed in achieving the objectives of this study. The first section describes the overall research framework of the study. The second section provides the methodology used to explore the current practices of managing EoL rooftop solar photovoltaic panels in Australia. The third section employs several methods to develop an optimised system approach in dealing with solar photovoltaic waste in SA. The last section describes the life cycle assessment framework used in assessing the environmental impacts of EoL rooftop solar photovoltaic panels in South Australia within the developed assessment framework.

According to the requirements of the National Statement on Ethical Conduct in Human Research (2007), this research was involved in recruiting participants to take part of the study that required ethics approval. The low-Risk Human Research Review committee has reviewed the ethics application for this study and approved it (Approval number: H-2020-244), with the approval letter provided in appendix E.

3.2 Research framework

The research framework illustrated in figure 3.1 below describes the various methodology employed in achieving the overall aim of the study. This study addressed three main objectives which are: Exploring the current practices of managing EoL rooftop solar photovoltaic panels in Australia; Developing an optimised system approach in dealing with solar photovoltaic waste in Australia; and assessing the environmental impacts of EoL rooftop solar photovoltaic panels in Australia within the developed assessment framework.



Research Content	Research Approach	Study Activities
Identifying gaps Formulating the research questions	Literature review Brainstorming Chapter 1,2	1.conductive extensive literature review on the subject area. 2.Identifyig the gaps in literature and developing a research methodology.
Research objective 1 Exploring the current practices of managing end-of-life rooftop solar photovoltaic panels in Australia	Literature review Experts interview Qualitative analysis Fuzzy Delphi Method Chapter 2, 4	1. Identifying the various technologies and composition of solar photovoltaic panels in Australia. 2.Examining the alternative strategies and initiatives of end-of life treatment pathways for solar photovoltaic panels in Australia. 3.Developing an assessment framework for managing end-of-life solar photovoltaic panels in Australia
Research objective 2 Developing an optimised system approach in dealing with solar photovoltaic waste in Australia	Weibull distribution modelling Hotspot analysis Location allocation modelling Vehicle routing problem Chapter 2, 4, 5	1.Quantifying the amount of waste generated from the decommissioning of rooftop solar photovoltaic panels in Australia. 2.Investigating the influence of reverse logistics and infrastructure needs on the management of solar photovoltaic waste in Australia. 3.Optimising a system network for the collection and transport of end-of-life rooftop solar photovoltaic panels for recycling and recovery in Australia.
Research objective 3 Assessing the environmental impacts of end-of-life rooftop solar photovoltaic panels in Australia within the developed assessment framework.	Expert interview Field survey Life cycle assessment SimaPro software: LCA assessment Chapter 2, 4, 5, 6	1.Comparing the environmental impacts of different policy options in the management of end-of-life solar photovoltaic panels in Australia. 2.Investigating the environmental influence of transport on the recycling of end-of-life solar photovoltaic panels. 3.Providing policy suggestions for the management of solar photovoltaic waste in Australia.
Conclusion		

Figure 3.1: Research framework

The methods to achieve objective 1 includes the use of qualitative instrument to collect data from experts and stakeholders associated with the management of solar PV waste in Australia. The interview data is then collected and analysed using NVivo software. A comprehensive literature review was conducted to develop indicators for the questionnaire design. Stakeholders were then recruited for the research. The responses from the participants were analysed to develop a conceptual framework for the study.

To achieve the objective 2, several methodological approaches were employed. The first was to quantify the waste in the next 30 years using postcode data from previous and current installations. A hotspot analysis was conducted using GIS to identify the suburbs with the highest rate of projected waste in 30 years' time. An allocation and vehicle routing problem are then simulated to optimise the travel distances covered by trucks from transfer stations to the recycling centre. The pollutant emissions from the trucks considering the scenarios created was also estimated using the methodology for calculating transport emissions and energy consumption (MEET).

The last objective was achieved through a life cycle approach. Using previous studies as the system boundary and inventory data, the environmental impacts of solar PV waste management in South Australia was simulated under three different scenarios using the SimaPro software.

3.3 Methods for achieving objective 1

The objective one adopts a modified Fuzzy Delphi method (FDM) in exploring the management practices of solar photovoltaic waste in Australia. The limited representativeness and restricted generalizability of the outcome of qualitative research paradigm is a main shortcoming associated with the field (Silverman, 2013). However, FDM's cost effectiveness and limited informants in the research field can be employed to improve the efficiency and quality of the method (Padilla-Rivera et al., 2021).

3.3.1 Survey design

The study uses semi-structured interviews as the instrument for collecting primary data for analysis. Veal (2017) posited that, semi structured interviews facilitate in-depth analysis through the generation of rich datasets from the subject being explored and the real attitudes of respondents are revealed through this technique (Ghauri et al., 2020). One set of interviews were designed for industry professionals including manufacturers, distributors, waste consultants, recovery, and recycling experts. The other set of interviews were designed for government participants including government organizations and institutions related to the management of PV waste. The structure of the interview is as follows, the first part collected the demographic data and experience of the respondents. The second part contains information on developments in solar PV technologies in Australia, policies, and regulations on solar photovoltaics in Australia, strategies, and initiatives of PV waste treatment pathways. A pilot study was conducted to make sure the questions were familiar to the target respondents and the minutes were reasonable. The results from the interview were used to develop a survey questionnaire using a 5-point Likert scale to gather the experts' consensus. This is developed through a set of algorithms based on the linguistic terms from the triangular fuzzy numbers. This was then sent for approval to the Human Research Ethics Committee (HREC) where an ethics approval number H-2020-244 is received.

3.3.2 Identification of field experts

In conducting the interviews, all participants were selected purposively (Etikan & Bala, 2017; Palys, 2008) within Australia who falls within the criteria set for the research. The snowball sampling (Atkinson & Flint, 2001) was also applied to ascertain respondents that are not known to the researchers. Owing to the issues of Covid-19, all participants were reached and interviewed through Zoom or Phone. In the case of participants within the State of the researchers (South Australia) who could participate face-to-face and choose to do that, all social distancing rules were observed within that State. In this case, the interview was conducted in a public space or other comfortable place that makes both participants and researchers feel safe. The criterion for selection limits the participants by their knowledge in the area as well as their experience in the field. Thus, respondents should be experts working in the solar photovoltaic industry for at least two years and should have experience on solar photovoltaics in Australia. The only exclusion criterion was a limit of less than two years in the PV industry.

The participants selected for the study were members of governmental organizations or spokesperson within the Australian Renewable Energy Agency, Clean Energy Regulator, Department of Energy and Water, Department of Agriculture, Water and the Environment /Environment Protection Authority, National Waste and Recycling Industry Council, Green Industry SA; Members of institutions such as the Australia Photovoltaic Institute and the Waste Management and Resource Recovery Association of Australia; Spokesperson of Manufacturers, Distributors/Installers, Consultants within the solar PV industry (This was retrieved from the member list of clean energy council approved retailers and crossed check using the Australian Business Register (ABN) Lookup; Experts within the recovery and recycling of solar PV industry.

A database of who does what in the PV waste management field and personal information was ascertained through contact search on LinkedIn and institutional webpages for the purpose of recruitment. This information was not used for the analysis. The participants were contacted through their institutional email and/or LinkedIn addresses initially to ascertain their availability and willingness to participate in the studies. If their personal information was not available, the researcher contacted the chief operation officer or spokesperson of the institution for them to connect the researcher to the right people. The participant information sheet and consent forms were made available to all potential participants for them to decide whether they are going to participate. Once the contact is successful, a suitable time was arranged for the interview.

3.3.3 Interview process

After the ethics approval, the participant information sheet and consent form were made available to the identified participant on the initial contact through their institutional emails to advise them on the preliminary information of the study and as an invitation to participate in the research during recruitment. Participants were given time to voluntarily respond to the mail based on the information given them. Consent was obtained from participants using the consent forms, to explicitly acquire the use of data for the study and potential future research projects. If the participants decide to participate in the study, a comfortable date was set for the interview that was conducted virtually or through the phone because of the restrictions on Covid-19 which will help reduce any potential discomfort for the participants. The first round of interviews took place on January 2021. It took approximately 6 months to complete 80% of the interviews and another 4 months to finalize the remainders.

Table 3.1: Characteristics of respondents

No	Organisation	Position	Code
1	Government / Consultants /Institutions	Chief Executive	P1
		Program Lead Investment facilitation	P2
		Industry Research Analyst	P3
		Project Officer	P4
		Technical Standards and Safety Officer	P5
2	Industry practitioners (Manufacturers, recyclers, distributers, installers)	Sales Associate	P6
		Business Developer	P7
		Project Consultant	P8
		Co-founder	P9
		Head of Recycling	P10
		Chief Executive officer	P11
		Director	P12
		Chief Technology Officer	P13

Note: Name of organisations are removed from the demographics to respect and protect the confidentiality of participants as stated in the ethics document number H-2020-244.

The number of interviews conducted for this research is 13 qualified experts within the solar PV industry. This consist of Government/Consultants organizations and Industry practitioners associated with the management of solar PV waste in Australia. The interview was concluded when the state of new information was satisfied, which meant that it had reached the "saturation effect". The interview on average lasted for 20 to 60 minutes. A total of 15 respondents agreed to participate after contacting 35 respondents. In the end, 13 respondents (see table 3.1) took part in the interviews. This consisted of 5 respondents from the government/consultants and 8 respondents from the solar PV industry.

To provide a fair presentation and accurate analysis of the data, NVivo software for qualitative data analysis, is used to analyze the interview data (Welsh, 2002). With consent from the participants, all the interviews were audio or video recorded. The interviews were then transcribed within Microsoft Word and coded into nodes using NVivo. Personal details such as names are replaced with unique codes when analyzing the data to protect the identity and privacy of the participants. Thus, in the case of this study the participants comments, and details are presented anonymously. Thematic analysis is applied in establishing a good understanding of the interview data (Jankowicz, 2013). The established themes under the interview design were the bases for the development of the survey instrument for the FDM. Verbatim quotations from the interviews are also used to support the discussion derived from the analysis.

3.3.4 Fuzzy Delphi Method

This study adopts a modified FDM to develop a conceptual framework for end-of-life solar photovoltaic management in Australia. The FDM is a combination of the conventional Delphi method with fuzzy theory. This was created to avoid the ambiguousness in the Delphi method when it comes to consensus from the panel, it also reduced the time for investigation (Marlina et al., 2022). Several researchers have recommended a sample size of between 5 to 20 experts for a Delphi panel (Okoli and Pawlowski, 2004; Rowe and Wright, 2001).

There are three main stages when it comes to the FDM process. The first one is the input preparation, which includes the information gathering, questionnaire preparation and expert selection. The second stage is the data analysis which consists of changing the linguistic terms to fuzzy numbers, setting the threshold and percentage for consensus, and defuzzification. The last stage is the final decision where you make the decision based on the results from the analysis. FDM has been applied in waste management studies such as sustainable solid waste management (Bui et al., 2020). The FDM procedure is adopted in this study to assess the significance of individual criterion from experts using linguistic variables (Negash et al., 2021). To translate the qualitative information into values, the fuzzy triangular numbers (TFNs) were used to handle the linguistic preferences of the participants as shown in table 3.2.

Table 3.2: Fuzzy triangular numbers for FDM assessment.

Linguistic terms	Likert Scale	Triangular fuzzy numbers		
		n1	n2	n3
Strongly agree	5	0.6	0.8	1
Agree	4	0.4	0.6	0.8
Not sure	3	0.2	0.4	0.6
Disagree	2	0	0.2	0.4
Strongly disagree	1	0	0	0.2

The respondent evaluation score was aggregated using the geometric mean, the fuzzy weight (F_m) of each criterion was determined.

$$F_m = \left\{u_m = \min(u_{nm}), v_m = \left(\sum_{m=1}^{k}(v_{nm})\right)^{1/k}, w_m = max(w_{nm})\right\} \qquad 1$$

From equation 1, where m is the significance evaluation score criterion m, n is the expert rated criterion m, k is the number of experts, and u, v, and w stand for the lower, middle, and upper values of the TFNs, respectively.

The aggregated fuzzy weights of each criterion are defuzzified using the equation below:

$$D_m = \frac{u_m+v_m+w_m}{3} m = 1,2,3,\ldots y \qquad 2$$

From equation 2, y is the number of criteria. The threshold (τ) for screening out the nonsignificant criteria was set: $D_m \leq \tau$, then the $_m$th criterion is rejected; if $D_m \geq \tau$, then the criterion is accepted. Under a typical situation, $\tau = 0.5$ is used. The percentage approval from experts should be more than 75%.

3.4 Methods for achieving objective 2

3.4.1 Study area

South Australia has a population around 1.77 million and covers a total land area of 983,482 km^2 making the fifth largest by population and fourth largest by area among the Australian states and territories. Rooftop solar panels constitutes 20% of Australian households' energy, making it the world's highest uptake of residential solar panels (Zander et al., 2019). In September 2020, there was a low demand for grid-based power across three states as records were sent tumbling because of the solar power boom in Australia. In particular, South Australia (SA) achieved a key milestone with the state becoming the first state in Australia and anywhere in the world to be powered entirely by solar power for over an hour in October 2020 (CEC, 2021).

3.4.2 Waste projection scenarios and spatial statistical analysis

Geographic Information System provides an effective tool in analysing the spatial representation of data of different types in geographical visualised platform. It aids in the collection, output and distribution, analysis, storage and maintenance of spatial information and data (Chari et al., 2016). The dataset used for the estimation is obtained from *Clean Energy Council*. The data contains solar PV installations of capacity less than 100kW from the year 2001 to 2021. In this study, this data was then compared and verified with data from Australian Photovoltaic Institute (APVI) data on similar installations in South Australia. The waste scenarios early and regular loss are forecasted using the acquired data as mentioned earlier.

3.4.3 Waste forecasting via Weibull distribution modelling

The current postcode installation data was collected from the Clean Energy Regulator (2021) resources on postcode data for small-scale installations as of June 2021. The dataset is current as of 31st April 2021 from the year 2001. The waste is calculated into early and regular loss scenarios (as shown in appendix C). The solar PV waste is calculated using the formulae;

$$F(t) = 1 - \mathrm{e}^{-\left(\frac{t}{\tau}\right)^{\beta}} \tag{3}$$

Where, the Weibull function is F(t), the life in years of the panels is t, the scale parameter which is the average lifetime of the panels is equal to τ. The shape factor, which is β, is responsible for the Weibull curve. All the years were calculated separately and then merged into one worksheet.

3.4.4 Hotspot mapping technique

Hotspot analysis measure the statistical significance of p-values and z-values derived from the identification of spatial clustering of low (cold spot) and high (hot spot) values (Chen et al., 2018). This spatial statistical method is used in different disciplines describing how high a value or region is relative to their surroundings. Spatial analysis provides valuable insights through the analysis of connections, locations, and attributes in spatial data (Amiri et al., 2021). This research focuses on the mapping cluster method using the Getis-Ord (Gi*) hotspot analysis.

Getis and Ord (1995) was the first study to introduce the autocorrelation method which is the Getis-Ord (Gi*) spatial statistics. Their methods are able to discriminate between cold spots and hot spots as compared to other previous methods. The G* is able to tell the difference between concentrated low and high value locations within local observations as well as identify spatial clustering (Songchitruksa and Zeng, 2010). Thus, the features surrounding a high value feature should also have high values to be considered as a high spot. The general form for Getis–Ord (G_i^*) is:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{4}$$

Where x_j is the attribute value for feature j,$w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{5}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \tag{6}$$

The G_i^* statistics is a z-score, so no further calculations are required. Low-value spatial clustering is represented by a negative z-score indicating a small p-value and a low z-score; however, high value spatial clustering is represented by a positive z-score indicating a small p-value and a high z-score (Chen et al., 2018; Prasannakumar et al., 2011).

3.4.4 Network Analysis and Route Optimisation

In GIS, a network is a system with elements that are interconnected. Connections of streets to one another or to intersections, cities that are connected by roads, and points that are connected by a series of lines can all be visualised using a network. A network dataset (NDS) can be generated for analysis using the extension, Network Analyst (NA), in ArcGIS ArcMap. The networks that are created from the feature source in NA are stored in the NDS. Network attributes within the features like the one-way street locations, speed limits, street restrictions for specific vehicles, road length for fuel consumption and travel time are used to model and measure impedances (Tavares et al., 2009). Network analysis is commonly used to minimise distance (shortest route) or minimise travel time (fastest route) when ascertaining the optimal route or path of an element.

Solid waste collection can be optimised using the network analysis. The software ArcGIS can be used to design and optimise route using real-time road conditions. Several researchers have used the software in the application of minimising distance or travel time in solid waste collection (Islam et al., 2021; Zsigraiova et al., 2013; Travers et al. 2009). This study determines the Minimize Weighted Impedance (P-Median) within the Location-allocation modelling and Vehicle Routing Problem (VRP) using ArcMap version 10.8.1. The distance and travel times from the GIS modelling and analysis are used to calculate the associated emissions of transporting solar PV waste within and around South Australia.

The data used for the network analysis were retrieved from the *Australian and SA government data directory*. Data such as the shapefile for roads, waste management facilities, administrative regions, and information on speed limits and heavy-duty vehicles were obtained from the Department for Infrastructure and Transport (DTI). In SA, speed limits for unsealed roads are permitted up to 80 km/h. Roads that are not traffic routes have 50 km/h as speed limits and a default of 100 km/h speed limit as the maximum speed legally permitted to travel outside built-up areas. The network dataset sets a mean of 60 km/h as heavy vehicles are limited even on some highways in SA.

3.4.5 Location-allocation modelling

Location-allocation modelling is used to determine the shortest route generated by an origin-destination matrix through the application of Dijkstra algorithm between a waste source and specified number of facilities or nodes (Yalcinkaya, 2020). The p-median approach is used in this study as it minimises the overall weighted distance, with facilities serving their nearest demand vertex (Revelle and Swain, 1970). Thus, the transportation distance and capacity of the facilities are determined through the allocation of the solar PV waste sources to the transfer stations. The p-median problem is formulated as follows:

$$\text{minimize,} \qquad \mathrm{Z} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_i x_{ij} a_{ij} \tag{7}$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} = 1, \qquad \forall\, i = 0,1,2,\dots,m, \tag{8}$$

$$a_{ij} \le y_j \quad \forall\, i = 0,1,2,\dots,m \text{ and } j = 0,1,2,\dots,n, \tag{9}$$

$$\sum_{j=1}^{n} y_j = k, \tag{10}$$

$$a_{ij}, y_j \in \{0,1\} \quad \forall\, i = 0,1,2,\dots,m \text{ and } j = 0,1,2,\dots,n,$$

Decision variables:

$$a_{ij} = \begin{cases} 1, & \text{if waste source } i \text{ is sent to a station located in } j \\ 0, & \text{otherwise} \end{cases} \tag{11}$$

$$y_j = \begin{cases} 1, & \text{if a station opened in } j \\ 0, & \text{otherwise} \end{cases}$$

Where, waste sources (solar PV waste) total is m; the total number of transfer stations is n; the chosen transfer stations in the model is k (k < n); index of potential transfer stations is j; index of waste sources is I; the shortest distance between potential stations and waste sources is represented by x_{ij}; the weight of the demand waste source at point i (known as the waste amount) is represented by d_i. The number of stations (k = 1, 2, 3, 4, …, n) as they increase are solved in this model. The objective function Z, as shown in equation (7) aims to minimise the overall distance between the waste sources and transfer stations. In assigning waste sources to transfer stations, equation (8) requires the assignment of one waste source to one station. If a station is not open, equation (9) does not assign any waste source. The restriction of several stations that is opened to k is achieved using equation (10).

A weight of 1 to 4 were allocated to the transfer stations, with 1 allocated to values that are not significant, and within the cold spot of 90% to 99% confidence. 2, 3 and 4 were allocated to hot spot with confidence level of 90%, 95% and 99% respectively. This was to make sure transfer stations within the hot spot zones were given the highest priority before the ones in the cold spots. For the demand points or waste sources, the weight used was the amount of waste generated at the location. A search tolerance of 50000 meters were set for the loading of the transfer stations and solar PV waste sources because of the large land mass in Australia.

3.4.6 Vehicle routing problem

Vehicle routing problem (VRP) solves the problem with parameters like type of output, network restrictions, network impedance and costs creating multiple routes to delivery facilities from one or more demand locations (Bozkaya et al., 2010). Dijkstra's (1959) work on his algorithm for shortest path has created an in-depth research phenomenon in road freight transportation through vehicle routing. Route optimisation which originates from the domain of graph theory and operations research continues to be used in the logistics domain where it has been adapted and extended with one being the VRP. A fleet of vehicles with a set of restrictions and different optimisation criterion can be optimised using the VRP (Schröder & Cabral, 2019). The VRP is determined using the extension within ArcMap 10.8.1 using the NA which has a built-in tabu search algorithm (Chari et al., 2016).

3.4.7 Pollutant Emissions

Waste collection and transportation influences the pollutants emitted through the operation conditions and travel distance of the vehicle in use. Pollutants such as PM, CO, CO_2 and NO_x are associated with heavy duty diesel vehicles which are commonly used for the collection and transportation of waste (Zsigraiova et al., 2013). This study uses the EURO IV diesel heavy duty vehicles for the calculation of the selected pollutants and referring to Hickman et al. (1999)

methodology for calculating transport emissions and energy consumption (MEET). The corresponding emissions are calculated based on the determined optimum route in section 3.4.6. The equation used to determine the emissions are shown below:

$$E_i = \sum_{Vehicle\ route} (E_{i,hot} + E_{i,cold}) \tag{12}$$

$$E_{i,hot} = \varepsilon_{i,c} d_{tr} \tag{13}$$

$$\varepsilon_{i,c} = \left(k_1 + av + bv^2 + cv^2 + \frac{d}{v} + \frac{e}{v^2} + \frac{f}{v^3}\right) \tag{14}$$

$$\times \left[\left(k_2 + rv + sv^2 + tv^3 + \frac{u}{v} - 1\right) z + 1\right]$$

$$E_{i,cold} = \varepsilon_{i,cold} N \tag{15}$$

The total pollutant emission i (g) is represented by E_i, $E_{i,hot}$ and $E_{i,cold}$ highlighting the total pollutant emissions, hot pollutant emissions and cold pollutant emissions respectively. The hot emission factor for pollutant i corrected for load (g/km) is represented by $\varepsilon_{i,c}$ and travel distance (km) is represented by d_{tr}. The mean velocity (km/h) is represented by v, whiles the coefficients k_1, a, b, c, d, e, f and k_2, r, s, t, u depends on the total weight of the selected vehicle. The fraction of the load transported is represented by z. The number of cold starts and cold emission factor for pollutant i (g/cold start) is represented by N and $\varepsilon_{i,cold}$ respectively. The values to the various coefficient are shown in appendix C.

3.5 Methods for achieving objective 3

3.5.1 Treatment process at the plant

The first step of the process is the collection of the EoL PV modules, in our case from transfer stations to the recycling plant. The distance of the PV waste from users to the transfer stations are estimated to be 100km for the treatment of 1 ton of PV module using a 7.5t truck. However, the rest of the distances calculated are used in the scenario analysis for an estimated 3000-ton treatment of PV waste annually at the recycling plant.

The second step is the treatment or recycling of the PV modules at the plant. As discussed above, the plant is situated at Lonsdale, operated by PV recycling plant in SA. The transfer of the EoL PV modules from the transfer stations to the recycling centres are normally assumed in several research (Ardente et al., 2019; Latunussa et al., 2016), however, this study uses an estimated distance from the transfer stations using different scenarios as described in chapter 5, which is a first and essential contribution when it comes to transport distances in the life cycle assessment of solar PV modules.

The PV modules are then unloaded by a forklift and transported to conveyor belts for dismantling. The whole process is associated with recycling 1000kg of PV waste within an hour as shown in table A1 (see appendix D). The disassembly is automated at the plant where the aluminium frame, cables and junction box are removed using a Cartesian robot and mechanical arm. The aluminium is then sold for treatment into aluminium ingots or used as a secondary material whiles the cables are collected for treatment in another plant. The plastic parts of the cables are then treated in an incineration plant with energy recovery.

The process is to treat the remaining materials after the mechanical detachment. A glass separation process is introduced to treat the waste panels without the cables and aluminium frames. The process separates the glass layer from the rest of the cells and layers of polymer (also called ‘PV sandwich’). To retrieve the PV sandwich and glass, an infra-red heat treatment process is introduced. Then a high-frequency knife button, regulated by speed and amplitude is used to mechanically detach the glass. Subsequently, a refinement process separates the sizes of the glass through sieving. The glass with impurities of mass around 2% after an optical-based separation system are sent to landfill. The PV sandwich is incinerated at the recycling plant after reducing their sizes by a cutting process, in our case there is no need to transport the PV sandwich to another incinerating plant. The process produces fly ash which is sent to a hazardous waste landfill assumed to be located 50km from the plant. The rest of the product (bottom ash) are crushed and sieved to retrieve the rest of the aluminium, whiles the rest is transferred to an acid leaching process.

The leaching process separates the silicon from other metals. During this process, water, and nitric acid (HNO_3) is mixed with the ash, this leaves the silicon as a residue in the dissolved solution of the various metallic oxides produced. Subsequently, the mixture containing the solution goes through vacuum filtration process for the recovery of the silicon. This helps recover the silicon at metallurgical grade. An electrolysis process is then introduced to recover the copper and silver from the solution at an efficiency of around 95%. This process emits an estimated 2kg per ton of treated PV waste in NOx gases. Calcium hydroxide is added to the acid solution after electrolysis to successfully neutralise it. A filter press is then used to filter the final output, separating it into a sludge (unrecovered metals with some residual calcium hydroxide and water) and liquid waste (calcium nitrate and water). These wastes are sent for disposal, transportation assumed to be 100km away. The input and output process are discussed in the life cycle inventory section.

3.5.2 Goal and scope definition

The goal of this LCA is to access the potential environmental impacts of recycling mono and multi crystalline silicon photovoltaic modules using a pilot recycling process and plant sitautated in SA. This process have been developed by adapting the Full Recovery End of Life Photovoltaic (FRELP) process piloted by the Italian company “SASIL S.p.A”. for treating end of life solar crystalline silicon PV panels.

3.5.3 Functional Unit

The functional unit (FU) of this process is the recycling of 1000kg of EoL crystalline silicon modules separated into mono and multi crystalline silicon modules as illustrated in table A1 in the supplementary material. The FU does not include other module components such as the external cables and inverters but includes the internal cables.

The inputs and output are estimated based on the market share of both technologies. Mono-Si panels are estimated to have a market share of 55% with multi-Si panels having 45% market share. The latter is constructed from isolated crystals with the former based on one large crystal (Daljit Singh et al., 2021). The quantity of waste panels for the Mono and Multi c-Si are 1,350 and 1,650 tons, respectively.

3.5.4 System Boundary

The system boundary of this LCA considers the photovoltaic technologies mono and multi-crystalline modules. This process follows a gate to gate approach, which considers only the EoL scenario without the production and use stages. Figure 3.2 illustrates the system boundary from the EoL solar panels to their treatmemt options through the three established policy options.

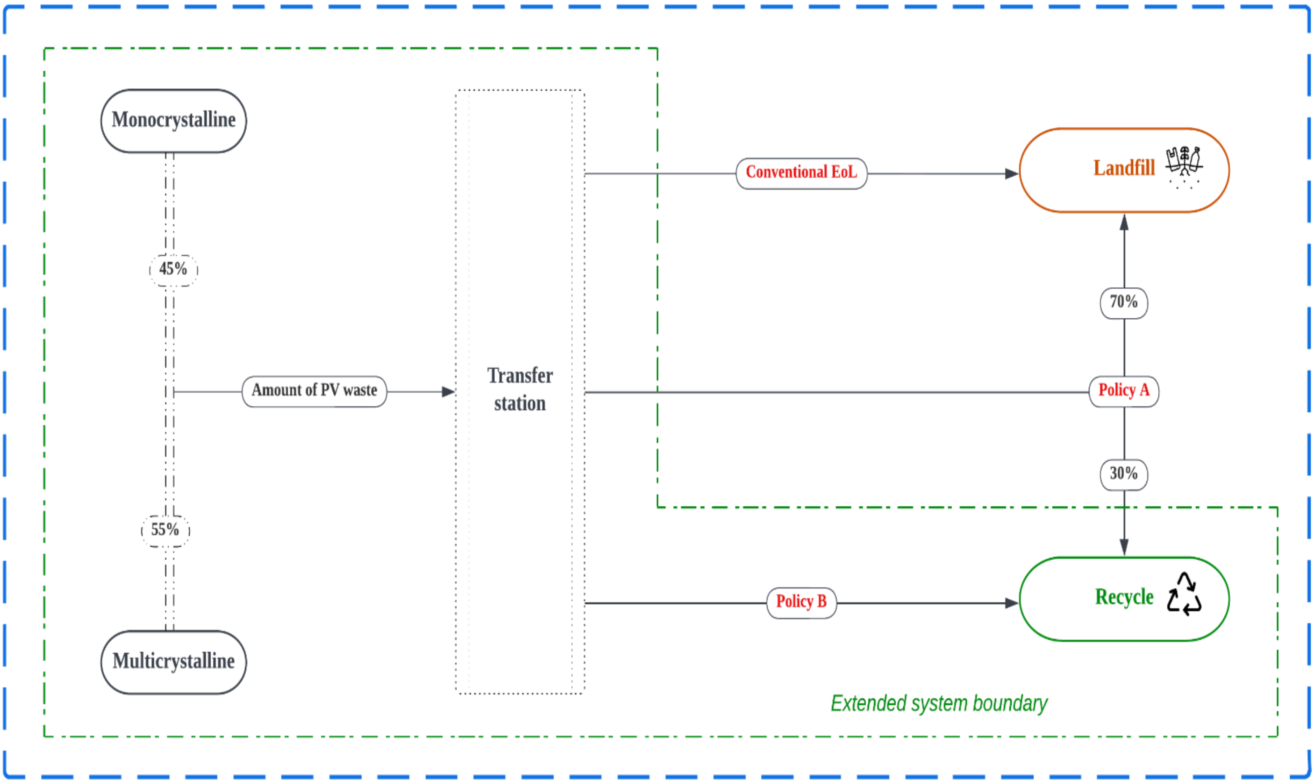


Figure 3.2: System boundary

The EoL scenario is based on three policy options:

- The first scenario considers the non existense of policies and regulations creating a situation where all the PV waste are transported to landfills which is the baseline scenario (Conventional EoL) as shown in figure one.
- The second policy option is the introduction of a voluntary product stewardship (VPS) by the government, this may see a 30% increase in recycling but 70% of the panels may end up in landfills.
- The last option is an introduction of robust mandatory product stewardship (MPS) or extended producer responsibility (EPR) which may see 100% of the panels being recycled. The detail of the options as associated with the other technologies are illustrated in table A3 in appendix D.

3.5.5 Life Cycle Inventory data

The data for the research was collected from several sources. The input/output sources were obtained through background and foreground data. Information from bibliographical and literature sources as well as personal interviews were acquired for the analysis. The study is conducted using a pilot recycling plant in Australia. The foreground information on site specific processes was obtained through tailored interview questionnaire from a PV plant as the main primary data for the assessment. Foreground data was collected in a form of interviews on the operation of the plant and modelled against the FRELP process to fill in the missing data. The transportation distance of EoL solar panels to the recycling plant was estimated in chapter 5.

Table 3.3: Details of the lifecycle inventory dataset used in this study

Item	Used for the process phase	Dataset used
Transport	Transport of PV waste to the recycling plant	Transport lorry 16-32 t EURO5/RER U/ AusSD S
	Transport of: PV waste to local collection point; cables to cable treatment plant and cable polymer to the incineration plant; glass residue to landfill; PV sandwich to incinerator; ash to the treatment plant; fly ash to special landfill.	Transport lorry 3.5-7.5 t EURO5/RER U/ AusSD S
	Transport of sludge from the recycling plant to landfill	Transport lorry 7.5-16 t EURO5/RER U/AusSD S
Diesel fuel	Unloading	Diesel burned in building machine/GLO U/AusSD S
Electricity	Disassembly, cable treatment, glass separation, glass refinement, cutting of PV sandwich, sieving, acid leaching, filtration, electrolysis, neutralisation, and filter press	Electricity, high voltage (AU) | market for |APOS, S
Disposal of fly ash in landfill	Incineration	Disposal average incineration residue 0%, water to residual material landfill/CH
Incineration of plastics from cables	Cable treatment	Disposal, wire plastic, 3.55% water, to municipal incineration/CH U/AusSD S
Incineration of PVF	PV sandwich incineration	Disposal, polyvinyl fluoride, 0.2% water, to municipal incineration/CH U/AusSD S
Incineration of EVA	PV sandwich incineration	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U/AusSD S
Landfilling of the contaminated glass	Glass treatment	Disposal, glass, 0% water, to inert material landfill/CH
Treatment for the recycling of cables	Cable treatment	Disposal, treatment of cables/CH
Production of heat (avoided impacts from energy recovery during the incineration)	Incineration of cable polymer and PV sandwich, energy recovery	Heat natural gas at industrial furnace > 100 kW/RER

Production of electricity (avoided impacts from energy recovery during the incineration)	Incineration of cable polymer and PV sandwich, energy recovery	Electricity, high voltage (AU) | market for |APOS, S
Landfilling of sludge with metal residuals	Filter press	Disposal, sludge, pig iron production, 8.6% water, to residual material landfill/CH S/ AusSD S
Landfilling of inert sludge	Filter press	Disposal, limestone residue, 5% water, to inert material landfill/CH U/AusSD S
Ca $(OH)_2$	Neutralisation	Lime hydrated loose at plant/CH U/ AusSD S
Nitric acid (HNO_3)	Acid leaching	Nitric acid 50% in H_2O at plant/RER U/ AusSD S
water	Acid leaching, electrolysis, neutralisation	Water, completely softened, at plant/RER U/AusSD S/ AusSD S
	Production process of photovoltaic panel	Photovoltaic panel, mono-Si wafer (GLO) | market for | APOS, S
	Production process of photovoltaic panel	Photovoltaic panel, multi-Si wafer (GLO) | market for | APOS, S
	Landfilling of the photovoltaic panels	122 Waste treatment, Landfill of waste, Metals nec, EU27 123 Waste treatment, Landfill of waste, Glass/inert, EU27 121 Waste treatment, Landfill of waste, Copper, EU27 120 Waste treatment, Landfill of waste, Aluminium, EU27 118 Waste treatment, Landfill of waste, Plastic, EU27
	Production process of photovoltaic panel	Transport, lorry 3.5-7.5 t EURO5/RER U/AusSD S

Background information on related data such as emissions from the treatment of waste, auxiliary materials, use of energy and the generation of energy, dataset of unit processes and allocation at point of substitution were acquired from secondary data from AusLCI and Ecoinvent database (AusLCI, 2019; Ecoinvent, 2022) and scientific literature (Ansanelli et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2020). Table 3.3 shows the details of the background lifecycle inventory dataset.

3.5.6 Life Cycle Impact Assessment

The LCA was modelled using the SimaPro software version 9.1.0.11. The Best Practice Guide for Mid-Point Life Cycle Impact Assessment in Australia (ALCAS Best Practice LCIA carbon neutral) was chosen for the assessment with thirhteen indicators comprising Climate change (Global warming): Gobal Warming Potentials (GWP) for a 100 year time horizon, as per IPCC

Forth Assessment Report (IPCC, 2007) in kgCO_2-eq; Resource (abiotic) depletion – minerals (ADE): abiotic depletion of minerals based on concentration of currently economic reserves and rate of de-accumulation in Sb-eq; Resource (abiotic) depletion – fossil fuels (ADF): abiotic depletion of fossil fuels based on energy content (lower heating value) in MJ; Water scarcity (WS) - Method of Ridoutt and Pfister (2010), with water stress indices of Pfister et al. (2009) in m^3H_2O-eq; Eutrophication (EP): eutrophication potentials which assumes both N- and P-species contribute in kgPO_4-eq; Acidification (AP): if assessed, use the change in critical load exceedance, currently based on European characterisation factors in kg SO_2-eq; Toxicity: human (cancer, HTC and non-cancer, HTN) and freshwater eco-toxicity (FET) based on USEtox- with regionalised characterisation factors of Australia, derived based on regionalisation approach in CTU; Photochemical ozone formation (oxidation): Photochemical Ozone Creation Potentials (POCP) in C_2H_4-eq; Particulate matter formation (PMF): Fate and exposure based on Wolff, using the CALPUFF model in kg$PM_{2.5\text{-eq}}$. ALCAS is selected for this study because of the geographical location of the studies, to help in achieving accurate results from the selected impact categories.

In a Life Cycle Assessment, energy recovery and material recycling benefits associated with the environment can be approached in several ways. The approach that is mostly used is to allocate credits for any recycling benefits (example is substituting the respective materials to be produced) (Held & Ilg, 2011). This was introduced in the assessment of the waste PV panels for this study.

3.6 Chapter summary

This chapter describes the various methods adopted to achieve the objectives of this study. The methods are comprehensively explained in the previous results chapters. A research framework is established to highlight the various objectives and their research approaches and finally the activities undertaken under them.

Chapter 4. Results: Part 1

4.1 Introduction

There are insufficient options in Australia when it comes to the appropriate management of hazardous materials from solar PV waste. This study investigates the management of EoL PV panels in Australia using a modified Fuzzy Delphi Method (FDM) to gather data through interviews and questionnaires from experts in the field. Chapter 4 examines the Australian market when it comes to current solar PV technologies and the ones that are being installed frequently. The absence of policies and regulations results in unregulated movement and tracking of solar PV waste as described in this chapter. Moreover, infrastructure and logistics has been a significant problem because of the geographical spread of the country and how it affects transportation and the supply chain. The findings establish a conceptual framework for the current treatment of solar PV waste in Australia.

4.2 List of manuscripts

This part of the research has been produced as a journal article, published in *Sustainable Horizons*:

Oteng, D., Zuo, J., & Sharifi, E. (2020) "An expert-based evaluation on end-of-life solar photovoltaic management: An application of Fuzzy Delphi Technique". *Sustainable Horizons, 4,* 100036.

The paper is presented here in a reformatted version for consistency of the thesis presentation. The published manuscript can be found in Appendix B.

Statement of Authorship

Title of Paper	An expert-based evaluation on end-of-life solar photovoltaic management: An application of Fuzzy Delphi Technique
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Oteng, D., Zuo, J., & Sharifi, E. (2022). An expert-based evaluation on end-of-life solar photovoltaic management: An application of Fuzzy Delphi Technique. Sustainable Horizons, 4, 100036.

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Contribution to the Paper	Conceptualization, Methodology, Data curation; Writing - original draft; Formal analysis		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	03/11/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Jian Zuo		
Contribution to the Paper	Conceptualization, Supervision, Writing - review & editing		
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4.3 An expert-based evaluation on end-of-life solar photovoltaic management: An application of Fuzzy Delphi Technique

Abstract

The implementation of solar photovoltaic (PV) waste management options is of concern to international bodies, policymakers, and communities as it is not only related to life cycle environmental impacts but the preparation of a long-term plan and its successful implementation. There are insufficient options in Australia when it comes to the appropriate management of hazardous materials from solar PV waste. This study investigates the management of end-of-life (EoL) PV waste in Australia. A modified Fuzzy Delphi Method (FDM) is adopted in gathering data through interviews and questionnaires from experts in the field. The FDM analysis revealed the results showing the decisions made by the experts. The results show that, crystalline silicon panels were the most common panels on the Australian market and the ones that are being installed frequently. On policies, although the Australian government has banned PV waste from going to landfill since 2014, there were no regulations or action plans to manage PV waste. The absence of policies and regulations results in unregulated movement and tracking of solar PV waste in and out of Australia as well as within and across the states. The extent of the PV recovery and recycling is still under investigation. Moreover, infrastructure and logistics has been a significant problem because of the geographical spread of the country and how it affects transportation and the supply chain. Findings led to the establishment of a conceptual framework for the current treatment of solar PV waste in Australia.

1 Introduction

Solar photovoltaic (PV) energy is efficient, safe, and reliable. The interest in solar energy is at an all-time high because of the benefits mentioned. The global effort to achieve sustainable environmental goals has seen several government push for clean energy, which has seen the dramatical rise of solar energy use across the world (IEA-PVPS, 2021; IPCC, 2012). When it comes to green energy, increased adoption of solar PV delivers an effective solution (Dominguez & Geyer, 2019). Conventional power generation plants could be replaced or complemented by photovoltaic technology because of its current maturity. However, the upsurge in the global waste stream should be envisaged for the coming years. With old modules being replaced by new and some reaching their end-of-life (EoL), a significant amount of PV waste may end up in landfills if proper managerial steps are not considered and implemented (Khawaja et al., 2021).

Among the sources of electric energy generation, the amount of waste per unit energy attributed to solar PV waste is significantly high (Baldwin et al., 2015). This situation is alarming because of the installation year, 1990, for solar panels in most developed countries. Weckend et al. (2016) explains that this will see an estimated global solar PV waste of 60 million tons being disposed into landfills in the year 2050. Dangerous elements like cadmium, chromium and lead in landfills could be harmful to the environment and human health if steps are not taken to curb the situation (Majewski et al., 2021). Landfilling is not sustainable long-term and is not an environmentally friendly option. With these heavy metals present in the panels, significant environmental issues may arise due to leaching or contamination in the soil or groundwater (Farrell et al., 2020).

According to Tsanakas et al. (2020), with the increase patronage in solar PV, value creation opportunities may be created through proactively adopting principles within a circular economy. The need for reuse of rare earth materials from end-of-life solar PV back into the supply chain and the avoidance of negative impacts to the environment and human health associated with inappropriate hazardous material disposal (Salim et al., 2021), are key drivers for creating an effective sustainable policy for solar PV waste. The efficiency of new solar cells and their commercial supply have been the center of solar PV research in the past years. Currently, a significant body of research on solar PV waste is looking at the management and recycling of end-of-life solar PV across the world (Oteng et al., 2021; Xu et al., 2018).

According to Daniela-Abigail et al. (2022), the successful implementation of a long-term PV waste management plan which is tailored to a specific country is of concern to international bodies, policymakers and communities because of the environmental impacts associated with solar PV waste. Thus, to successful create a sustainable infrastructure for solar PV waste management, various stakeholders are required to contribute to achieving a long-term sustainability goal. Recently, a lot of countries are trying to ascertain effective ways to manage the PV waste stream among them is Australia which has the highest adoption of rooftop solar PV in the world. Majewski et al. (2021) posits that, there are insufficient management options in Australia when it comes to the appropriate management of hazardous materials from solar PV waste. They also emphasize that; recyclers and recovery units currently lack the capability to recover valuable resources and materials from end-of-life solar PV.

There are existing studies on the drivers, barriers, and enablers of solar PV waste (Curtis, Buchanan, Smith, et al., 2021; Mahmoudi, Huda, Alavi, et al., 2019; Hengky K. Salim et al., 2019) management, others, on the life cycle assessment of solar PV end of life in Australia (Mahmoudi et al., 2020, 2021) without necessarily investigating the current practices of solar PV waste management. Salim et al. (2021) also researched into the dynamic modelling of PV product stewardship transition in Australia. None of these studies in Australia, establishes the current managerial practices related to the movement, monitoring, and recycling of solar PV waste management through government and industry experts. This study bridges the gap by looking at the various practices associated with the management of end-of-life solar PV through expert interview and analysis. It adds to literature by conducting a comparative analysis between other countries in the management of PV waste. The study further develops a conceptual framework of the current PV waste management practices and suggests potential future directions in Australia.

2 Literature review

Technologies across solar photovoltaics and some of the practices related to the management of PV waste are reviewed in this section. A search criterion has been developed to ascertain the appropriate keywords for the review. Keywords include "treatment" OR "waste" OR "End-of-life" OR "dispos*" OR "recover*" "reus*" OR "recycl* AND "pv panels" OR "photovoltaic cells" OR "photovoltaic" OR "solar panels", were used as the search query using Booleans "OR" and "AND". This search was conducted in the Web of Science Core Collection occurring within the topic search. The search occurred on the 10th of December 2019 for the design of interviews for primary data collection and updated on the 31st of March 2022.

Table 1: Reviewed themes on PV waste management practices

S/N	Themes	Code	Sub-themes
1	**Solar panel technology (ST)**	**ST1**	First generation
		ST2	Second generation
		ST3	Third generation
2	**Policies and regulations (PR)**	**PR1**	Policies and regulations in place
		PR2	No policies and regulations in place
3	**Monitoring, tracking and logistics (ML)**	**ML1**	Collection, monitoring and tracking
		ML2	No monitoring and tracking
4	**Infrastructure needs (IN)**	**IN1**	Optimised recovery and recycling
		IN2	Current/available infrastructure
		IN3	No infrastructure
5	**Treatment Pathway (TP)**	**TP1**	Recycling and recovery
		TP2	Landfilling and disposal
		TP3	Exportation (Interstate and overseas)
		TP4	Reuse or reconditioning
		TP5	Incineration
		TP6	Other practices

Note: Details are available in the supplementary material (table A1)

The keywords occur within the waste research studies conducted by researchers within the field of solar photovoltaics (Mahmoudi, Huda, et al., 2019a; Oteng et al., 2021; Salim et al., 2021). The Web of Science is used because of its quality and coverage of over 1.7 billion cited references within 155 million records in 34, 000 journals in different disciplines (Clarivate

Analysis, 2020). A comprehensive literature review was conducted on solar PV waste research (Oteng et al., 2021) and a further classification was analyzed per the themes in table 1. The classification consists of; solar panel technology: policies and regulations: monitoring, tracking and logistics: treatment pathway: and collection and infrastructure needs of solar PV waste. This formed the themes for the interview design and structure for primary data collection. Table A1 in the supplementary material shows the various themes involved in solar PV waste management literature and describes the process thereof.

2.1 Solar photovoltaic technologies

At the gigawatt scale of electricity production, solar photovoltaic technology is known to be the cleanest and safest among existing sources of renewable energy (IEA-PVPS, 2021). There has been a tremendous increase in the development of solar technology since its discovery in the 19th century. This development has seen dramatic changes to technological generation and efficiency, solar cell types, and technical fields within its mechanics, electronics, physics, and chemistry. Therefore, the production and application levels has dynamically improved on the market (Shubbak, 2019).

There are three classes of solar PV technology (Sundaram et al., 2016). These classes are known as the first, second and third generations of PV technology. The ones currently available on the market for consumers are the first and second generations. The first-generation technology are crystalline silicon (c-Si) wafer-based cells. Among the second generation are the single-junction Gallium Arsenide (GaAs) Cells, amorphous Silicon (a-Si) cells, Copper indium gallium di-selenide (CIGS) cells, and the Cadmium telluride (CdTe) cells which are also known as thin film technologies. These two technologies are available in several applications because of their mass production in the solar PV market. With a staggering 93% production capacity, c-Si cells dominate with 24% attributed to mono-crystalline and 69% attributed to the multi-crystalline technologies. The total production of the thin films forms 7%

of the technologies. The amorphous Silicon, Cadmium telluride constitutes 3% and 2.5% respectively, with less than 2% attributed to the Copper indium gallium di-selenide (Shubbak, 2019).

The third generation is still yet to reach the market (Farrell et al., 2020) with a lot of research being conducted for its commercialization. The third generation of PV technologies is emerging including the multijunction cells, Dye Sensitized Solar Cell (DSSC), perovskite solar cells (PSC) and organic solar cells (OPV) which are under research for commercialization. The aim is to make the manufacturing innovative to supply electricity at low cost (Oteng et al., 2021; Shubbak, 2019; Sundaram et al., 2016).

2.2 Policy and regulations governing solar PV waste

The production of electricity using solar panels has increased recently. Their end-of-life management is essential as these panels in the coming years will be sent to landfills if proper legislative directives and robust systems are not put in place to handle the collection and storage of solar PV waste (Dominguez & Geyer, 2019). Recycling and monitoring of PV waste stream and the implementation of innovative management technologies are critical to the reduction of environmental impacts associated with end-of-life solar PV (Majewski et al., 2021). According to Zou et al. (2017), there is a tremendous market growth of solar PV in countries like the USA, India, Australia, China, and Japan, however, they lack specific regulatory measure in the management of EoL solar PV (Oteng et al., 2021).

To minimize landfilling and optimize recycling of end-of-life solar PV, the European Union (EU) implemented the WEEE directive which includes an integrated approach to regulate the generation of PV waste in Europe (Jain et al., 2022). The EoL collection and recovery of solar PV is entirely the responsibility (financial and physical liability) of distributors and manufacturers under the Extended Producer Responsibility (EPR) as formulated in the WEEE

EU/2012/19 directive (WEEE Directive, 2012). This is expected to aid in the devolvement of innovative recycling technologies from manufactures. The products life is expected to be extended and the reuse and recycling process will be easier (Khawaja et al., 2021). A recycling and recovery rate of 75-80% is required under the WEEE for PV waste panels when it was revised in 2012 through 2018 and expected to increase to 80-85% rate by mass (Majewski et al., 2021).

However, in countries like the USA, each state must introduce its own recycling regulations. There is no federal regulation or statutes that handles the management of solar PV waste (Curtis, Buchanan, Heath, et al., 2021). There are, however, industry and state led policies that are emerging to address the management of PV waste in the USA. The framework within these state-led policies is diverse and applies to different actors in the management activities of EoL panels. (Curtis, Buchanan, Heath, et al., 2021; Nain & Kumar, 2022; Weckend et al., 2016). The first state to require manufactures to collect and recycle or reuse EoL PV modules was Washington, which enacted the law in 2017. California in January 2021 have passed a regulation to manage EoL panels as universal hazardous waste allowing for the modules not to be chemically and thermally treated during its recycling processes. States like North Carolina (Bill 329) and New Jersey (Bill 601), in 2019 passed a senate bill and created a commission to study options associated with the management of solar PV waste (Curtis, Buchanan, Heath, et al., 2021).

PV waste is still not considered as e-waste in China, thus, there are no regulations governing its management even with the introduction of a policy for recycling e-waste in 2011 (Weckend et al., 2016). Research has been started on the technological development, safe disposal, and recycling of solar PV waste in China (Mahmoudi et al., 2021). Japan does not have any regulatory approach towards the management of EoL PV modules too (Nain & Kumar, 2022).

PV waste is currently treated under the general waste law in India, with no regulatory or policies to manage this stream separately (Daniela-Abigail et al., 2022; Jain et al., 2022).

Currently, Australia does not have any regulations or legislations in the management of EoL PV modules. However, in 2019 it was listed as a priority in product stewardship scheme development under the National Waste Policy Action Plan (Australian Government, 2019). The regulation in the management of PV waste is expected to be developed by 2023 (Majewski et al., 2021; Oteng et al., 2021).

2.3 Recycling and recovery options for PV waste

The number of installed solar panels that will reach their end-of-life in the next 25-30 years is astounding, as they may reach around 60 million tons. Across the globe, there are a lot research going into the recycling and recovery of solar panels with researchers developing several processes and activities such as chemical and mechanical recycling approached, the economic challenges and social impacts (Heath et al., 2020; Padoan et al., 2019; Vargas & Chesney, 2021). The question of whether these processes and current approaches are sufficient to address the environmental impacts of PV waste remains to be confirmed.

The main problem associated with the recycling industry of solar PV waste and panels ending up in landfills is because of not meeting the collection and recycling targets due to the lack of appropriate regulations and policies (Dominguez & Geyer, 2017; Oteng et al., 2021; Salim et al., 2021). Also, the issue of local governments, users, and producers' clear roles when it comes to financial and non-financial responsibilities need further clarifications (Fthenakis, 2000; Mahmoudi, Huda, Alavi, et al., 2019; H. K. Salim et al., 2019). Again, the tailoring of collection, transport and recycling associated with the management of solar PV waste generation needs to be quantified in relation to its pollution and emission generation (Majewski et al., 2021).

According to Salim et al. (2021), there is no funding allocated to recycling when it comes to the collection of solar PV waste in Australia. There is a limited number of recyclers in regional states operating in Australia. Because of the limited market development, unsustainable funding inflow and little incentive in the recovery of solar PV waste, many of these upcoming recyclers may not survive for long. Consumers prefer landfill disposal compared to recycling and recovery alternatives due to the higher waste levy rates considering the current high collection fee within different Australian states (Salim et al., 2021).

3 Material and methods

This study adopts a modified Fuzzy Delphi method (FDM) in exploring the management practices of solar photovoltaic waste in Australia. The limited representativeness and restricted generalizability of the outcome of qualitative research paradigm is a main shortcoming associated with the field (Silverman, 2013), However, FDM is cost effectiveness and limited informants in the research field can be employed to improve the efficiency and quality of the method (Padilla-Rivera et al., 2021). The methodological approach is shown in figure 1, which describes the modified FDM used to achieve the objectives of the study. The process of the methodology is described thereafter.

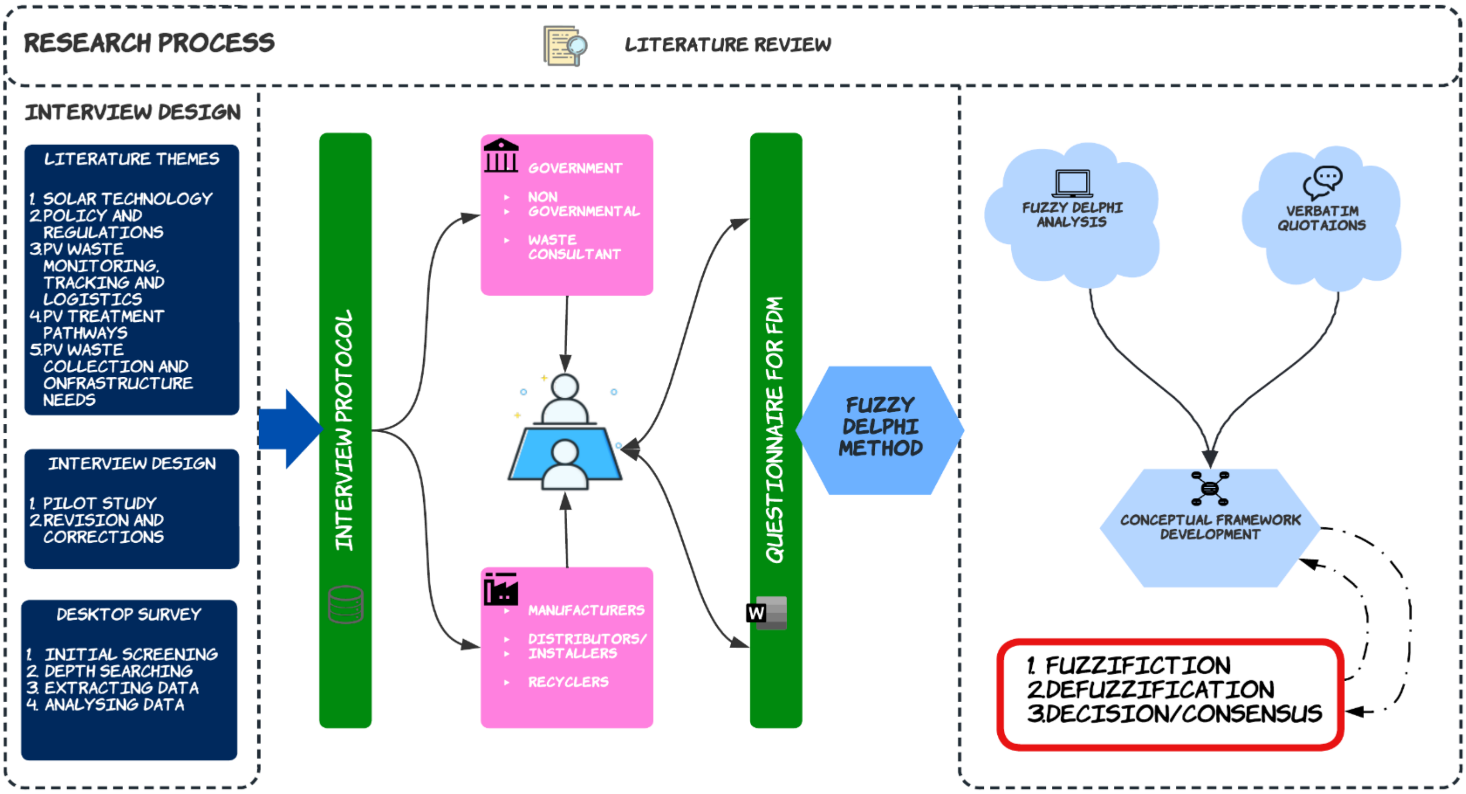

Fig. 1. Methodological approach

3.1 Survey design

This study uses semi-structured interviews as the instrument for collecting primary data for analysis. Veal (2017) posits that, semi structured interviews facilitate in-depth analysis through the generation of rich datasets from the subject being explored and the real attitudes of respondents are revealed through this technique (Ghauri et al., 2020). One set of interviews were designed for industry professionals including manufacturers, distributors, waste consultants, recovery, and recycling experts. The other set of interviews were designed for government participants including government organizations and institutions related to the management of PV waste. The structure of the interview is in two parts. The first part collected the demographic data and experience of the respondents. The second part contains information on developments in solar PV technologies in Australia, policies, and regulations on solar photovoltaics in Australia, strategies, and initiatives of PV waste treatment pathways. A pilot study was conducted to make sure the questions were familiar to the target respondents and the minutes were reasonable. The results from the interview were used to develop a survey questionnaire using a 5-point Likert scale to gather the experts consensus. This is developed through a set of algorithms based on the linguistic terms from the triangular fuzzy numbers. This was then sent for approval to the Human Research Ethics Committee (HREC) which received an ethics approval number H-2020-244.

3.2 Identification of field experts

In conducting the interviews, all participants were selected purposively (Etikan & Bala, 2017; Palys, 2008) within Australia who falls within the criteria set for the research. The snowball sampling (Atkinson & Flint, 2001) was also applied to ascertain respondents that are not known to the researchers. Owing to the issues of Covid-19, all participants were reached and interviewed through Zoom or Phone. In the case of participants within the State of the researchers (South Australia) who could participate face-to-face and choose to do that, all social distancing rules were observed within that State. In this case, the interview was conducted in a public space or other comfortable place that makes both participants and researchers feel safe. The criterion for selection limits the participants by their knowledge in the area as well as their experience in the field. Thus, respondents should be experts working in the solar photovoltaic industry for at least two years and should have experience on solar photovoltaics in Australia. The only exclusion criterion was a limit of less than two years in the PV industry.

The participants selected for the study were members of governmental organizations or spokesperson within the Australian Renewable Energy Agency, Clean Energy Regulator, Department of Energy and Water, Department of Agriculture, Water and the Environment /Environment Protection Authority, National Waste and Recycling Industry Council, Green Industry SA; Members of institutions such as the Australia Photovoltaic Institute and the Waste

Management and Resource Recovery Association of Australia; Spokesperson of Manufacturers, Distributors/Installers, Consultants within the solar PV industry (This was retrieved from the member list of clean energy council approved retailers and crossed check using the Australian Business Register (ABN) Lookup; Experts within the recovery and recycling of solar PV industry.

A database of who does what in the field and personal information was ascertained through contact search on LinkedIn and institutional webpages for the purpose of recruitment. This information was not used for the analysis. The participants were contacted through their institutional email and/or LinkedIn addresses initially to ascertain their availability and willingness to participate in the studies. If their personal information was not available, the researcher contacted the chief operation officer or spokesperson of the institution for them to connect the researcher to the right people. The participant information sheet and consent forms were made available to all potential participants for them to decide whether they are going to participate. Once the contact is successful, a suitable time was arranged for the interview.

3.3 Interview process

After the ethics approval, the participant information sheet and consent form were made available to the identified participant on the initial contact through their institutional emails to advise them on the preliminary information of the study and as an invitation to participate in the research during recruitment. Participants were given time to voluntarily respond to the mail based on the information given them. Consent was obtained from participants using the consent forms, to explicitly acquire the use of data for the study and potential future research projects. If the participants decide to participate in the study, a comfortable date was set for the interview which was conducted virtually or through the phone because of the restrictions on Covid-19 which will help reduce any potential discomfort for the participants. The first round of interviews took place on January 2021. It took approximately 6 months to complete 80% of the interviews and another 4 months to finalize the remainders.

Table 2: Characteristics of respondents

No	Organisation	Position	Code
1	Government / Consultants /Institutions	Chief Executive	P1
		Program Lead Investment facilitation	P2
		Industry Research Analyst	P3
		Project Officer	P4
		Technical Standards and Safety Officer	P5
2	Industry practitioners (Manufacturers, recyclers, distributers, installers)	Sales Associate	P6
		Business Developer	P7
		Project Consultant	P8
		Co-founder	P9
		Head of Recycling	P10
		Chief Executive officer	P11
		Director	P12
		Chief Technology Officer	P13

Note: Name of organisations are removed from the demographics to respect and protect the confidentiality of participants as stated in the ethics document number H-2020-244.

The number of interviews conducted for this research is 13 qualified experts within the solar PV industry. This consist of Government/Consultants organizations and Industry practitioners associated with the management of solar PV waste in Australia. The interview was concluded when the state of new information was satisfied, which meant that it had reached the “saturation effect”. The interview on average lasted for 20 to 60 minutes. A total of 15 respondents agreed to participate after contacting 35 respondents. In the end, 13 respondents (see table 2) took part in the interviews. This consisted of 5 respondents from the government/consultants and 8 respondents from the solar PV industry.

To provide a fair presentation and accurate analysis of the data, NVivo software for qualitative data analysis, is used to analyze the interview data (Welsh, 2002). With consent from the participants, all the interviews were audio or video recorded. The interviews were then transcribed within Microsoft Word and coded into nodes using NVivo. Personal details such as names are replaced with unique codes when analyzing the data to protect the identity and privacy of the participants. Thus, in the case of this study the participants comments, and details are presented anonymously. Thematic analysis is applied in establishing a good understanding of the interview data (Jankowicz, 2013). The established themes under the interview design were the bases for the development of the survey instrument for the FDM. Verbatim quotations from the interviews are also used to support the discussion derived from the analysis.

3.4 Fuzzy Delphi Method

This study adopts a modified FDM to develop a conceptual framework for end-of-life solar photovoltaic management in Australia. The FDM is a combination of the conventional Delphi method with fuzzy theory. This was created to avoid the ambiguousness in the Delphi method when it comes to consensus from the panel, it also reduced the time for investigation (Marlina et al., 2022). Several researchers have recommended a sample size of between 5 to 20 experts for a Delphi panel (Okoli and Pawlowski, 2004; Rowe and Wright, 2001).

There are three main stages when it comes to the FDM process. The first one is the input preparation, which includes the information gathering, questionnaire preparation and expert selection. The second stage is the data analysis which consists of changing the linguistic terms to fuzzy numbers, setting the threshold and percentage for consensus, and defuzzification. The last stage is the final decision where you make the decision based on the results from the analysis. FDM has been applied in waste management studies such as sustainable solid waste management (Bui et al., 2020). The FDM procedure is adopted in this study to assess the significance of individual criterion from experts using linguistic variables (Negash et al., 2021). To translate the qualitative information into values, the fuzzy triangular numbers (TFNs) were used to handle the linguistic preferences of the participants as shown in table 3.

Table 3: Fuzzy triangular numbers for FDM assessment.

Linguistic terms	Likert Scale	Triangular fuzzy numbers		
		n1	n2	n3
Strongly agree	5	0.6	0.8	1
Agree	4	0.4	0.6	0.8
Not sure	3	0.2	0.4	0.6
Disagree	2	0	0.2	0.4
Strongly disagree	1	0	0	0.2

The respondent evaluation score was aggregated using the geometric mean, the fuzzy weight (F_m) of each criterion was determined.

$$F_m = \left\{u_m = \min(u_{nm}), v_m = \left(\sum_{m=1}^{k}(v_{nm})\right)^{1/k}, w_m = max(w_{nm})\right\} \qquad 1$$

From equation 1, where m is the significance evaluation score criterion m, n is the expert rated criterion m, k is the number of experts, and u, v, and w stand for the lower, middle, and upper values of the TFNs, respectively.

The aggregated fuzzy weights of each criterion are defuzzified using the equation below:

$$D_m = \frac{u_m+v_m+w_m}{3} m = 1,2,3, \dots y \qquad 2$$

From equation 2, y is the number of criteria. The threshold (τ) for screening out the nonsignificant criteria was set: $D_m \leq \tau$, then the $_m$th criterion is rejected; if $D_m \geq \tau$, then the criterion is accepted. Under a typical situation, $\tau = 0.5$ is used. The percentage approval from experts should be more than 75%.

4 Results and discussions

The results of the analysis from the Interviews and FDM are presented under the major themes highlighted in the literature review with additional support from verbatim quotations from the interview transcripts. The themes include solar technologies in Australia, policies and regulations in Australia, PV waste monitoring, tracking and logistics in Australia, treatment pathways in Australia, and PV waste collection and Infrastructure needs in Australia. The waste flow and recycling opportunities are expanded with comparative literature from the solar PV field. The work also draws on current and relevant literature to better understand the situation and recommend solutions.

4.1 Fuzzy Delphi analysis

The table below (table 4) shows the results from the FDM, showing the themes, sub themes, fuzzy evaluation. Average of fuzzy numbers and the decisions made. The agreements of the experts are gathered using the Fuzzy Delphi technique, making sure that the percentage agreement is equal or greater than 75%.

Table 4: FDM results

Themes	**Codes**	**Sub themes**	**Score**		**Decision**
			Fuzzy Evaluation	**Average of fuzzy numbers**	
Solar panel technology (ST)	**ST1**	First generation	9.400	0.723	**Accepted**
	ST2	Second generation	3.733	0.287	**Rejected**
	ST3	Third generation	1.733	0.133	**Rejected**
Policies and regulations (PR)	**PR1**	Policies and regulations in place	4.467	0.344	**Rejected**
	PR2	No policies and regulations in place	7.000	0.538	**Accepted**
Monitoring, tracking and logistics (ML)	**ML1**	Collection, monitoring and tracking	2.667	0.205	**Rejected**
	ML2	No monitoring and tracking	9.000	0.692	**Accepted**
Infrastructure needs (IN)	**IN1**	Optimised recovery and recycling	2.200	0.169	**Rejected**
	IN2	Current/available infrastructure	6.600	0.508	**Accepted**
	IN3	No infrastructure	2.600	0.200	**Rejected**
Treatment Pathway (TP)	**TP1**	Recycling and recovery	9.600	0.738	**Accepted**

	TP2	Landfilling and disposal	7.800	0.600	**Accepted**
	TP3	Exportation (Interstate and overseas)	8.400	0.646	**Accepted**
	TP4	Reuse or reconditioning	8.600	0.662	**Accepted**
	TP5	Incineration	7.400	0.569	**Accepted**
	TP6	Other practices	8.400	0.646	**Accepted**

Table 4 shows the decision from the results from the FDM analysis and serves as a validation and consensus from the experts. This is discussed in the sections below supported by some verbatim comments from the experts.

4.2 Solar technologies in Australia

The solar panel technology's theme shows a decision of one accepted and two rejected. The fuzzy evaluation (FE) for ST1, ST2 and ST3 are 9.400, 3.733 and 1.733 respectively. The Average of fuzzy numbers (AFN) show a value of 0.723 for ST1, 0.287 for ST2 and 0.133 for ST3. The decision to accept the first generation as the most installed panels in Australia received a high consensus with some experts having more to share on the topic. The verbatim comments from some of the experts are discussed. There are several solar technologies on the Australian market. Most of the participants confirmed the Mono and Poly crystalline silicon panels as the most installed in Australia:

> *'… Most of the time is mono and poly, the industry is only known mostly mono and poly …. Because the standards are using the industry mono and poly, that is 80% of the supplies maybe 90% …' [P2]*
>
> *'Well, there is two, polycrystalline and monocrystalline, they are generally the most common panels…. So, we do the Poly and the monocrystalline panels here.'[P4]*

Others [P6 and P9] also explained that they only recycle the mono and poly crystalline silicon panels. According to D'Adamo et al. (2017), 85% to 90% of the global PV market is made up of the Crystalline Si module technology. Australia is not far from these statistics as explained by Mahmoudi, Huda, et al. (2019a) in their PV waste forecast in Australia. This also showed the current PV waste stream and what the future waste stream will look like. The researchers also wanted to highlight the knowledge on the new technologies that were flooding the market and whether new technologies will continue to be developed:

> *... I think newer technologies will be things like roof tiles like Tesla, if the products are becoming simpler and easier to install the volume will grow more and more. ... I think, flexible solar panels and roof tiles are probably where the next ones are pretty much heading ... [P2]*

According to *[P2]*, the Tesla roof and flexible panels are some of the new technologies in the market. With the development and adoption of Building Integrated Photovoltaics (BIPVs), the makeup of the PV waste stream may change in the coming years. Moreover, cell technologies like copper indium gallium selenide, gallium arsenide, and cadmium telluride continues to compete with the c-Si technology which is the most installed currently (Heath et al., 2020). Monitoring of the technological changes is very important to the industry as iterated in the analysis, closely linked to their capacity to address how recycling is satisfied in the future. According to Heath et al. (2020), this deployment recycling cycle should be closely monitored. This is supported by *[P6]*, who also confirmed these emerging technologies and how the design and capacity is changing with these new technologies.

4.3 Policies and regulations in Australia

The results revealed that PR1 had a fuzzy evaluation score of 4.46 and the average of fuzzy number score of 0.344. PR2 received an FE score of 7.000 and an AFN score of 0.538. The values are further justified in the discussion. Looking at the policies and regulations, the respondents were asked if they knew of the existence of any regulations that guides the management of solar PV panels. The common answers are no, however, there were interesting discussions that came out. Especially, [P7] had an interesting take on this:

> *'The government can do some research and provide guidance, but I think is still an industry problem and is a civilian problem. People themselves should be a bit more aware of the choices that they make...' [P7]*

The respondent's argument was based entirely on how the industry can push and be the leader in this process of recycling and recovery. The voluntary participation without government intervention is not ideal. Moreover, the lack of collection points for PV waste and cheap disposal fee has seen the increase of PV waste in landfills (Salim et al., 2021). The respondent also made mention of how the government can educate the community on the toxic or harmful elements in the panels which can leach into the ground at the EoL stage. On this question of a working policy and regulation, [P3] posits that:

> *'One of my colleagues has been involved I mean I will not call it a policy but trying to work on a product stewardship, but I mean it is still in its infancy ... but, no, there is none in place and even the product stewardship is taking some time and trying to get all the states talking to each other on it as well. I am not aware of anyone (policy or regulation) in place but what I am aware of its we are still working on that product stewardship.'[P3]*

Australia, as rightly confirmed by all the respondents is working on a product stewardship that will govern the management of solar PV waste. This is still in the process and believe to be ready by 2023. Others also brought the researchers attention on the landfill ban of PV waste in some states:

> *'In Victoria there is a landfill ban on PV models. That was introduced in 2019, I think. ... There are no other states that have that sort of legislation yet.' [P12]*

There were some few interesting takes from experts from industry and that from the government sector. One industry expert was of the view that, the PV waste is an industry and civilian problem. People should be more aware, and that the policy and education should start from them to achieve and effective regulation on PV waste management in Australia. The establishment and development of a policy and product stewardship for PV waste can contribute to the reduction of unregulated disposal of damaged and unwanted PV waste panels. An effective management scheme can serve as an indicator on renewable energy uptake, promote sustainable energy targets related to exceptionally implemented regulatory and policy frameworks clearly contributing to the countries energy resilience (Majewski et al., 2021). This will provide Australia with a guide to appropriately establish a recycling infrastructure and support for PV waste management.

4.4 PV waste monitoring, tracking and logistics in Australia

The collection, monitoring and tracking of PV waste is a big issue in Australia because of the spread of the land, The results clearly identify the problems when it comes to monitoring showing an FE an AFN of 9.000 and 0.692 respectively for ML2, and 2.667 and 0.205 for ML1. To quantify the amount of waste to manage, a proper tracking and monitoring of waste flow is significant. There are other waste like construction and demolition waste that are monitored and recycled in Australia. The first-generation panels have been installed over some decades and will be coming to their EoL stage soon. The lack of awareness on the part of some manufactures and consumers on the importance of recycling and material recovery within the PV supply chain has led to the disposal of EoL PV into landfills, rather than recycling the panels. Landfilling is believed to be the cheaper options therefore the enormous patronage (Khawaja et al., 2021). This is what the respondents had to say:

> *'... If there is hail damage for example and the panels get broken, and gets replaced ... a lot of these ends up going through middlemen who ends up selling them privately or they*

> *go down to recycling stores where a lot of these companies buy or get these panels cheap and then they sell them out ...' [P9]*

> *'...I think that is the one area where we can see some real regulation, or I think there should be an onus on the property developer to demonstrate where the waste is ended up ... I think if the recourse came back to the developer and he had to prove where it was disposed off, the illegal dumping and things like that would certainly dry out.' [P12]*

The comments of the participants demonstrate the unregulated movement of solar PV waste in and out of Australia as well as within the states. Because there are no policies in place (Majewski et al., 2021), some of them are already being dumped into landfills. Even with some states banning solar PV waste from Landfill, there is still no regulation as to what should be done with the panel at the EoL stage. This is a major problem as it promotes illegal dumping and unregulated movement of the waste stream in and out of Australia. There are some few companies like Reclaim PV, they have started the process of collecting and treatment of solar PV waste. However, data on this waste stream is very low as suggested by [P5]:

> *'...So, that is where a lot of work needs to be done and I mean we are even looking to do some here in Victoria because the level of data is very low... [P5]*

The low data makes it difficult to know the current waste flow and logistics associated with waste solar PV. Some of these are sent overseas for reuse and reconditioning without proper testing [P3, P8, P10]. Regulated waste flow will be significant to the management of PV waste, especially recovering essential and rare metals back into the supply chain. This promotes a good circular economy for the sector. Solar PV waste is a new form of waste stream which is now growing, the effective monitoring of this waste stream will aid policy makers and practitioners to better understand the situation and approach it thereof.

4.5 PV waste collection and Infrastructure needs in Australia

The results from the FDM reveals that, IN1 received an FE score of 2.200 and an AFN score of 0.169. IN2 received an FE score of 6.600 and an AFN score of 0.508. The last one which is IN3 received an FE score of 2.600 and an AFN score of 0.200. This is interpreted as the availability of a facility for the treatment of PV waste, which is known to some and others not having an idea of this facility. The absence of a policy or economic drivers is preventing the motivation of the solar industry from taking sustainable management decisions on EoL PVs. However, initiatives and standards led by the industry can promote sustainable PV waste management decisions that are environmentally friendly and economical (Tura et al., 2019). Most were of the view that, the government should make incentives available, others looked at the environmental benefits and commercial viability of the whole process:

> *'Government initiatives and assistance will motivate, but it will obviously come down to cost and time ... If it is mandated by law then that passes the cost to the customer, if its optional then it is a soft slope, you either take it or you do not take it ...' [P4]*
>
> *'I just think is capital and labor intensive. We are going to understand what its involved and if there is an opportunity there, we will try and take advantage of it.' [P9]*
>
> *'Obviously, the driver for the company is the cost benefit and we must make money for us to survive and to grow, but the core of what we are doing is passion about the environment. [P11]*

The need for infrastructure is important in the management of solar PV waste. The federal state and local governments may invest in PV recycling if there is resource security, supply chain stability, job creation and new market opportunities (Curtis, Buchanan, Smith, et al., 2021; Dominguez & Geyer, 2019; Weckend et al., 2016). Again, the market demand for these recycled materials will improve if manufacturers are encouraged to use a percentage of recycled materials. Recyclers are not motivated because of the current domestic market and its low commodity value (D'Adamo et al., 2017; Salim et al., 2021). An efficient collection network will also reduce some economic burden (Oteng et al., 2022a) and drive recyclers to recover solar PV waste. Respondents gave their views on the drivers and barriers that hinder Australia when it comes to solar PV waste infrastructure needs:

> *'... because it is an Australian kind of problem where we are all so spread out ... when you think of the solar farms, they are a long way probably the biggest barrier I see now and the lack of data when it comes to the feedstocks...' [7]*

Others [P9, P12] commented on the profitability of the venture and the opportunities that comes with recycling solar panels. But the most stressed problem was the geographical spread of the country and how it will make it difficult for recyclers to cope with the logistics of transporting and recovering the materials as well as returning it back to the production stream.

4.6 Treatment Pathways in Australia

The results shows that TP1 has an FE value of 9.600 and an AFN value of 0.738, TP2 has an FE value of 7.800 and an AFN value of 0.600, TP3 has an FE value of 8.400 and an AFN value of 0.646, TP4 has an FE value of 8.600 and an AFN value of 0.662, TP5 has an FE value of 7.400 and an AFN value of 0.569, and TP6 has an FE value of 8.400 and an AFN value of 0.646. There are several routes that solar PV waste may take at the EoL stage. Currently, some Australian states have banned the disposal of solar panels going into landfills. This has seen some individuals and companies who have started the collection and treatment of solar PV waste. Some states are also providing incentives for the recycling of solar panels. The researchers established the current treatment of solar PV waste in Australia through this theme and further received respondents' comments on the best treatment pathway for solar PV waste in Australia. It was established that:

> *'…if they came to one of our processing facilities, we would turn them away and send them to the landfill…' [P2]*

> *'Recycling is something that we are doing … If you recycle in an efficient way and you get the right amount of materials back from the panels …, I think it is great.' [P10]*

Most of the panels were going into landfill, however, there are some companies that are collecting and treating solar panels in Australia. There is the lack of innovation and incentives when it comes to recycling of PV waste (Oteng et al., 2021) in Australia as some of the respondents affirmed. However, some industry professionals are voluntarily creating their own innovations and systems to (Oteng et al., 2022a) aid in the recovery of solar PV waste (Islam et al., 2020; Mahmoudi et al., 2021). The extent of the recovering and recycling is still under investigation. The opinions of the respondents on the best treatment pathway for Australia when it comes to PV waste management was answered in different ways:

> *There should be a five-year roadmap where people should start thinking about how to incorporate recycling into the cost factors and almost give people a heads up when any panels that are being decommissioned after a certain time must follow a strict regulation …' [P2]*

> *So, just things like that I think moving towards making the recycling processes that are happening, you know more organic in terms of if there are chemicals being used it should be more organic, easier to dispose of and/or maybe reusable. [P8]*

From the comments, respondents were happy and eager to embrace change but wanted it to be executed appropriately with a comprehensive plan. Others wanted the innovation to be safe enough so not to cause more harm with the recycling and recovery processes.

4.7 The situation in other countries compared to Australia

According to Chowdhury et al. (2020), the technological market share of solar panels is dominated by silicon based (c-Si) panels. This takes 95% share of the global market (IRENA, 2019). Because Australia does not manufacture solar panels (a local manufacturer Tindo Solar started recently), old panels are supplied through the global supply chain, therefore, the technology in the Australian market is linked to that of the global market. Making the first-generation panels the predicted future waste stream.

The European Union including countries like United Kingdom, Germany, Italy, and France has established a WEEE directive governing the management of EoL PV (Berger et al., 2010; Majewski et al., 2021; Weckend et al., 2016). Countries like the USA, India, China, and Japan, lack specific regulatory measure in the management of EoL solar PV. This study identifies Australia as one of the countries without policy or regulations in place in the management of solar PV waste.

Jain et al. (2022) posits that, there is a resource challenge because of the supply crunch and competitive consumption in the manufacturing of solar PV modules related to critical metals such as copper, aluminum, cadmium, tellurium, silver, silicon, lithium, germanium. This metals from recycling could feed into this stock by about 90% reduction in the waste owing to high recyclability. This will also ensure and prevent these precious metals from going into deficit in the future with proper innovative research, thus, also diverting them from Landfill (Curtis, Buchanan, Smith, et al., 2021; Farrell et al., 2020; Hengky K. Salim et al., 2019; Xu et al., 2018). Australia can benefit from this economically, by creating incentives for innovative recycling as established in countries like the United Kingdom, Germany, and France. Moreover, the pollution levels generated, and costs associated with the transport flows of recycling plants are very high in Australia (D’Adamo et al., 2017). The solution to this issue could come from treating different waste typologies at the same recovering center. Recently, the local government in South Australia and Victoria, have created incentives for recyclers and academics to develop ways of recovering precious metals from solar panels.

There is a market for the recovered products especially the glass and aluminum but not the entire PV panels in Australia. The unavailability of market for materials may have a serious impact on the industries supply chain (Farrell et al., 2020). Recyclers in Australia are developing consumers interest in the recycled materials.

4.8 Proposed framework of PV waste management practices

According to Farrell et al. (2020), to promote resource efficiency, a framework is needed to provide proper signals to stakeholders associated with the management of solar PV waste. The current management practices within the Australian PV waste industry have been conceptualized in figure 3. It demonstrates the currently installed solar panels in Australia, which may end up in landfills, exported or recycled. The monitoring and movement of the three generations of PV waste is also highlighted. Currently, there is no tracking of PV waste within and across State boarders. With no policy in Australia, the diagram establishes the current industry and consumer practice at the EoL stages. The recycling and infrastructure needs are also identified, showing the current practice in Australia. This framework serves as an elaborate picture of the current solar PV waste situation in Australia.

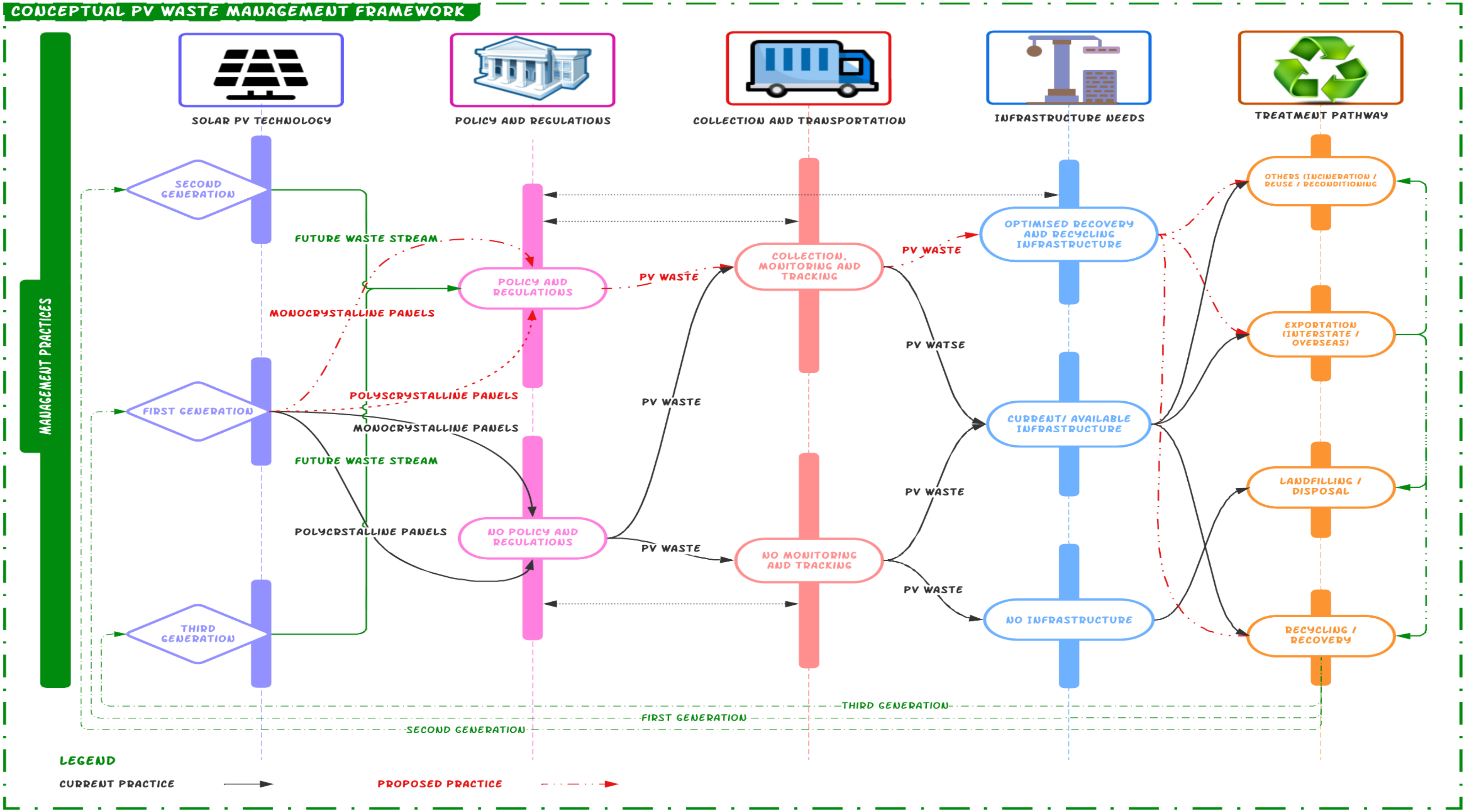

Fig. 3. Conceptual framework of solar PV waste management practices

Among the three generations of solar PV technology, the first generation specifically the mono and polycrystalline modules are the technologies currently installed and flooding the PV waste stream in Australia. In the coming years, whiles planning for the first generations, government and stakeholders should be aware of the growth of the other technologies and appropriate measures taken to effectively manage their end of life. There is currently a ban of PV waste from going to landfills, however, no policy to regulate the movement and management of this stream. This means that, the PV waste stream is not monitored and tracked in Australia. There are companies such as Reclaim PV, PV industries and Lotus energy collecting and finding ways to treat end-of-life solar PV. Some States are also providing incentives to the recyclers and academics to develop innovative recycling technologies. Currently, most of them are still being dumped in landfills in several States. Some of them are sent to different countries for either treatment, reuse or dumped in landfills as shown in the treatment pathway in the framework. Unless a legislation or policy is confirmed or established, the first-generation panels are expected not to be regulated and monitored, thus, leaving industry to lead the recovery and recycling process, with few going to landfills. The ones that go through the currently available infrastructure may end up being exported, reused, or recycled. Proper monitoring and tracking should be available for all PV technologies to make it easier to track at the end-of-life stage. An optimized recycling and recovery infrastructure should be available in the state to cater for this waste stream as illustrated in the framework.

For the second and third generation (top-left and bottom-left of Figure 3), the future PV waste stream generated may use existing waste management policy and regulations. Because the new technologies are now being installed and may take some years until they reach their end of life, their movement and monitoring may be established by then, since the Australian government has listed PV waste in section 108A of the Product Stewardship Act 2011. A committee has been set to develop a regulation on solar PV waste and this is expected in the year 2023. This will guide the panels as they reach the EoL stage, however, they may be updated to suit the new technologies as their composition vary and specific directions will eb needed for each.

5 Conclusion and policy implications

The implementation of PV waste management options is of concern to international bodies, policymakers, and communities. This is not only related to life cycle environmental impacts, but also to the preparation of a long-term plan and its successful implementation. The analysis of experts' interviews revealed that, crystalline silicon panels were the most common panels on the Australian market and the ones that were being installed frequently. New emerging panels with better capacities and innovative designs are also being developed and commercialized.

On policies, even thou the government has banned PV waste from going to landfill, currently, there is no policy or regulation to manage them. A product stewardship that will govern the management of solar PV waste is forthcoming, but this is still in the process and is expected to be ready for consideration by 2023. The long process of legislation approval and implementation will create a void in PV waste management in Australia at least for another few years and may leave a significant amount of solar PV waste behind before the forthcoming product stewardship legislation becomes operational. The absence of policies and regulations validates the unregulated movement and tracking of solar PV waste in and out of Australia as well as within the states.

A limited number of individual companies such as Reclaim PV (South Australia), PV Industries (New South Wales) and Lotus Energy (Victoria), have started the collection and treatment of solar PV waste with some state governments providing incentives to recyclers and researchers to develop innovative recycling approaches. However, the extent of the recovery and recycling is under investigation. Infrastructure and logistics predicament are among the key findings. The most stressed problem is the geographical spread of the country and its effect on the logistics of transporting and navigating the supply chain when it comes to cost and resources.

The established conceptual framework of the current treatment of solar PV waste in Australia, provides researchers and industry with the practical situation on the ground and define an appropriate system boundary for life cycle assessment and policy research. This can serve as a guide for industry to fully understand the current situation on solar PV management to appropriately establish recovery and recycling needs. Future research should be conducted on the life cycle assessment of PV waste management based on the conceptual framework. Again, because consumers are not in the scope of this study, consumers' willingness to accept regulations and associated collection fees should be investigated.

Chapter 5. Results: Part 2

5.1 Introduction

The collection and transportation involved in solar PV waste treatment has a significant impact on environmental sustainability. However, designing a holistic reverse logistic (RL) network will play an essential role in the reduction of the associated cost and environmental impacts. This chapter forecasts the PV waste in South Australia in the next 30 years. The chapter further estimates the pollutant emission associated with the collection and transportation of the waste for recycling and recovery using hotspot analysis, location allocation modelling and vehicle routing problem. The results reveal a 34.77% reduction in pollutant emission from the optimised transfer stations and the additional recycling facility. The chapter recommends policy support and regulations from government to effectively manage solar PV waste treatment and logistics.

5.2 List of manuscripts

This part of the research has been produced as a journal article, published in *Journal of Environmental Management*:

Oteng, D., Zuo, J., & Sharifi, E. (2022) "Environmental emissions influencing solar photovoltaic waste management in Australia: An optimised system network of waste collection facilities". *Journal of Environmental Management*, 314, 115007. DOI: https://doi.org/10.1016/j.jenvman.2022.115007.

The paper is presented here in a reformatted version for consistency of the thesis presentation. The accepted manuscript can be found in Appendix C.

Statement of Authorship

Title of Paper	Environmental emissions influencing solar photovoltaic waste management in Australia: An optimised system network of waste collection facilities
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Oteng, D., Zuo, J., & Sharifi, E. (2022) "Environmental emissions influencing solar photovoltaic waste management in Australia: An optimised system network of waste collection facilities". *Journal of Environmental management*, *314*, 115007. https://doi.org/10.1016/j.jenvman.2022.115007

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Contribution to the Paper	Conceptualization, Methodology, Data curation; Writing - original draft; Formal analysis		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	02/11/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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5.3 Environmental emissions influencing solar photovoltaic waste management in Australia: An optimised system network of waste collection facilities

Abstract

The Australian urban construction electricity sector has witnessed a transformational effect in the use of small-scale solar photovoltaic (PV) systems in the past decade. Currently, Australia is among the highest rate of rooftop solar PV users with over 20% of households connected. This will see a rapid growth in the volume of PV waste in the coming years when these PV systems come to their end-of-life or require replacement. The collection and transportation involved in solar PV waste treatment has a significant impact on the environmental sustainability while designing a holistic reverse logistic (RL) network will play an essential role in the reduction of the associated cost and environmental impacts. The Weibull distribution model is employed in this study to forecast the PV waste in the next 30years in South Australia. The study further estimates the pollutant emission associated with the collection and transportation of the waste for recycling and recovery using hotspot analysis, location allocation modelling and vehicle routing problem. Generation of pollutants Particulate Matter (PM), Carbon Monoxide (CO), Carbon dioxide (CO_2) and Nitrogen Oxides (NOx) associated with transport and energy consumption are estimated through three routing scenarios. Results indicate that, there would be 109,007 tons of PV waste generated in urban and suburban context in South Australia by 2050. Among the three routing scenarios generated, the third scenario with optimised transfer stations and an additional recycling facility showed a 34.77% reduction in pollutant emission. Such additional PV waste management facilities requires policy support and regulations to effectively manage solar PV waste treatment and logistics.

1 Introduction

Solar energy is renewable, non-polluting and efficient. The prospect of using Photovoltaic (PV) technology to meet the future energy needs of the world has seen a massive increase in the utilisation of solar PV power. Electricity generated by solar PV will become the primary source of global energy within the current century (Fatemeh et al., 2019; Xu et al., 2018). Therefore, the potential to produce clean energy globally, has created a large market for solar PV panels (Chowdhury et al., 2020). There is a rapid growth in the use of rooftop solar because it reduces the electricity bills for users, households also generate revenue through feed-in tariffs and self-generated electricity from the solar panels. The financial stress related to energy is substantially reduced as Australian households with solar PV saves an average of A$538 on electricity bills annually compared to households without solar PV systems (Best et al., 2021). There is also government initiative such as price subsidies which has seen the cost of solar panels fall considerably. The uptake of rooftop solar reduces emissions such as carbon dioxide (CO_2) from the electricity sector (Best et al., 2019) and is encouraged by a lot of countries to aid in achieving the greenhouse gas emission (GHG) reduction goals. The Australian electricity city sector has seen a transformational effect in the use of small-scale solar PV systems. Australia is among the highest rate of rooftop solar PV users with over 20% of households using solar PV as of December 2018 and greater than 3GW of new rooftop solar capacity added in 2020, setting a new installation record (IEA, 2016; CEC, 2021). South Australia and Queensland are the states with the highest solar PV percentage for residential dwellings with an installation average of 37%, with PV systems and localities having rooftop solar densities of over 50% (Egan et al., 2020).

There are two different types of PV capacity, i.e. the distributed (residential) and utility scale PV systems. When it comes to waste collection, both types have their own unique challenges. Distributed solar panels are located on rooftops or owner-occupied lands. They are customer-sited panels (Goe and Gaustad, 2016a) and maintains the largest share of capacity in Australia (APVI, 2021). The utility scale are large installations that occupies a lot of land area with capacity greater than 100kW. There are a number of challenges that come with handling the waste of distributed and utility scale PV. Third party contractors mostly purchase from different types of manufactures when installing distributed scale solar panels. Therefore, issues like decreased efficiency, weathering, breaking that causes the panels to reach its end of life creates a huge problem for owners as they do not know what to do with these panels (Oteng et al., 2021; Goe and Gaustad, 2016a). Thus, to prevent negative impacts of leaching to humans and the environment, recycling is often recommended (Choi and Fthenakis, 2010).

1.1 Research gap and objectives

First Solar a solar panel manufacturer collects its end-of-life (EoL) utility scale panels for recycling, however, this option is not available for distributed scale panels. This option is normally referred to as the producer take-back system. Goe and Gaustad (2016a) posits that, the incentive for the collection and recycling of end-of-life solar is very low with the panels eventually ending up in municipal waste streams if there are no legislative interventions. There is need to aim towards recycling and treating these wastes from PV modules which is becoming a global problem. The treatment involves the systematic and holistic management of these discarded PV modules which are inevitable. There is a global push to develop recycling infrastructure and guidelines in the management of PV waste and this requires an integrated framework, nevertheless, the focus has been regionalised (Mahmoudi et al., 2021). Several countries like the UK and EU have legislations that require solar PV panels to be recycled at their end-of-life and others like Australia and Japan continues to work towards related legislations (Majewski et al., 2021). The role of policymakers on how to involve investors in the treatment of end-of-life PV heavily relies on the research and development programs, financial incentives and the enactment of suitable regulation and legislations to create an economically profitable climate for PV waste management. However, the valuable material contents, proximity of suitable recycling facilities to PV waste stream, and the geographic concentration of end-of-life panels are major considerations when it comes to the economic feasibility of treating solar PV waste (Mahmoudi et al., 2021). Currently, there have been efforts to recycle solar PV waste with some companies setting up recycling facilities in Australia. This includes creating a reverse logistic network and collection system for distributed PV panels for the recycling and recovery of end-of-life solar panels in Australia.

The reduction of risks in the investment of treatment programs for EoL solar PV is very critical as it creates an avenue for investors and policy makers. Enaction of policies and legislations heavily rely on how reliable and accurate the future prediction of the total amount, value of reclaimable material and the material composition of waste from solar PV panels. This also has a huge impact on the economic feasibility of treatment processes. The clearer the results the higher the profitability as well as a proper assessment of the environmental burdens that comes with it, which serves as a great incentive for investors and policy makers to take a better step in the successful treatment of waste from solar PV modules (Peeters et al., 2017). The introduction of various incentives from the government and the increase of public awareness on the environment has seen a rapid increase in the installation of residential rooftop PV in Australia. However, the environmental and economic performance of solar PV waste is yet to be thoroughly examined in the Australian condition (Oteng et al., 2021; Nicholls et al., 2015) especially from the pollutant emission aspects related to transportation.

The collection and transportation involved in solar PV waste treatment has a significant impact on the environment and sustainability. Reverse logistics (RL) according to Stock (1992), is *"... the term often used for the role of logistics in re-cycling, waste disposal and management of hazardous materials; a broader perspective includes all issues relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal*". The design of a holistic reverse logistic (RL) network will effectively aid in the collection and transportation of PV waste to reduce the costs and environmental impacts in the treatment of EoL PV waste both globally and regionally. However, there is a lack of active research and development on EoL PV waste generation and distribution in the Organisation for Economic Co-operation and Development (OECD) member countries when it comes to a holistic RL network (Mahmoudi et al., 2021). The collection and transport of waste should be critically designed to reduce pollutants and emissions into the air. The consumption of a litre of fuel produces 2.5g of CO_2, 30g of NOx, 20g of VOC, 100g of CO, and other poisonous, harmful substances like compounds of heavy particles, sulfur and lead (Ilić et al., 2014). Thus, environmental impacts of road transport from EoL PV waste should be comprehensively understood to prevent the increase of GHG emissions. Goe and Gaustad (2016) posits that, the environmental trade-off between recovery energy use and transport distance of PV waste, as well as the impacts from its geographic dispersion has not been explicitly investigated.

In Australia, Islam et al. (2020) estimated the optimised capacity and location of recycling facilities and collection points in New South Wales between 2001 and 2017 through a spatial distribution of generated solar PV waste. This was explored across various councils using the historical PV deployment of the state. They also revealed that, forecasting the waste generation using the Weibull distribution model would have been useful. Again, in locating the recycling facilities, reference should be made to councils that generate a lot of PV waste. This study is the first of its kind in solar PV waste management research that addresses the distance and pollutant emissions associated with the collection and transportation of end-of-life solar PV. This research goes *further* to estimate the waste volume using the Weibull distribution-based model, in addition estimating the distance and emission of solar PV waste management at its end of life making reference to postcodes that generate a lot of PV waste. Thus, the main objectives of this study are to: a) forecast the generation of solar PV waste volume within South

Australia (SA) in each postcode using the Weibull distribution-based model; b) analyse patterns under early and regular loss waste scenarios to create the spatial distribution of solar PV waste volume; c) optimise a system for the collection and transport network of solar PV waste to recycling and recovery facilities within the highest waste generated postcodes; and d) determine the influence of vehicle routes on pollutant emissions on the generated network.

2 Materials and methods

This section defines the study area and its contribution to the energy market and explains the spatial characteristics of solar PV waste generation across SA using the Weibull distribution-based model. The optimisation of the routing distances of recycling and landfill facilities across South Australia is also elucidated, how the Geographic Information System (GIS) was used in achieving the aforementioned and its associated environmental impacts are clarified.

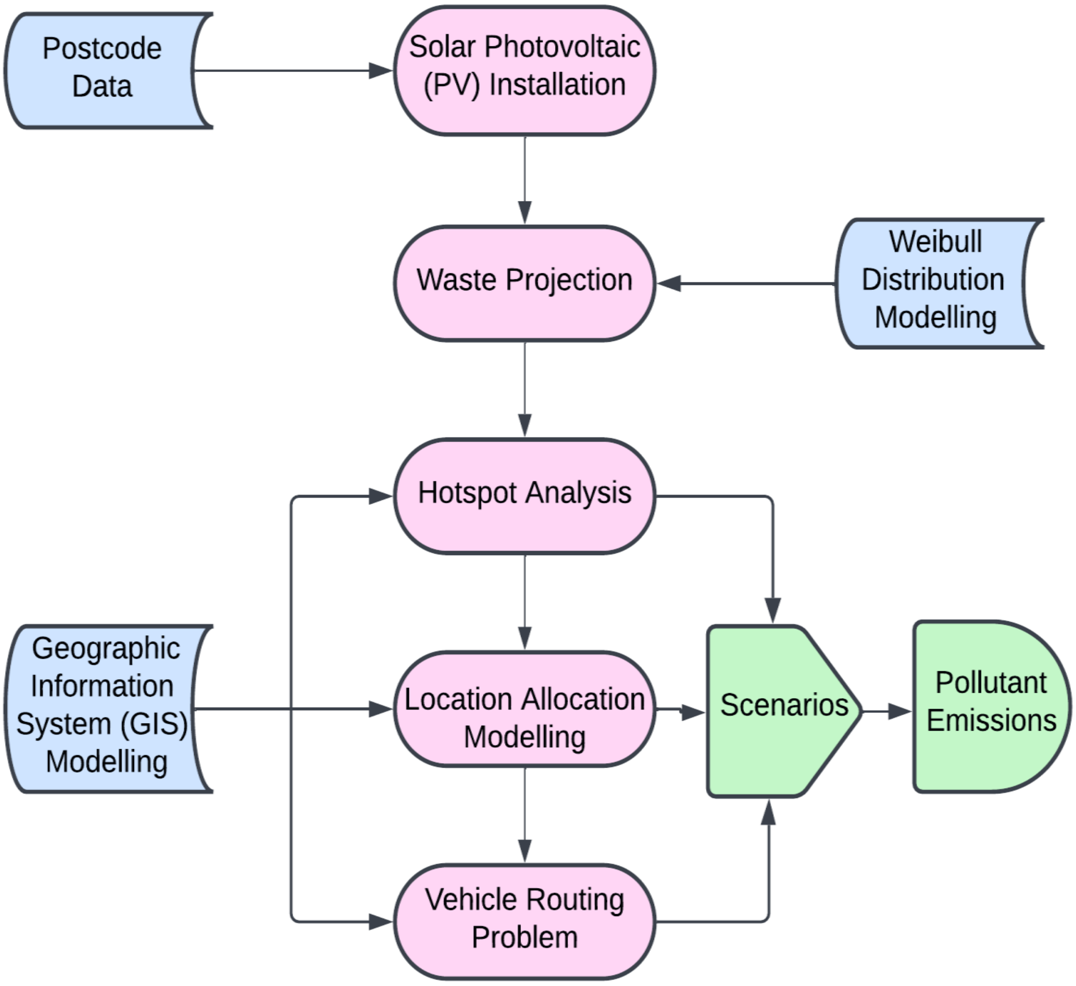

Fig. 1. Flow chart of the study process

2.1 Study area

South Australia has a population around 1.77 million and covers a total land area of 983,482 km^2 making the fifth-largest by population and fourth-largest by area among the Australian states and territories. Rooftop solar panels constitutes 20% of Australian households' energy, making it the world's highest uptake of residential solar panels (Zander et al., 2019). In September 2020, there was a low demand for grid-based power across three states as records were sent tumbling because of the solar power boom in Australia. In particular, South Australia (SA) achieved a key milestone with the state becoming the first state in Australia and anywhere in the world to be powered entirely by solar power for over an hour in October 2020 (CEC, 2021).

2.2 Waste projection scenarios and spatial statistical analysis

Geographic Information System provides an effective tool in analysing the spatial representation of data of different types in geographical visualised platform. It aids in the collection, output and distribution, analysis, storage and maintenance of spatial information and data (Chari et al., 2016). The dataset used for the estimation is obtained from Clean Energy Council. The data contains solar PV installations of capacity less than 100kW from the year 2001 to 2021. In this study, this data was then compared and verified with data from Australian Photovoltaic Institute (APVI) data on similar installations in South Australia. The waste scenarios early and regular loss are forecasted using the acquired data.

2.2.1 Waste forecasting via Weibull distribution modelling

The current postcode installation data was collected from the Clean Energy Regulator (2021) resources on postcode data for small-scale installations as of June 2021. The dataset is current as of 31st April, 2021 from the year 2001. The waste is calculated into early and regular loss scenarios (as shown in the supplementary information). The solar PV waste is calculated using the formulae;

$$F(t) = 1 - e^{-\left(\frac{t}{\tau}\right)^{\beta}} \tag{1}$$

Where, the Weibull function is F(t), the life in years of the panels is t, the scale parameter which is the average lifetime of the panels is equal to τ. The shape factor, which is β, is responsible for the Weibull curve. All the years were calculated separately and then merged into one worksheet.

2.2.2 Hotspot mapping technique

Hotspot analysis measure the statistical significance of p-values and z-values derived from the identification of spatial clustering of low (cold spot) and high (hot spot) values (Chen et al., 2018). This spatial statistical method is used in different disciplines describing how high a value or region is relative to their surroundings. Spatial analysis provides valuable insights through the analysis of connections, locations and attributes in spatial data (Amiri et al., 2021). This research focuses on the mapping cluster method using the Getis-Ord (Gi*) hotspot analysis.

Getis and Ord (1995) was the first study to introduce the autocorrelation method which is the Getis-Ord (Gi*) spatial statistics. Their methods are able to discriminate between cold spots and hot spots as compared to other previous methods. The G* is able to tell the difference between concentrated low and high value locations within local observations as well as identify spatial clustering (Songchitruksa and Zeng, 2010). Thus, the features surrounding a high value feature should also have high values to be considered as a high spot. The general form for Getis–Ord (G_i^*) is:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j}\, x_j - \bar{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{2}$$

Where x_j is the attribute value for feature j,$w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{3}$$

$$\mathrm{S} = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \tag{4}$$

The G_i^* statistics is a z-score so no further calculations are required. Low-value spatial clustering is represented by a negative z-score indicating a small p-value and a low z-score, however, high value spatial clustering is represented by a positive z-score indicating a small p-value and a high z-score (Chen et al., 2018; Prasannakumar et al., 2011).

2.3 Network Analysis and Route Optimisation

In GIS, a network is a system with elements that are interconnected. Connections of streets to one another or to intersections, cities that are connected by roads, and points that are connected by a series of lines can all be visualised using a network. A network dataset (NDS) can be generated for analysis using the extension, Network Analyst (NA), in ArcGIS ArcMap. The networks that are created from the feature source in NA are stored in the NDS. Network attributes within the features like the one-way street locations, speed limits, street restrictions for specific vehicles, road length for fuel consumption and travel time are used to model and measure impedances (Tavares et al., 2009). Network analysis is commonly used to minimise distance (shortest route) or minimise travel time (fastest route) when ascertaining the optimal route or path of an element.

Solid waste collection can be optimised using the network analysis. The software ArcGIS can be used to design and optimise route using real-time road conditions. Several researchers have used the software in the application of minimising distance or travel time in solid waste collection (Islam et al., 2021; Zsigraiova et al., 2013; Travers et al. 2009). This study determines the Minimize Weighted Impedance (P-Median) within the Location-allocation modelling and Vehicle Routing Problem (VRP) using ArcMap version 10.8.1. The distance and travel times from the GIS modelling and analysis are used to calculate the associated emissions of transporting solar PV waste within and around South Australia.

The data used for the network analysis were retrieved from the Australian and SA government data directory. Data such as the shapefile for roads, waste management facilities, administrative regions, and information on speed limits and heavy-duty vehicles were obtained from the Department for Infrastructure and Transport (DTI). In SA, speed limits for unsealed roads are permitted up to 80 km/h. Roads that are not traffic routes have 50 km/h as speed limits and a default of 100 km/h speed limit as the maximum speed legally permitted to travel outside built up areas. The network dataset sets a mean of 60 km/h as heavy vehicles are limited even on some highways in SA.

2.3.1 Location-allocation modelling

Location-allocation modelling is used to determine the shortest route generated by an origin-destination matrix through the application of Dijkstra algorithm between a waste source and specified number of facilities or nodes (Yalcinkaya, 2020). The p-median approach is used in this study as it minimises the overall weighted distance, with facilities serving their nearest demand vertex (Revelle and Swain, 1970). Thus, the transportation distance and capacity of the facilities are determined through the allocation of the solar PV waste sources to the transfer stations. The p-median problem is formulated as follows:

$$\text{minimize,} \qquad \mathrm{Z} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_i x_{ij} a_{ij} \tag{5}$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} = 1, \qquad \forall\, i = 0,1,2,\dots,m, \tag{6}$$

$$a_{ij} \le y_j \quad \forall\, i = 0,1,2,\dots,m \; and \; j = 0,1,2,\dots,n, \tag{7}$$

$$\sum_{j=1}^{n} y_j = k, \tag{8}$$

$$a_{ij}, y_j \;\in \{0,1\} \quad \forall\, i = 0,1,2,\dots,m \; and \; j = 0,1,2,\dots,n, \tag{9}$$

Decision variables:

$$a_{ij} = \begin{cases} 1, & if\ waste\ source\ i\ is\ sent\ to\ a\ station\ located\ in\ j \\ 0, & otherwise \end{cases}$$

$$y_j = \begin{cases} 1, & if\ a\ station\ opened\ in\ j \\ 0, & otherwise \end{cases}$$

Where, waste sources (solar PV waste) total is m; the total number of transfer stations is n; the chosen transfer stations in the model is k (k < n); index of potential transfer stations is j; index of waste sources is I; the shortest distance between potential stations and waste sources is represented by x_{ij}; the weight of the demand waste source at point i (known as the waste amount) is represented by d_i. The number of stations (k = 1, 2, 3, 4, …, n) as they increase are solved in this model. The objective function Z, as shown in equation (5) aims to minimise the overall distance between the waste sources and transfer stations. In assigning waste sources to transfer stations, equation (6) requires the assignment of one waste source to one station. If a station is not open, equation (7) does not assign any waste source. The restriction of several stations that is opened to k is achieved using equation (8).

A weight of 1 to 4 were allocated to the transfer stations, with 1 allocated to values that are not significant, and within the cold spot of 90% to 99% confidence. 2, 3 and 4 were allocated to hot spot with confidence level of 90%, 95% and 99% respectively. This was to make sure transfer stations within the hot spot zones were given the highest priority before the ones in the cold spots. For the demand points or waste sources, the weight used was the amount of waste generated at the location. A search tolerance of 50000 meters were set for the loading of the transfer stations and solar PV waste sources because of the large land mass in Australia.

2.3.2 Vehicle routing problem

Vehicle routing problem (VRP) solves the problem with parameters like type of output, network restrictions, network impedance and costs creating multiple routes to delivery facilities from one or more demand locations (Bozkaya et al., 2010). Dijkstra's (1959) work on his algorithm for shortest path has created an in-depth research phenomenon in road freight transportation through vehicle routing. Route optimisation which originates from the domain of graph theory and operations research continues to be used in the logistics domain where it has been adapted and extended with one being the VRP. A fleet of vehicles with a set of restrictions and different optimisation criterion can be optimised using the VRP (Schröder & Cabral, 2019). The VRP is determined using the extension within ArcMap 10.8.1 using the NA which has a built-in tabu search algorithm (Chari et al., 2016).

2.4 Pollutant Emissions

Waste collection and transportation influences the pollutants emitted through the operation conditions and travel distance of the vehicle in use. Pollutants such as PM, CO, CO_2 and NO_x are associated with heavy duty diesel vehicles which are commonly used for the collection and transportation of waste (Zsigraiova et al., 2013). This study uses the EURO IV diesel heavy duty vehicles for the calculation of the selected pollutants and referring to Hickman et al. (1999) methodology for calculating transport emissions and energy consumption (MEET). The corresponding emissions are calculated based on the determined optimum route in section 2.4.2. The equation used to determine the emissions are shown below:

$$E_i = \sum_{Vehicle\ route} (E_{i,hot} + E_{i,cold}) \tag{10}$$

$$E_{i,hot} = \varepsilon_{i,c} d_{tr} \tag{11}$$

$$\varepsilon_{i,c} = \left(k_1 + av + bv^2 + cv^2 + \frac{d}{v} + \frac{e}{v^2} + \frac{f}{v^3}\right) \tag{12}$$
$$\times \left[\left(k_2 + rv + sv^2 + tv^3 + \frac{u}{v} - 1\right) z + 1\right]$$

$$E_{i,cold} = \varepsilon_{i,cold} N \tag{13}$$

The total pollutant emission i (g) is represented by E_i, $E_{i,hot}$ and $E_{i,cold}$ highlighting the total pollutant emissions, hot pollutant emissions and cold pollutant emissions respectively. The hot emission factor for pollutant i corrected for load (g/km) is represented by $\varepsilon_{i,c}$ and travel distance (km) is represented by d_{tr}. The mean velocity (km/h) is represented by v, whiles the coefficients k_1, a, b, c, d, e, f and k_2, r, s, t, u depends on the total weight of the selected vehicle. The fraction of the load transported is represented by z. The number of cold starts and cold emission factor for pollutant i (g/cold start) is represented by N and $\varepsilon_{i,cold}$ respectively. The values to the various coefficient are shown in the supplementary material, table A5.

3 Results and findings

The results of the analysed data are explained in this section. The location-allocation and vehicle routing modelling of the projected PV waste (results provided in *appendix C*) is described in this section. This therefore provides a basis for the location-allocation modelling for transfer stations and route optimisation analysis of different waste scenarios. This helps to achieve a more sustainable approach in terms of pollutant emission reduction when handling the transportation and logistics of solar PV waste in Australia. The explanation to the above is further explained in this section.

3.1. Location allocation modelling of PV waste to transfer stations

Location allocation modelling is used in multi-facility location problem to optimise and solve reverse logistic network problems in mane situations. To minimise the total waste collection and recycling distance in the state. The location allocation modelling was adopted to locate the collection centres with the aim of reducing and optimising travel distance in the transportation of future PV waste. The data on the location of transfer stations were collected from the national database retrieved from data.gov.au. The national waste management database consists of 108 transfer stations located in South Australia. This number was used as the baseline and centres for the collection of PV waste. The waste sources from the regular loss scenario is used for all analysis as it provides a standard waste loss scenario for solar PV panels. A network dataset was then built using the data provided and a projected coordinate South Australia Lambert was used for the modelling. Transfer stations within Australia are facilities that temporarily holds different types of waste from collection vehicles and are them reloaded to transport vehicles to disposal or treatment sites across the state or country. The PV waste sources as shown in figure 2, are the collection centres or waste sources from solar PV.

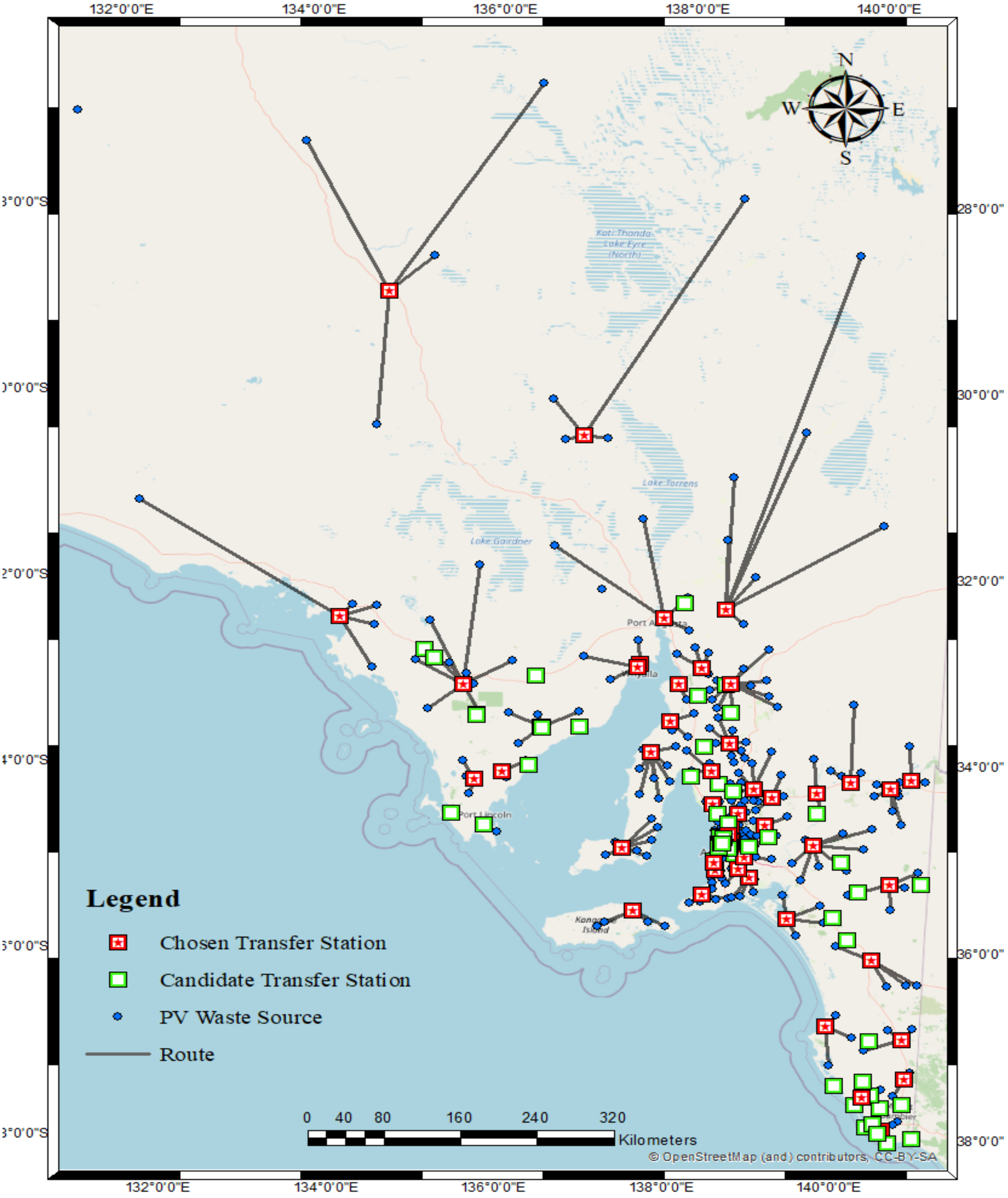

Fig. 2: location-allocation modelling of waste sources to transfer stations

The equations (5) to (9) were applied were applied in locating these facilities. The data was analysed using ArcGIS location allocation layer with emphasis on minimizing impedance which corresponds to the p-median problem. With 108 candidate or potential facility locations identified, 54 were selected and optimised for the collection of PV waste as it proved economical and logistically efficient. The criteria for selection was based on the proximity of the transfer stations to each other and waste demand of each transfer station. Table A4 in the supplementary information provide a detail waste demand coverage and distance covered on the selected transfer stations. The selected transfer stations were then use to model the vehicle routing problem and create other scenarios to create an optimised reverse logistic network for solar PV waste collection and recycling.

3.2. Vehicle optimisation and routing scenario analysis

The network dataset used for the location allocation modelling was used for the routing analysis. Some few assumptions were considered in the mapping of the routes. The shapefile of the road network data was retrieved from the South Australian government database provided by the department for infrastructure and transport. An average speed limit for all roads were set to 60km/h since heavy duty trucks are limited to that speed limit on most highways and freeways. A time window was set at 8:00am to 5:00pm for all transfer stations with a service time of 30minutes. A break of 1 hour was also set in between the time windows. One inaccessible transfer station (Kangaroo Island resource and recovery centre) was removed from the analysis because of its location. One recycling centre was set for the analysis because of the presence of one recycler in South Australia. Lonsdale was chosen at the current site of the recycling facility for modelling.

The original distribution of 108 transfer stations was set as the base scenario with the omission one transfer station. Two other network scenarios were created to aid in achieving an optimal and efficient reverse logistic network for PV waste collection and recycling to minimise pollutant emissions associated with the collection and transport of PV waste. Two heavy duty trucks with a gross weight in the range of 7.5 – 16 and 16 – 32 tonnes were selected to be used in the collection of the waste from the transfer stations to the recycling centre.

The first scenario and baseline (Figure B1 in Supplementary Information) looked at the distribution of the waste source to all the available transfer stations in the state. The results revealed that truck 1 covered a total distance of 3074.92 km and 51.25 hours within a week. The second truck covered a distance of 2727.53 km in 45.46 hours within the week. Even though, truck 2 covered 54 orders compared to 53 for truck 1, the distance covered was less. This shows the long distances between transfer stations in the South Australia outbacks compared to the cities and urban areas. The total distance covered by the two trucks is 5802.45 km.

The second scenario used the optimised transfer stations from the location allocation modelling for the route analysis as shown in Figure B2 (in Supplementary Information). The distance covered by truck 1 is 2536.05 km in 42.27 hours with truck 2 covering 2536.92 km within 42.28 hours. Truck 1 and 2 covered 26 and 27 transfer stations respectively. A total of 5072.97 km was covered for all the 53 transfer stations within the week.

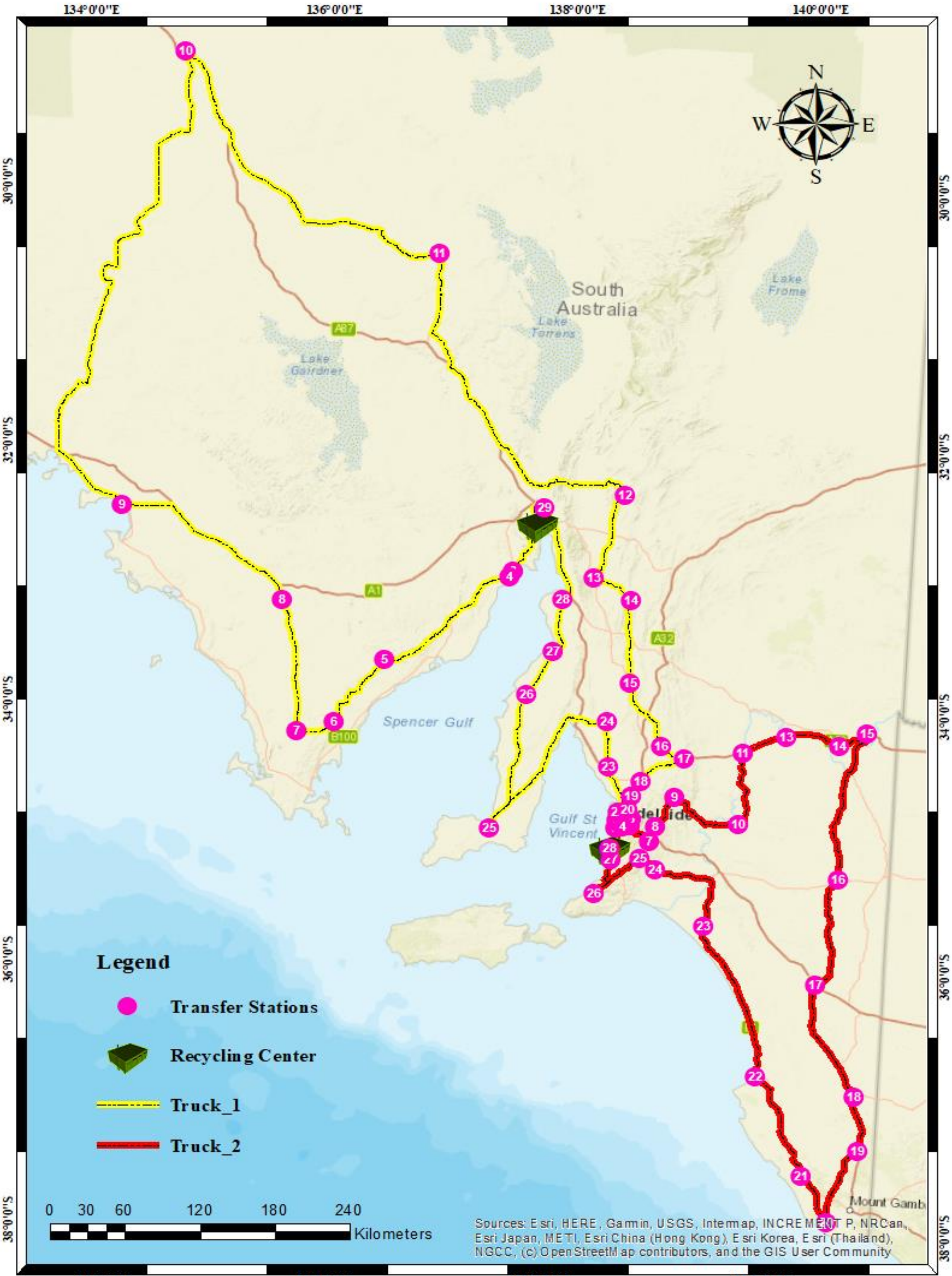

Fig. 3: Route analysis of optimised transfer stations to two recycling centres

The third and last scenario shown in figure 3, considered introducing an additional transfer station at one of the hotspots and closer to most of the outback. An additional recycling facility was introduced at Port Augusta to cater for the transfer stations around that area. However, the optimised transfer stations were still used for the analysis. The analysis revealed that, truck 1 and 2 covered 2691.38 km and 1396.13 km with hours of 44.86 and 23.27 respectively. Truck one covered a lot of distance because of the wide distances between transfer stations especially stations 9, 10 and 11.

Table 1: Comparison of distance and percentage reduction between scenarios

	Travel distance (Km)	*Distance reduced (Km)*	*Percent reduction (%)*	*Total travel time (Hrs)*	*Time reduced (Hrs)*	*Percent reduction (%)*
			Scenario One (Baseline)			
Truck 1	3074.92			51.25		
Truck 2	2727.53			45.46		
Total	***5802.45***			***96.71***		
			Scenario Two			
Truck 1	2536.05	538.87	17.5	42.27	8.98	17.5
Truck 2	2536.92	190.61	7.0	42.28	3.18	7.0
Total	***5072.97***	***729.48***	***12.6***	***84.55***	***12.16***	***12.6***
			Scenario Three			
Truck 1	2691.38	383.54	12.5	44.86	6.39	12.5
Truck 2	1396.13	1331.40	48.8	23.27	22.19	48.8
Total	***4087.51***	***1714.94***	***29.6***	***68.13***	***28.58***	***29.6***

The comparison between the scenarios clearly highlights the differences in travel distance and coverage hours of the two trucks. It also provides a measurement of the current situation and how it can be improved. The two scenarios 2 and 3 recorded a 12.6 and 29.6 percent reduction of the total distance and time covered by the two trucks. A significant decrease in travel distance and time seen in scenario 3 puts emphasis on the major effect of establishing more recycling facilities in the state.

3.3 Pollutant Emission based on route optimisation

The effect of the travel distance on the pollution emitted was calculated using the methodology by Hickman et al. (1999). Using the equation (10) to (13), the pollutant emissions for Particulate matter (PM), Nitrogen oxides (NO_x), Carbon dioxide (CO_2) and Carbon monoxide (CO) is calculated. Table A5 in the supplementary information provides the coefficient values for equation (12) and (13).

Using two heavy duty trucks of weight 7.5 – 16t and 16 – 32t, three routing scenarios were modelled and analysed using ArcGIS ArcMap 10.8.1. *Scenario 1: Baseline*. The 108 transfer stations with the exemption of the one situated on kangaroo island were modelled. With one recycling centre and 107 demand points, two trucks with loading capacities of 5.2 and 6.9 were used for the collection of the solar PV waste to the recycling centres. The trucks covered a distance of 3074.92 and 2727.53 km respectively. Both trucks with respect to emissions released 5704, 78603, 7440167 and 23851 grams of PM, NO_X, CO_2 and CO respectively as recorded in table 3. This scenario served as the baseline for this study. *Scenario 2: Optimised stations*. The second scenario used the 54 optimised stations with the exemption of the station on kangaroo island because of road transport limitations. With the same number of trucks and loading capacities, the total distance covered was reduced. However, because the recycling centre was one the travel distance didn't reduce as much. Table 2 details the pollutant emissions on this scenario. *Scenario 3: Additional recycling centre*. The last scenario used the same setup from the previous scenario (2) with the addition of an extra recycling centre to aid in reducing the load on the first recycling centre. There was a massive reduction in the emissions with this scenario. The total emissions recorded were 3801, 46543, 4792486 and 15559 grams of PM, NO_X, CO_2 and CO respectively.

Table 2: Results of pollutant emissions from the three different routing scenarios

	Scenario One[1] (Baseline)			*Scenario Two[2]*			*Scenario Three[3]*		
	Truck 1	Truck 2	**Total**	Truck 1	Truck 2	**Total**	Truck 1	Truck 2	**Total**
Travelled distance (Km)	3074.92	2727.53	**5802.45**	2536.05	2536.92	**5072.97**	2691.38	1396.13	**4087.51**
Total travel time (Hrs)	51.25	45.46	**96.71**	42.27	42.28	**84.55**	44.86	23.27	**68.13**
Number of Transfer stations covered	53	54	**107**	26	27	**53**	27	26	**53**
				Pollutant Emission (g)					
PM	2,424	3,280	**5,704**	1,999	3,051	**5,050**	2,122	1,679	**3,801**
NO_x	25,622	52,981	**78,603**	21,132	49,278	**70,410**	22,426	27,117	**49,543**
CO_2	2,707,291	4,732,876	**7,440,167**	2,232,899	4,402,160	**6,635,059**	2,369,643	2,422,843	**4,792,486**
CO	9,207	14,644	**23,851**	7,595	13,621	**21,216**	8,060	7,499	**15,559**

[1] One recycling centre serving 107 transfer stations; [2] One recycling centre serving 53 transfer stations; [3] Additional recycling centre making it two recyclers to 53 transfer stations

The three scenarios highlighted the impact of optimising the reverse logistics of end-of-life solar PV panels through the collection and transportation from transfer stations to recycling facilities. Among the scenarios, the third routing scenario showed a significant decrease in the four pollutant emissions.

4 Discussion

4.1 Solar PV waste growth and recovery opportunities

The government of Australia in 2016, announced in the national waste policy that, the coming years will see an increase growth of waste from solar PV which needs to be appropriately treated. Accordingly, a local analysis of the PV waste assessment is necessary. Designing a sustainable reverse logistic network necessitates the demonstration of the percentage of waste quantities in each state in Australia (Mahmoudi et al., 2019) to highlight the problems pertaining to the state. Padoan et al. (2019) posits that, the complication that comes with the recycling of end-of-life solar PV is also accompanied by the low concentration of waste PV modules for recovery. However, the recent increase in the adoption of solar PV modules worldwide and in Australia has shifted a lot of government attention on the management of these modules when they reach their end of life. The old installed panels are coming to their end of life and most of them are being sent into the landfills as reported in the 2020 national waste report. The results of the waste projection in South Australia on both scenarios shows a significant amount of waste from PV in the year 2051.

The results of the projected waste provide data to address the assessment of environmental policy regulation and recycling strategies. Using the same equation (1), Mahmoudi et al. (2019) modelled the PV waste stream in Australia within a 30-year period with data from 2001 to 2017. The data used in this study adds the data from the year 2018 to 2021 in the estimation of the PV waste. This study also considered only installation capacity below 100k because of the huge penetration of rooftop solar panels in most of the states in Australia. However, the results also confirm the enormous amount of PV waste stream in the coming years. A strategy to recycle and recover these panels sustainably should be considered by the government as they enact policies and regulations in the coming years. Oteng et al. (2021) in their recent studies emphasised on the need to recycle end of life solar panels as they may negatively impact the environment and human health. Reclaim PV, a company in South Australia has established a recycling plant in Lonsdale which was used in this study as the location of the recycling centre. The results of this study provide relevant information on the quantity and quality of PV waste flow within South Australia in the coming years which is also significant for all parties and stakeholders within the solar PV waste management system.

4.2 Influence of reverse logistics of solar PV waste recycling on pollutant emissions

The results prove the significance of logistics in the collection and transportation of solar PV waste in the coming years and how it will affect the decision of policy makers and industry in the management of PV waste in Australia. A projection of the waste from the already installed panels provides the opportunity for policy makers and industry to better prepare and institute appropriate treatment programs in the management of these wastes. However, the valuable material content, the proximity of PV waste sources to recovery centre and the concentration of the PV waste geographically is a major contribution when it comes to the economic feasibility of the treatment program (Mahmoudi et al., 2021; Fthenakis, 2000) which also affects the amount of emissions released into the atmosphere. The scenarios put emphasis on the effect collection and transportation has on the environment and how this could be reduced.

According to Taveras et al. (2009), a substantial percentage of the budget used in managing waste (including the cost of labour) is mainly associated with the collection and transportation of solid waste. The vehicles release emissions like NO_x and CO_2 in significant amounts which contributes greatly to acid rain and the greenhouse effect. A total CO_2 emission of 1118 million tons was produced by road freight transportation in 2010, accounting for 3.5% of CO2 emission produced worldwide. If there are no major changes, an increase of 30.5% is expected in the year 2050 within the entire logistics sector worldwide. The environmental impact from road freight transportation needs to be reduced to achieve the climate change related objectives through a sustainable reduction of CO2 emissions (Schröder & Cabral, 2019). Therefore, financial and environmental benefits can be achieved if the outputs of these pollutants are reduced by creating an appropriate reverse logistic network for the recycling and recovery of solar PV waste.

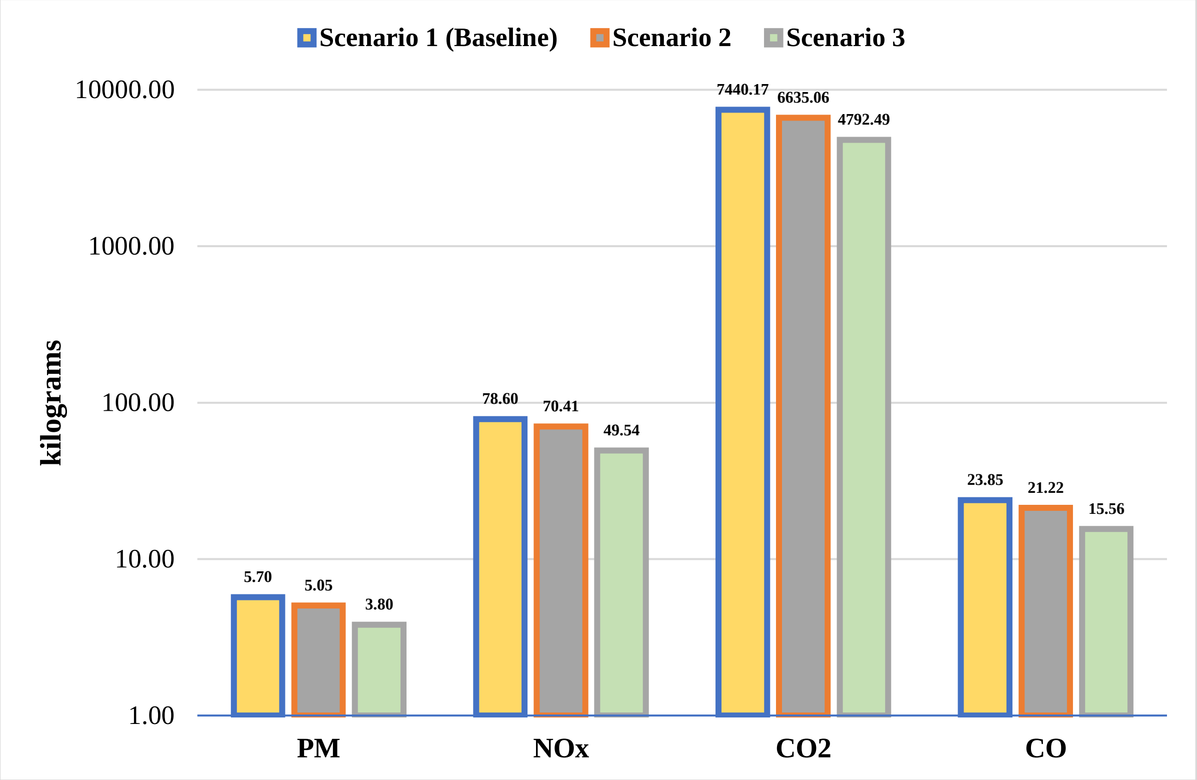

Fig. 4: Pollutant emissions of route optimisation scenarios

The geographical dispersion of PV waste sources makes the logistics in the collection and transportation of solar PV very difficult (Padoan et al., 2019). This is made much more difficult in a country like Australia where facilities like the transfer stations and recycling facilities are far apart from each other creating more coverage distance for vehicles. Therefore, a significant amount in pollutant emissions from vehicles. However, there is a substantial decrease in the pollutant emissions from PM, NO_x, CO_2 and CO when comparing the three routing scenarios from the results (figure 4).

4.3 The effect of policy and regulations on the logistics of PV waste management

According to Australia’s net zero emission targets for 2050, transport emission would have fallen by 39 MT CO_2-e (Australian Government, 2021). With regulations and targets to reduce transport emission, it is imperative that solar PV recycling reduce transport emissions which contributes a huge part of solar PV waste recycling and recovery (Oteng et al., 2021). The involvement of parties in the PV waste management sector mainly depends on proper laid down policies and incentives (D`Adamo et al., 2017). Policy and regulations that creates an avenue for various parties within an environmental and economic sense in the treatment of decommissioned PV panels cannot be ignored (Mahmoudi et al., 2019). A recent study by Jain et al. (2021) emphasied on the importance of policy and regulations in the effective management of solar PV waste. However, there are no current regulations established in the state of South Australia and Australia when it comes to the management of end-of-life solar panels. The “which bin” initiative in South Australia which promotes the proper disposal of various types of waste does not provide a bin for solar PV waste and recommends users to reach out to their local councils. The 2020 National Waste Report revealed that, most of the waste from solar PV were going into the landfill. With the recommendation to recycle these panels, it means the government has to do a lot when it comes to the management of solar PV waste by establishing policies and regulations as soon as possible. This was further established in a study by Majewski et al. (2021), calling for a robust establishment of end-of-life PV product stewardship and effective management schemes to aid in the reduction of greenhouse gas emissions. This will help reduce emissions and contribute to the net zero emission targets set for 2050 by the Australian Government.

5. Conclusions

The study provides significant information on pollutant emissions from the logistics in the collection and transportation of solar PV waste through establishing scenarios using different methodological approaches. It was revealed that, about 15 postcodes generated over 1000t of solar PV waste using the early and regular loss scenarios. The hotspot analysis confirmed the results with these areas of the postcodes having a hotspot of 99% confidence. Using the results from the hotspot analysis, 54 transfer stations were optimised using their travel distances. The optimisation of travel distance of the transfer stations saw a reduction in the pollutant emissions.

Among the three routing scenarios studied, an introduction of an additional recycling centre saw the reduction of the pollutant emission (PM, NO_x, CO_2 and CO) drastically. This research draws on a lot of implications when it comes to policy and practice. The policy aspect focuses on how government should fast-track the introduction of regulations and product stewardship to govern end of life solar PV waste in Australia. Effective product stewardship will help regulate the waste from landfills and motivate industry partners to seize the opportunity to collect and recycle end of life solar panels. Again, industry in collaboration with the government should set up recycling facilities in suitable areas with an effective reverse logistic network design that will reduce the pollutant emission of vehicles. Similarly, the use of electric vehicle/trucks can also significantly reduce the emission of transportation.

The results of this study also add to the body of knowledge on solar PV waste management, especially, on the collection and transportation emissions of the treatment of PV waste. Future research should aim at investigating a sustainable policy for the treatment of end-of-life PV modules. The pollutant emission and travel distances can serve as data for life cycle assessment of recycling and recovery of various PV technologies. The results of the hotspot analysis can be used to establish new recycling facilities for the state and to generate new recycling areas using suitability analysis.

Chapter 6. Results: Part 3

6.1 Introduction

This chapter evaluates the environmental impacts of three policy options for EoL mono and multi crystalline silicon (c-Si) solar PV modules. The impact of transport distance from transfer stations to the recycling centre is also assessed. The life cycle assessment associated with the different product stewardship scenarios reveals relevant results associated with climate change. The chapter highlights that the non-existence of a product stewardship will produce a global warming impact of 1E+05 kgCO2eq for both modules. The highest environmental impact regarding the transport distances was the scenario of one recycling centre serving over 107 transfer stations with a global warming potential of 1E+06 kgCO2eq as discussed in the chapter. The research model assessed in the chapter is the first conceptual and methodological framework for life cycle assessment (LCA) in transport related analysis. Since transport is very significant in PV recycling processes, the chapter recommends further analysis on other forms of low-impact modes of transportation.

6.2 List of manuscripts

This part of the research has been produced as a journal article, under revision in *Journal of Cleaner Production*:

Oteng, D., Zuo, J., & Sharifi, E. (In revision) “An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: An environmental lifecycle assessment”. *Journal of Cleaner Production* (JCLEPRO-D-22-23447_R1)

The paper is presented here in a reformatted version for consistency of the thesis presentation. The submitted manuscript can be found in Appendix D.

Statement of Authorship

Title of Paper	An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: An environmental lifecycle assessment
Publication Status	☐ Published ☐ Accepted for Publication ☑ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Oteng, D., Zuo, J., & Sharifi, E. (In revision) "An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: An environmental lifecycle assessment". *Journal of Cleaner Production* (*JCLEPRO-D-22-23447_R1*)

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Name of Principal Author (Candidate)	Daniel Oteng		
Contribution to the Paper	Conceptualization, Methodology, Data curation; Writing - original draft; Formal analysis		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its ir[redacted]he primary author of this paper.		
Signature		Date	03/11/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Signature		Date	03/11/2022

6.3 An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: An environmental lifecycle assessment

Abstract

The growth of solar photovoltaic (PV) waste in the coming years requires implementation of effective management options. Australia, with one of the highest rates of rooftop solar PV, is still developing policy options to manage these panels when they reach their end-of-life. This study evaluates the environmental impacts of three options for mono and multi crystalline silicon (c-Si) solar panel waste modules. The impact of transport distance from transfer stations to the recycling centre is also assessed. The life cycle assessment revealed that, -1E+06 kgCO$_2$eq and -2E+06 kgCO$_2$eq are associated with the mandatory product stewardship scenarios under global warming potential for mono and multi c-Si solar modules, respectively. However, the non-existence of a product stewardship will produce a global warming impact of 1E+05 kgCO$_2$eq for both modules. The global warming effects revealed that, collecting and recycling most of the multi c-Si panels were not effective (-365.00 kg CO$_2$-eq, -698.40 kg CO$_2$-eq, -1032.00 kg CO$_2$-eq) compared to keeping them away from the landfills and fully recycling (-2E+06 kg CO$_2$-eq) them. It was also highlighted that, the highest environmental impact regarding the transport distances was the scenario of one recycling centre serving over 107 transfer stations with a global warming potential of 1E+06 kgCO$_2$eq. This research model serves as the first conceptual and methodological framework for life cycle assessment (LCA) in policy and transport related analysis. Since transport is incredibly significant in PV recycling processes, it is recommended that, to further reduce these impacts, other forms of low-impact modes of transportation may be explored.

1 Introduction

The last decade has seen a massive production of photovoltaic systems. This is because of the depletion of fossil sites which has been highlighted as an ongoing risk associated with the increasing use of conversional energy resources (IEA-PVPS, 2021; Savvilotidou et al., 2017). Moreover, with the increasing energy demand and cost of materials for manufacturing declining, there is a tremendous growth within the renewable energy sector especially in the solar photovoltaic (PV) industry (Mahmoudi et al., 2019; Nain & Kumar, 2020b). Crystalline silicon (c-Si) and thin films are the common commercially available photovoltaic panels. The latter is cost effective and more flexible; whereas the former has the advantage of high efficiency and higher market share (Daljit Singh et al., 2021; Nain & Kumar, 2020c).

The designed lifetime of solar PV modules ranges from 25 to 30 years. Most of the crystalline silicon modules are reaching or have already reached their lifetime and may lead to a tremendous amount of waste generated in the next years (Nain & Kumar, 2020c; Sica et al., 2018). There are precious and carcinogenic metals including tellurium, selenium, copper, silver, lead, chromium, silicon, and cadmium in solar photovoltaic systems, which at the end of their operational life requires recovery and recycling to prevent environmental pollution and also to extract the valuable metals (Tao & Yu, 2015).

The growing interest in renewable energy sources has seen the rise in the installation of solar PV technology in recent years. The first-generation technology based on the crystalline silicon (c-Si) has remained the dominant technology. However, in 2012 the second-generation (cadmium telluride) was the second largest technology in the market with a production output of 1.8 GWp (Kranz et al., 2013; Ramos-Ruiz et al., 2017). The c-Si technology covers the market share with 90% among which 45% is mono, 55% is multi and ribbon Si represents 2%. The remaining 10% is represented by the thin-film technology, having cadmium telluride (CdTe) with the biggest share of 5%, amorphous-Si (a-Si) with 3% and copper indium gallium di-selenide (CIGS) representing 2% (Daljit Singh et al., 2021; Sica et al., 2018).

As much research is focused on producing new recyclable high-tech panels and improving the efficiency and performance of these panels, managing old panels has become an expensive and complex problem (Fthenakis, 2000). There are studies that are recently looking into the consequences of these disposals, with some developing methods and techniques in both policy and industrial vision to help alleviate the environmental problems (Giacchetta et al., 2013; Nain & Kumar, 2021; Oteng et al., 2022a).

According to Motta et al. (2016), there is little attention given to the evaluation of inappropriate solar PV disposal and its associated environmental risks. Especially, the toxicity of the hazardous chemicals to the environment through their release of toxic elements into water sources (Nain & Kumar, 2021). The potential risks to human health and the environment, and the impact of metal release into landfills needs to be investigated to ascertain their fate in realistic environmental setting (Nain & Kumar, 2020c).

1.1. Research background and gap

Many countries do not yet have regulations that guides the management of end-of-life (EoL) solar panels; therefore, a lot of these panels end up in landfills. Again, recycling processes are not economically feasible yet in many countries because of the number of EoL solar panels available (Lunardi et al., 2018). The lifetime of solar panels can range from 25 to 30 years, with such relatively long lifetime, the amount of solar panels in the current waste stream are considered to be low. This has had a big influence on the late or non-inclusion of EoL solar PV waste in the legislations and regulations of several countries (Granata et al., 2014). Due to the Waste Electrical and Electronic Equipment (WEEE) directive, many countries in the European Union have boasted of legislations covering the management of EoL PV modules. Yet, there are several other countries around the world like Australia, China, and Japan who are still in the process of developing a comprehensive product stewardship for solar PV waste modules.

Recycling the PV panels at their EoL is environmentally favourable against landfilling, as most of the rare and valuable metals can be recovered and upcycled. This prevents hazardous and toxic substances being dumped at landfills potentially leaching into the soil and groundwater, projecting adverse effects on the ecosystems and humans via negative physiological and biochemical effects (Deng et al., 2019; Lunardi et al., 2018; Oteng et al., 2022a). The use of a solar PV module throughout its 25 to 30 years operation could result in zero-emissions, making it a preferred choice of green power generation. However, the environmental impact of the entire lifecycle of the PV module must be stressed, because of the production emissions and EoL management challenges (Deng et al., 2019). Recently, researchers are developing cost-effective alternatives to the management of solar PV waste as the volume is increasing sharply. With landfill not an option for discarding waste PV modules because of its unsustainable practice, recycling is the preferred alternative (Corcelli et al., 2018; Deng et al., 2019; Fthenakis, 2000).

Crystalline silicon PV modules currently make up the majority of installed solar systems, both commercially and residentially (Mahmoudi, Huda, & Behnia, 2019) and needs to be effectively assessed to ascertain its environmental impacts. With a lot of pilot studies on the recycling of EoL solar PV modules (especially the c-Si modules), there has been numerous improvements to get industry and policy makers on board. However, there is still the lack of knowledge and information on the environmental impacts on the treatments of crystalline silicon PV waste panels (Lunardi et al., 2018) regionally, to serve as data for life cycle assessment to help make informed policy decisions. This study adopts a pilot recycling process tailored to a regional case study for the environmental impact assessment.

Several studies on the environmental impact on c-Si PV modules mostly assume full landfilling or recycling scenarios for EoL PV modules (Dias et al., 2021; Lunardi et al., 2018; Mahmoudi et al., 2020) without necessarily comparing them to practical product stewardship arrangements to ascertain the effects that could have on the choice of treatment option. Moreover, the transport distances in several studies assumes distances (Ansanelli et al., 2021; Ardente et al., 2019; Latunussa et al., 2016) for the environmental impact assessment which is a huge gap in LCA research which this study addresses.

In Europe, solar PV waste is included in the category of Waste Electrical and Electronic Equipment (WEEE) and requires appropriate treatment of the waste stream. However, in Australia there is no effective policy guidelines, and if appropriate preventive and corrective measures are not implemented could become a huge problem, becoming the most significant stream of e-waste (Farrell et al., 2020; Majewski et al., 2021) in the country. As a result, this study investigates the environmental impacts associated with the mono and multi crystalline silicon (c-Si) modules because of their market share in the Australian PV industry. The paper addresses the following questions: i) what are the environmental impacts of mono and multi c-Si EoL solar PV within three policy options; ii) what are the impacts of transport for recycling PV waste within three established transport scenarios.

2 Material and Methods

This section explains the various approaches in developing a system for the environmental assessment of the EoL PV modules. The case context of South Australia is described in this section. The life cycle assessment processes are also detailed. “Life Cycle Assessment (LCA) is a methodology used to evaluate the potential environmental impacts of products or services along all their entire life cycle, with a “cradle to grave” approach. LCA allows to (i) assess the environmental burdens associated with a product, process, or activity, by identifying and quantifying energy and material hotspots and (ii) identify and evaluate opportunities for environmental improvements” (Consoli, 1993)

2.1 Case of South Australia

The research is conducted in South Australia using process data from a recycling plant situated at Lonsdale. The recycling plant started operations in August 2014. However, in the initial stages the idea was to collect the EoL panels until there was a substantial amount for recycling. Since 2021, they have managed to pilot a recycling process at the early stages. Because the recycling process of the plant is still ongoing and at its early stages, data from literature and the ecoinvent database (Ecoinvent, 2022) are used to complement the data collected from the plant. Ethics approval has been granted for this research. The operating director of the plant was interviewed, and several observations were made on different days to the plant for the collection of data for this research. This is important to ensure reliability of the results, data should be collected from recyclers even though available estimates from experts and databases are often used (Ziemińska-Stolarska et al., 2021).

2.1.1 Treatment processes at the plant

The first step of the process is the collection of the EoL PV modules from transfer stations to the recycling plant. The distance of the PV waste from users to the transfer stations are estimated to be 100km for the treatment of 1 ton of PV module using a 7.5t truck (Latunussa et al., 2016; Mahmoudi et al., 2020). However, the rest of the distances calculated are used in the scenario analysis for an estimated 3000-ton treatment of PV waste annually at the recycling plant.

The second step is the treatment or recycling of the PV modules at the plant. As discussed above, the plant is situated at Lonsdale, operated by Reclaim PV in South Australia. The transfer of the EoL PV modules from the transfer stations to the recycling centres are normally assumed in several research (Ardente et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2020). This study uses an estimated distance developed previously by the authors (Oteng et al., 2022a) from the transfer stations using different scenarios, which is a first and essential contribution when it comes to transport distances in the LCA of solar PV modules.

The PV modules are then unloaded by a forklift and transported to conveyor belts for dismantling. The full process is associated with recycling 1000kg of PV waste within an hour as shown in table A1 (see supplementary material). The disassembly is automated at the plant where the aluminium frame, cables and junction box are removed using a Cartesian robot and mechanical arm. The aluminium is then sold for treatment into aluminium ingots or used as a secondary material whiles the cables are collected for treatment in another plant. The plastic parts of the cables are then treated in an incineration plant with energy recovery.

The process is to treat the remaining materials after the mechanical detachment. A glass separation process is introduced to treat the waste panels without the cables and aluminium frames. The process separates the glass layer from the rest of the cells and layers of polymer (also called ‘PV sandwich’). To retrieve the PV sandwich and glass, an infra-red heat treatment process is introduced. Then a high-frequency knife button, regulated by speed and amplitude is used to mechanically detach the glass. Subsequently, a refinement process separates the sizes of the glass through sieving. The glass with impurities of mass around 2% after an optical-based separation system are sent to landfill. The PV sandwich is incinerated at the recycling plant after reducing their sizes by a cutting process, without the need to transport the PV sandwich to another incinerating plant. The process produces fly ash which is sent to a hazardous waste landfill assumed to be located 50km from the plant. The rest of the product (bottom ash) are crushed and sieved to retrieve the rest of the aluminium, whiles the rest is transferred to an acid leaching process.

The leaching process separates the silicon from other metals. During this process, water, and nitric acid (HNO_3) is mixed with the ash, this leaves the silicon as a residue in the dissolved solution of the various metallic oxides produced. Subsequently, the mixture containing the solution goes through vacuum filtration process for the recovery of the silicon. This helps recover the silicon at metallurgical grade. An electrolysis process is then introduced to recover the copper and silver from the solution at an efficiency of around 95%. This process emits an estimated 2kg per ton of treated PV waste in NO_x gases. Calcium hydroxide is added to the acid solution after electrolysis to successfully neutralise it. A filter press is then used to filter the final output, separating it into a sludge (unrecovered metals with some residual calcium hydroxide and water) and liquid waste (calcium nitrate and water). The waste is sent for disposal, transportation assumed to be 100km away. The input and output process are discussed in the life cycle inventory section.

2.2 Environmental Life Cycle Assessment

2.2.1 Goal and scope definition

The goal of this LCA is to access the potential environmental impacts of recycling mono and multi crystalline silicon photovoltaic modules using a pilot recycling process and plant situated in South Australia. This process has been developed by adapting the Full Recovery End of Life Photovoltaic (FRELP) process piloted by the Italian company “SASIL S.p.A”. for treating EoL solar crystalline silicon PV panels.

2.2.2 Functional Unit

The functional unit (FU) of this process is the recycling of 1000kg of EoL crystalline silicon modules separated into mono and multi crystalline silicon modules as illustrated in table A1 in the supplementary material. The FU does not include other module components such as the external cables and inverters but includes the internal cables.

The inputs and output are estimated based on the market share of both technologies. Mono-Si panels are estimated to have a market share of 55% with multi-Si panels having 45% market share. The latter is constructed from isolated crystals with the former based on one large crystal (Daljit Singh et al., 2021). The quantity of waste panels for the Mono and Multi c-Si are 1,350 and 1,650 tons, respectively.

2.2.3 System Boundary

The system boundary of this LCA considers the photovoltaic technologies mono and multi-crystalline modules. This process follows a cradle to grave approach, which considers only the EoL scenario without the production and use stages. Figure 1 illustrates the system boundary from the EoL solar panels to their treatment options through the three established policy options.

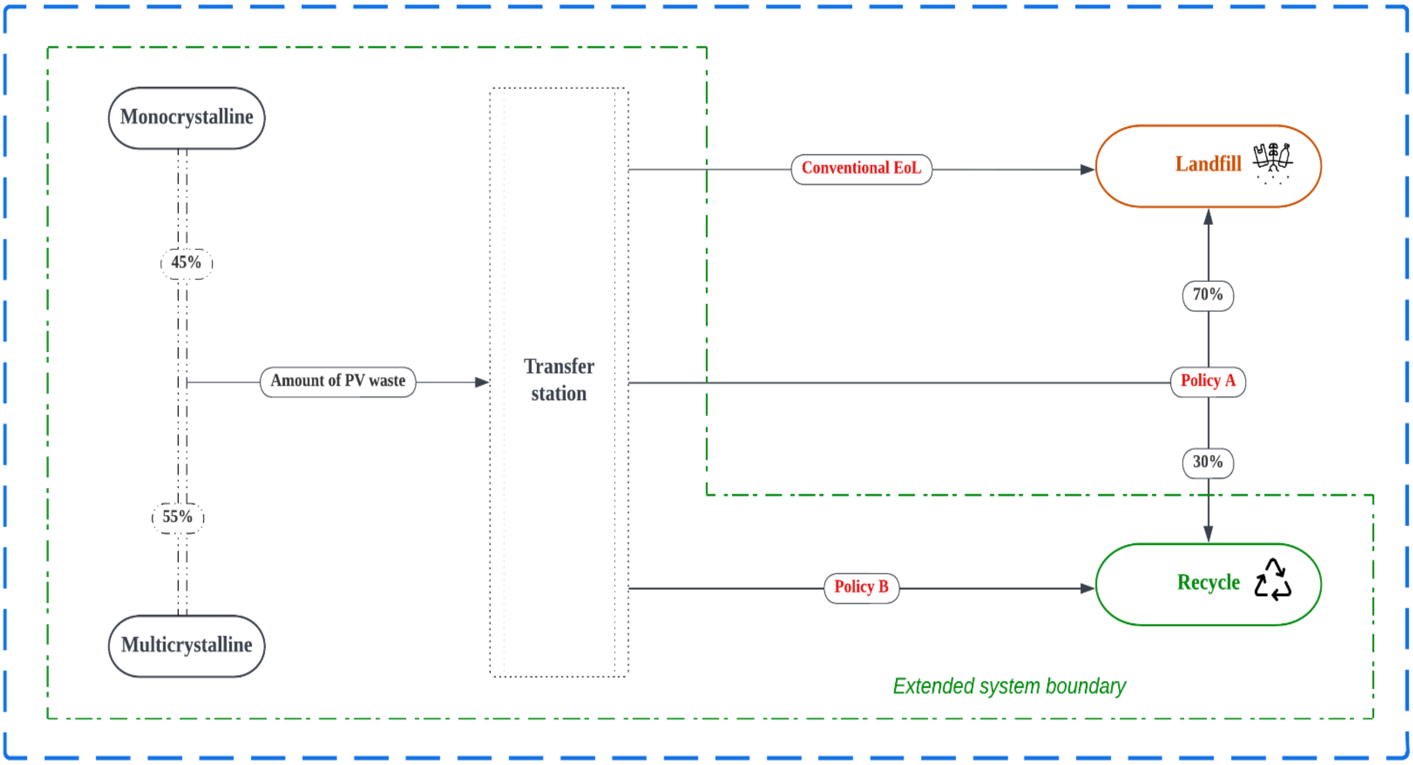

Fig 1: System boundary

The EoL scenario is based on three options:

- The first scenario considers the non-existence of policies and regulations creating a situation where all the PV waste are transported to landfills which is the baseline scenario (Conventional EoL) as shown in figure one.
- The second policy option is the introduction of a voluntary product stewardship (VPS) by the government, this may see a 30% increase in recycling but 70% of the panels may end up in landfills.

- The last option is an introduction of robust mandatory product stewardship (MPS) or extended producer responsibility (EPR) which may see 100% of the panels being recycled. The detail of the options as associated with the other technologies are illustrated in table A3 in the supplementary material.

2.2.4 Life Cycle Inventory data

The input/output sources were obtained through background and foreground data. Information from bibliographical and literature sources as well as personal interviews were acquired for the analysis. The foreground information on site specific processes was obtained through tailored interview questionnaire from a PV plant as the main primary data for the assessment. Foreground data was collected in a form of interviews on the operation of the plant and modelled against the FRELP process to fill in the missing data. The transportation distance of end-of-life solar panels to the recycling plant was estimated. Table 1 shows the detail information of the inventory data for the assessment.

Table 1: Details of inventory data for the recycling of 3000 tonnes of crystalline solar PV.

Input/output	**Quantity**		**Unit**	**Note**
	Mono c-Si	**Multi c-Si**		
Input				
PV waste panels	1350	1650	ton	Estimated annual PV waste flow to the year 2050 in South Australia
Electricity	153.29	187.36	KWh	Required power for different treatment processes as explained in the processes in section 2
Diesel fuel	1.54	1.88	Litre	Used for forklift operations
Water	418.11	511.02	ton	Water consumption for acid leaching, electrolysis, and neutralisation process
HNO_3	9.56	11.68	ton	Acid leaching process
$Ca(OH)_2$	49.28	60.23	ton	Neutralisation of acid solution
Output, recovered materials				
Aluminium scrap	246.58	301.37	ton	
Glass scrap	926.10	1131.90	ton	
Copper scrap	5.91	7.23	ton	
Silicon metal (Metallurgical grade)	46.82	57.22	ton	
Silver	0.68	0.83	ton	

Lead	0.36	0.44	ton	
Tin	0.36	0.44	ton	
Output, energy recovered				
Electricity	335.93	410.59	KWh	Produced through the incineration of back-sheet layer, encapsulation, and polymers from cables
Thermal Energy	678.83	829.69	Mj	Produced through the incineration of back-sheet layer, encapsulation, and polymers from cables
Output, waste to Landfill				
Contaminated glass	18.90	23.10	ton	Disposal in landfill
Fly ash (hazardous waste)	2.7	3.30	ton	Disposal in hazardous waste landfill
Liquid waste	413.28	505.12	ton	Disposal in landfill
Sludge (hazardous waste)	67.84	82.91	ton	Contains metallic residue, disposal in special landfill
Output, emission to air				
NO_x	2.7	3.30	ton	Emission from electrolysis

Background information on related data such as emissions from the treatment of waste, auxiliary materials, use of energy and the generation of energy, dataset of unit processes and allocation at point of substitution were acquired from secondary data from AusLCI and Ecoinvent database (Ecoinvent, 2022; Lifecycles, 2022) and scientific literature (Ansanelli et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2020). Table A2 in the supplementary material shows the details of the background lifecycle inventory dataset.

2.2.5 Life Cycle Impact Assessment

The LCA was modelled using the SimaPro software version 9.1.0.11. The Best Practice Guide for Mid-Point Life Cycle Impact Assessment in Australia (ALCAS Best Practice LCIA carbon neutral) was chosen for the assessment with thirteen impact categories comprising Climate change (Global warming): Global Warming Potentials (GWP) for a 100 year time horizon, as per IPCC Forth Assessment Report (IPCC, 2007) in kgCO_2-eq; Resource (abiotic) depletion – minerals (ADE): abiotic depletion of minerals based on concentration of currently economic reserves and rate of de-accumulation in Sb-eq; Resource (abiotic) depletion – fossil fuels (ADF): abiotic depletion of fossil fuels based on energy content (lower heating value) in MJ;

Water scarcity (WS) - Method of Ridoutt and Pfister (2010), with water stress indices of Pfister et al. (2009) in m^3H_2O-eq; Eutrophication (EP): eutrophication potentials which assumes both N- and P-species contribute in $kgPO_4$-eq; Acidification (AP): if assessed, use the change in critical load exceedance, currently based on European characterisation factors in kg SO_2-eq; Toxicity: human (cancer, HTC and non-cancer, HTN) and freshwater eco-toxicity (FET) based on USEtox- with regionalised characterisation factors of Australia, derived based on regionalisation approach in CTU; Photochemical ozone formation (oxidation): Photochemical Ozone Creation Potentials (POCP) in C_2H_4-eq; Particulate matter formation (PMF): Fate and exposure based on Wolff, using the CALPUFF model in $kgPM_{2.5\text{-eq}}$. ALCAS is selected for this study because of the geographical location of the studies, to help in achieving accurate results from the selected impact categories.

In a Life Cycle Assessment, energy recovery and material recycling benefits associated with the environment can be approached in several ways. The approach that is mostly used is to allocate credits for any recycling benefits (example is substituting the respective materials to be produced) (Held & Ilg, 2011). This was introduced in the assessment of the waste PV panels for this study.

3 Results

This section details the results of the assessment of the various options analysed in the LCA. The assessment is divided into three options starting from full disposal which is the base scenario (Conventional EoL: full disposal into landfill); Policy A: 30% of the panels being recycled; and Policy B: 100% of the panels being recycled that is mandating manufacturers to recycle all solar panels. The results from the analysis can be a basis for the development of a sustainable product stewardship by the government as well as inform stakeholders on the environmental impacts associated with end-of-life management of solar PV modules

(Finkbeiner et al., 2006). The results also provide relevant information and suggestions for improvement.

3.1 Interpretation of Environmental analysis

The results are divided into three sections. First, the waste from monocrystalline silicon is assessed under the three policy options which covers the treatment of 1350 tonnes/year of the panels. The second results are from the Multicrystalline silicon modules also under the three policy options covering the treatment of 1650 tonnes/year of the panels. The last results discuss the comparative assessment of the three options as against each PV technology.

3.1.1 Monocrystalline Silicon

The figure 2 below shows the individual contributions of the three options analysed under the mono c-Si waste panels.

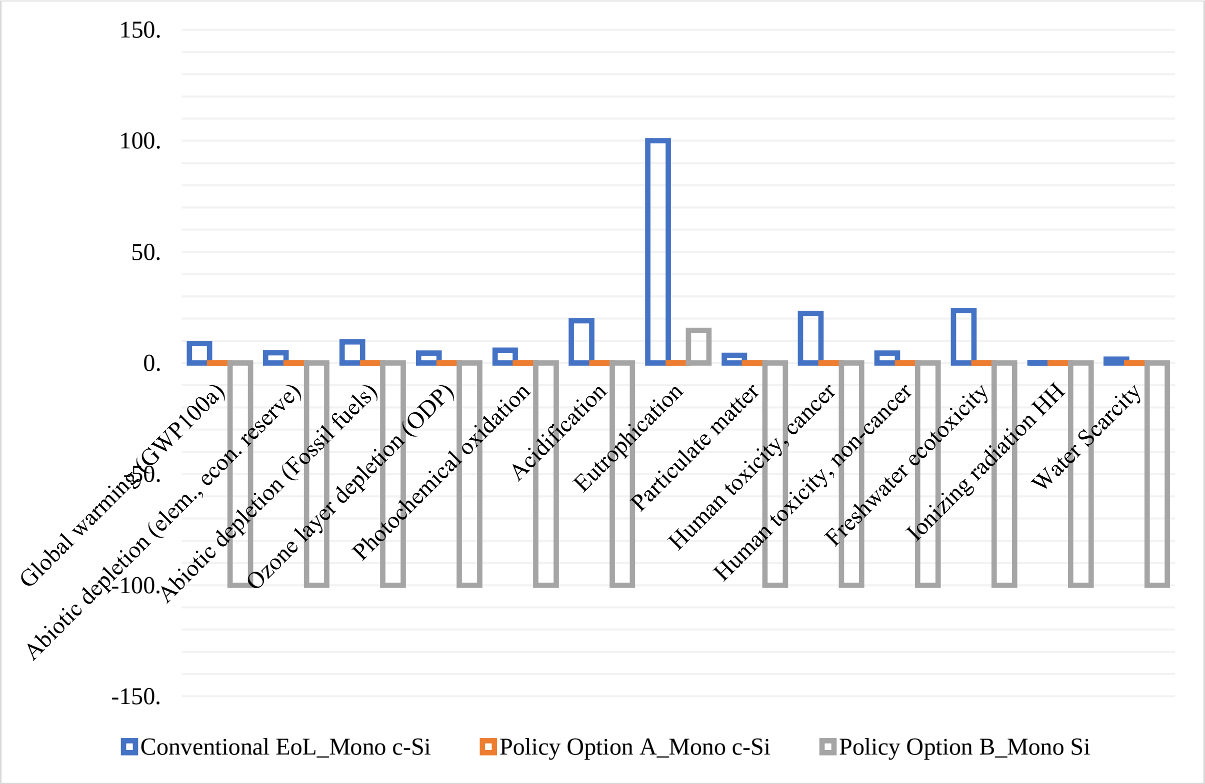

Fig 2: life cycle assessment of three options on end-of-life monocrystalline solar panels

It is noticed among the three options that, Conventional EoL, has the highest impact and burdens when you consider the fact that the panels will be landfilled at the end of their life. Again, the option A provide a buffer between the two. It shows less burden but not as much as the option B, which is the full treatment of the solar panels.

Table 2: life cycle assessment of three options on end-of-life monocrystalline solar panels

Impact category	**Unit**	**Conventional EoL_Mono c-Si**	**Policy Option A_Mono c-Si**	**Policy Option B_Mono c-Si**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	1E+05	-298.64	-1E+06
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	4.39	-0.03	-95.94
Abiotic depletion (Fossil fuels)	MJ NCV	1E+06	-3310.50	-1E+07
Ozone layer depletion (ODP)	kg CFC-$11_{\text{-eq}}$	0.01	-3E-05	-0.10
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	26.72	-0.12	-463.2
Acidification	kg $SO_{2\text{-eq}}$	1713.00	-1.51	-90
Eutrophication	kg $PO_{4\text{-eq}}$	401.00	0.30	58.81
Particulate matter	kg $PM_{2.5}$	38.86	-0.31	-1123.00
Human toxicity, cancer	CTUh	3E-04	-2E-07	-0.00
Human toxicity, non-cancer	CTUh	0.00	-9E-06	-0.04
Freshwater ecotoxicity	CTUe	3E+08	-179483.00	-1E+09
Ionizing radiation HH	kBq $U235_{\text{-eq}}$	11.70	-13.30	-44354.00
Water Scarcity	$m^3H_2O_{\text{-eq}}$	99.07	-1.71	-5943.00

From the table 2, the global warming potential for the Conventional EoL is much higher at around 1E+05 kg CO_2 eq, with A having around -298.60 kg CO_2 eq, and the last option B having -1E+06 kg CO_2 eq. This shows the major difference in the implementation of these regulations. The negative figures show the credits from the avoided products such as aluminium, solar glass, copper, silicon, silver, lead and tin. These products are assumed to be upcycled or used as alternative materials after recycling. There is a lot of credit in full recovery than a percentage of the panels as shown in the table. To get a good understanding of the processes, the recycling option was broken down to detail the burdens and credits of the processes. Figure 2 shows the burdens and credits of each process associated with the recycling of the panels.

From the supplementary materials figure B1, it is apparent that transport contributes massively to the burdens of the recycling which is shared by various assessment (Latunussa et al., 2016; Mahmoudi et al., 2020). The impact of the incineration and disposal of fly ash also has a significant impact on Eutrophication, human toxicity (cancer) and freshwater ecotoxicity. Thou, the incineration has a significant impact, it is also expected to recover thermal energy an amount of 500MJ and electricity of 250MJ through the combustion of the polymers.

3.1.2 Multicrystalline Silicon

The figure 3 shows the individual contributions of the three options analysed under the multi c-Si waste panels. The results are remarkably similar because the same recycling process is used in both cases.

Fig 3: Life cycle assessment of three options on end-of-life Multicrystalline solar panels

From the figure, a similar result can be observed among the indicators as compared to the mono c-Si panels. The highest impact and burdens are associated with the landfill option which explains that 100% of the panels will go to landfill if no regulations or policies are in place.

Table 3: life cycle assessment of three options on end-of-life Multicrystalline solar panels

Impact category	**Unit**	**Conventional EoL_Multi c-Si**	**Policy Option B_Multi c-Si**	**Policy Option C_Multi c-Si**
Global warming (GWP100a)	kg CO_{2-eq}	1E+05	-365.00	-2E+06
Abiotic depletion (elem., econ. reserve)	kg SB_{-eq}	5.37	-0.03	-117.30
Abiotic depletion (Fossil fuels)	MJ NCV	2E+06	-4046.00	-2E+07
Ozone layer depletion (ODP)	kg CFC-11_{-eq}	0.01	-3E-05	-0.13
Photochemical oxidation	kg C_2H_{4-eq}	32.66	-0.15	-566.10
Acidification	kg SO_{2-eq}	2094.00	-1.85	-11043.00
Eutrophication	kg PO_{4-eq}	490.10	0.37	71.88
Particulate matter	kg $PM_{2.5}$	47.50	-0.38	-1373.00
Human toxicity, cancer	CTUh	3E-04	-2E-07	-0.00
Human toxicity, non-cancer	CTUh	0.00	-1E-05	-0.04
Freshwater ecotoxicity	CTUe	4E+08	-2E+05	-2E+09
Ionizing radiation HH	kBq $U235_{-eq}$	14.30	-16.25	-54211.00
Water Scarcity	$m^3H_2O_{-eq}$	121.10	-2.10	-7264.00

Table 3 details the values of the various indicators contributed by the three options. Considering ozone layer depletion, recycling of all the panels which is policy option B measuring -0.13 kg CFC_{-11} eq contributes less impact than the options A measuring -3E-05 kg CFC_{-11} eq and Conventional EoL measuring 0.01 kg CFC_{-11} eq. This is the same for all the other indicators. With full recycling or policy option B having the least environmental impacts, a further assessment is performed to identify the associated burdens and credits of the recycling process and the various process contributions.

From figure B2 in the supplementary material, particulate matter, ozone layer depletion, acidification and eutrophication are highly impacted by the recovery of the metals from the bottom ash. Eutrophication is the most impacted when considering the process of acid neutralisation, electrolysis, acid leaching and sieving in the recovery of the metals. The other phases such as cutting of the PV sandwich, thermal separation, disassembly and unloading of the PV waste modules contributes little to the overall impacts.

3.1.3 Comparative assessment of different policy options

The figure 4 shows the comparative assessment of the individual contributions of the three options analysed under the mono and multi c-Si waste panels.

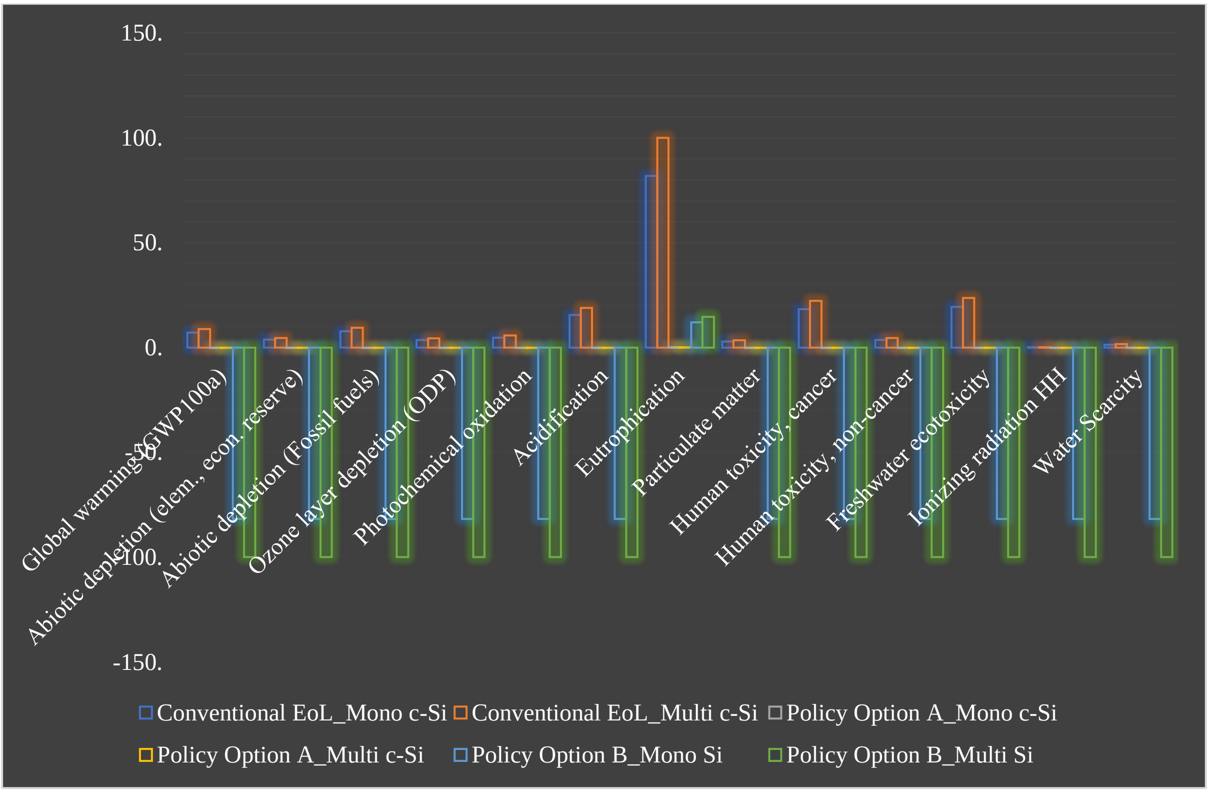

Fig 4: Comparative assessment of all policy options under the two technologies

It was imperative to compare the various policies against different technologies. Observing the Conventional EoL between the two technologies, reveals that, multi c-Si contributes more when it comes to burdens on the environment than the mono c-Si. This may stem from the percentage market share of multi c-Si as against the mono c-Si (Daljit Singh et al., 2021; Oteng et al., 2021). Thus, the amount of waste going to landfill will be more. This is the same for the other two options A and B.

Table 4: Comparative assessment of all policy options under the two technologies

Impact category	**Unit**	**Conventional EoL_Mono c-Si**	**Conventional EoL_Multi c-Si**	**Policy Option A_Mono c-Si**	**Policy Option A_Multi c-Si**	**Policy Option B_Mono c-Si**	**Policy Option B_Multi c-Si**
Global warming (GWP100a)	kg $CO_{2\text{-}eq}$	1E+05	1E+05	-298.60	-365.00	-1E+06	-2E+06
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-}eq}$	4.39	5.37	-0.03	-0.03	-95.94	-117.30
Abiotic depletion (Fossil fuels)	MJ NCV	1E+06	2E+06	-3310.00	-4046.00	-1E+07	-2E+07
Ozone layer depletion (ODP)	kg CFC-11$_{\text{-}eq}$	0.01	0.01	-3E-05	-3E-05	-0.10	-0.13
Photochemical oxidation	kg $C_2H_{4\text{-}eq}$	26.72	32.66	-0.12	-0.15	-463.20	-566.10
Acidification	kg $SO_{2\text{-}eq}$	1713.00	2094.00	-1.51	-1.85	-9035.00	-11043.00
Eutrophication	kg $PO_{4\text{-}eq}$	401.00	490.10	0.30	0.36	58.81	71.88
Particulate matter	kg $PM_{2.5}$	38.86	47.50	-0.31	-0.38	-1123.00	-1373.00
Human toxicity, cancer	CTUh	3E-04	3E-04	-2E-07	-2E-07	-0.00	-0.00
Human toxicity, non-cancer	CTUh	0.00	0.00	-9E-06	-1E-05	-0.04	-0.04
Freshwater ecotoxicity	CTUe	3E+08	4E+08	-2E+05	-2E+05	-1E+09	-2E+09
Ionizing radiation HH	kBq U235$_{\text{-}eq}$	11.70	14.30	-13.30	-16.25	-44354.00	-54211.00
Water Scarcity	$m^3H_2O_{\text{-}eq}$	99.07	121.10	-1.71	-2.10	-5943.00	-7264.00

From table 4, the particulate matter of Conventional EoL mono is 38.86 $PM_{2.5}$ whiles multi is 47.50 $PM_{2.5}$, for option A mono is -0.31 $PM_{2.5}$ whiles multi is -0.38 $PM_{2.5}$, for option B mono is -1123.00 $PM_{2.5}$ whiles multi is -1373.00 $PM_{2.5}$. The example from particulate matter clearly highlights the differences in the various options thou they are not very significant. This is because the market share between the technologies is not that significant. However, the multi c-Si panels contributes more to the environmental impacts as against the mono c-Si. In the same vain, the policy B for each contributes the least to the environmental impacts as against the Conventional and option A.

3.2 Sensitivity analysis

A sensitivity analysis of the various ways the PV waste should be recycled and how much is going to landfill was assessed. Since full recycling and landfilling are inevitable and are always discussed in the literature, the sensitivity analysis provides a way of measuring the impacts of

PV waste from different recycling and landfilling perspectives. The monocrystalline modules were first analysed. The percentage of recycling the panels were 30, 50 and 70 percent. This was to arrive at a relative decision on how the change in the collection of PV waste could affect the environment. The transition to a full recycling of PV waste may be slow, however, it will soon transition through a lower collection percentage to a higher percentage. Therefore, the need to analyse the impacts these may raise as many countries transition to a mandatory product stewardship, especially Australia.

Table 5: Sensitivity analysis on monocrystalline silicon modules

Impact category	**Unit**	**Mono c-Si_30%**	**Mono c-Si_50%**	**Mono c-Si_70%**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	-298.60	-571.40	-844.20
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	-0.03	-0.05	-0.07
Abiotic depletion (Fossil fuels)	MJ NCV	-3310.00	-6418.00	-9525.00
Ozone layer depletion (ODP)	kg CFC-11$_{\text{-eq}}$	-3E-05	-5E-05	-7E-05
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	-0.12	-0.22	-0.32
Acidification	kg $SO_{2\text{-eq}}$	-1.511	-3.66	-5.81
Eutrophication	kg $PO_{4\text{-eq}}$	0.30	0.23	0.16
Particulate matter	kg $PM_{2.5}$	-0.31	-0.54	-0.77
Human toxicity, cancer	CTUh	-2E-07	-5E-07	-8E-07
Human toxicity, non-cancer	CTUh	-9E-06	-2E-05	-2E-05
Freshwater ecotoxicity	CTUe	-2E+05	-5E+05	-8E+05
Ionizing radiation HH	kBq U235$_{\text{-eq}}$	-13.30	-22.17	-31.04
Water Scarcity	$m^3H_2O_{\text{-eq}}$	-1.71	-2.92	-4.13

Table 5 highlights the impacts of three different approaches in the collection of PV waste in Australia under the voluntary product stewardship arrangement. Comparing the three recycling percentages, there was a significant change on the impacts of a 70% recycling rate to a 50% and 30% recycling rate as graphically represented in figure B3 (see supplementary material). A GWP of -844.20 as against -571.40 and -298.60, reveals the climate change impact of recycling more to landfilling based on the current scenario. This is replicated in the ADE, ADF, ADP, POCP, AP, PMF, HTC, HTN, FET, IOR and WS. There is, however, a serious impact to EP because of the percentage going to landfill whether recycling or disposing of PV waste. The value of 0.30, 0.23 and 0.16 derived from the 30, 50 and 70 percent EP are single indicators based on the 'stoiciometric nutrification potentials' based on the Australian best practices owing to the absence of regionalised factors derived from fate-exposure models. The credits of the recycling may go back to the manufacturing stage but the process and landfilling of a number of the PV modules may have adverse effects on the ecosystems especially aquatic as compared to terrestrial due to Australia having low population densities and nutrient limited soils.

Table 6 shows the comparison of the three different scenarios of recycling and landfilling the Multicrystalline PV modules. Pertaining to the earlier evaluated voluntary product stewardship of 30%, a varying 50% and 70% were analysed to ascertain the impact changes to the environmental categories as graphically expressed in figure B4 (see supplementary material).

Table 6: Sensitivity analysis on Multicrystalline silicon modules

Impact category	**Unit**	**Multi c-Si_30%**	**Multi c-Si_50%**	**Multi c-Si_70%**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	-365.00	-698.40	-1032.00
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	-0.03	-0.06	-0.08
Abiotic depletion (Fossil fuels)	MJ NCV	-4046.00	-7844.00	-11642.00
Ozone layer depletion (ODP)	kg CFC-11$_{\text{-eq}}$	-3E-05	-6E-05	-9E-05
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	-0.15	-0.28	-0.39
Acidification	kg $SO_{2\text{-eq}}$	-1.85	-4.48	-7.10
Eutrophication	kg $PO_{4\text{-eq}}$	0.36	0.28	0.20
Particulate matter	kg $PM_{2.5}$	-0.38	-0.66	-0.95
Human toxicity, cancer	CTUh	-2E-07	-6E-07	-1E-06
Human toxicity, non-cancer	CTUh	-1E-05	-2E-05	-3E-05
Freshwater ecotoxicity	CTUe	-2E+05	-6E+05	-1E+06
Ionizing radiation HH	kBq U235$_{\text{-eq}}$	-16.25	-27.10	-37.94
Water Scarcity	$m^3H_2O_{\text{-eq}}$	-2.10	-3.57	-5.05

The GWP of -1032.00 kg $CO_{2\text{-eq}}$ shows the positive impact associated with collecting and recycling more PV waste to sending them to the landfill. This is influenced by the high collection rate of PV waste which will then be recycled. There is also a significant difference between the GWP for collecting and recycling some of the PV waste to fully recycling all the PV waste. Making reference to table 4, the GWP for fully recycling PV waste is significantly higher than all the scenarios of recycling a percentage of the multi c-Si waste panels. This is very important because of the effects of climate change such heat stress, infectious diseases, flooding, malnutrition and wildfires.

3.3 Optimised transport LCA analysis

One of the major limitations to LCA are the omissions and assumptions made on transport distances (Dias et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016), especially from the collection centres or transfer stations to the recycling plant, thou, it has significant impact on the recycling process.

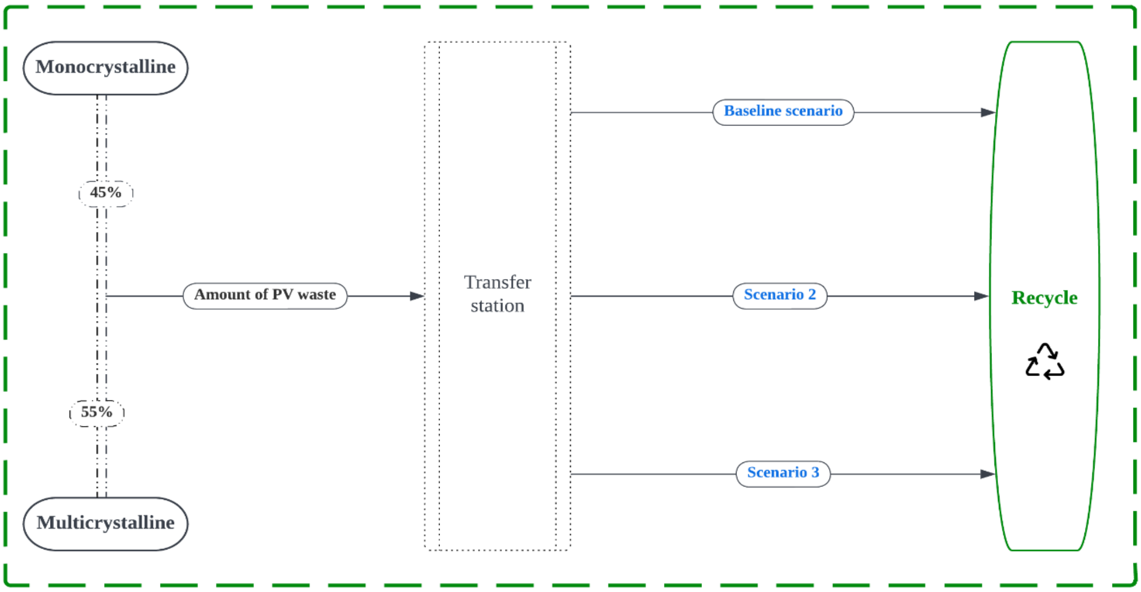

Fig 6: Extended system boundary

This study bridges that gap by using estimated travel distances as previously estimated by the authors (Oteng et al., 2022a) for the scenario analysis as shown in figure 6.

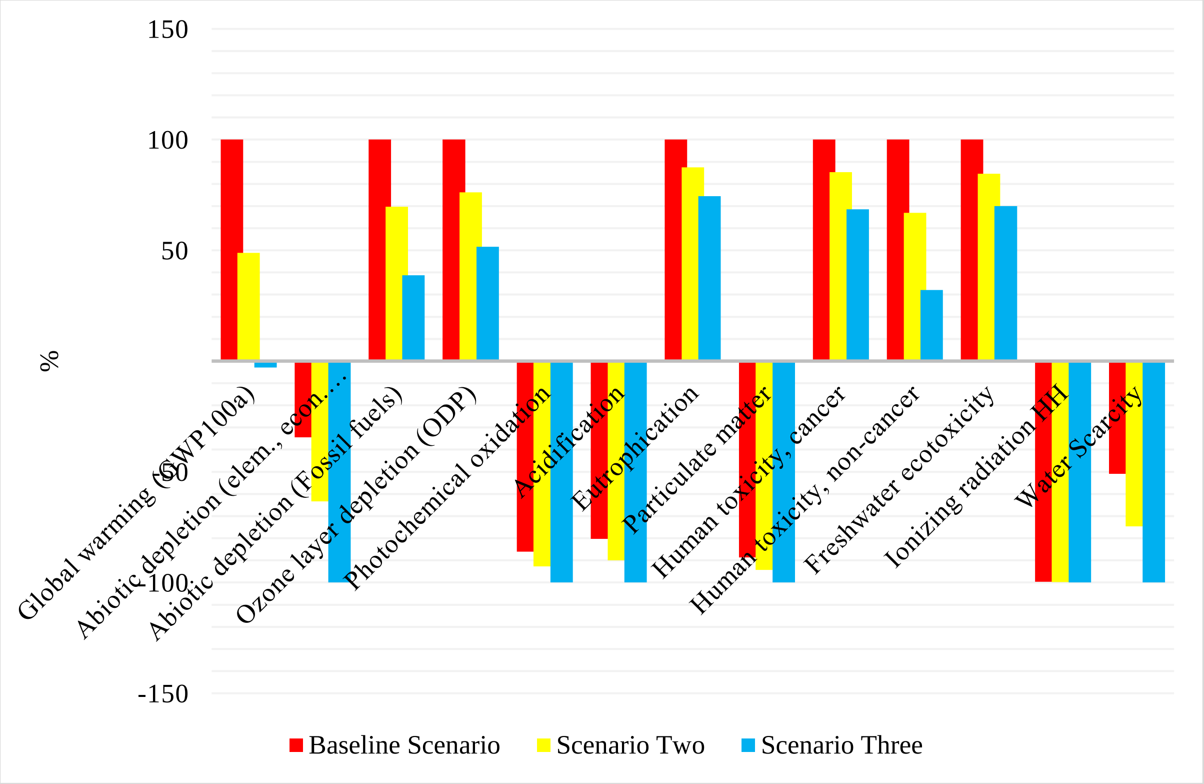

Fig 7: Different scenarios of transport distance of PV waste to recycling centres

The figure 7 highlights the contribution of three different transport distances as estimated by Oteng et al. (2022a) in their environmental emission assessment. The results, reveals that, scenario three which has the shortest distance among the others contributes less to the environmental impacts as compared to that of the baseline scenario and scenario two.

Table 7: Different scenarios of transport distance of PV waste to recycling centres

Impact category	**Unit**	**Baseline Scenario**	**Scenario Two**	**Scenario Three**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	1E+06	5E+05	-28722.00
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	-28.18	-51.78	-81.73
Abiotic depletion (Fossil fuels)	MJ NCV	2E+07	2E+07	1E+07
Ozone layer depletion (ODP)	kg CFC-11$_{\text{-eq}}$	0.29	0.22	0.15
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	-645.20	-695.90	-750.16
Acidification	kg $SO_{2\text{-eq}}$	-10522.00	-11793.00	-13106.00
Eutrophication	kg $PO_{4\text{-eq}}$	2231.00	1952.00	1662.30
Particulate matter	kg $PM_{2.5}$	-1691.00	-1799.00	-1906.70
Human toxicity, cancer	CTUh	0.02	0.02	0.01
Human toxicity, non-cancer	CTUh	0.05	0.04	0.02
Freshwater ecotoxicity	CTUe	2E+10	2E+10	1E+10

Ionizing radiation HH	kBq $U235_{-eq}$	-97499.00	-97639.00	-97796.00
Water Scarcity	$m^3H_2O_{-eq}$	-2917.00	-4277.00	-5731.00

Table 7 reports on the individual impacts categories associated with the three scenarios. The contribution of the scenario three shows a significant reduction in all the impact categories for example global warming potential has a value of -28722.00 kg CO_2 eq for scenario three, 5E+05 kg CO_2 eq for scenario two and 1E+06 kg CO_2 eq for the baseline scenario. The results affirm the need to introduce another recycling plant because of the long distances covered by transport trucks when transporting PV waste for recycling.

The limitations of this LCA are associated with the input and output data used for the flows and emissions of this study is developed from the FRELP pilot project. Again, the plant used in Lonsdale is at the initial stage of recycling. Therefore, the data used should be verified once the plant becomes fully operational in the coming years.

4 Discussion

The discussion details the comparative analysis of the results with previous and current literature to make inform decision and suggestions.

4.1 Recycling and recovery scenarios of EoL solar PV panels

There are several studies on the recycling of decommissioned solar PV panels using life cycle impact assessment (Ardente et al., 2019; Dias et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2020). Among these, Müller et al. (2006) posits that, there can be a total reduction of 37% from acidification, 24% from global warming potential, 26% from human toxicity potential and, 74% from terrestrial ecotoxicity through the recycling process of EoL PV modules from “cradle to grave”. Again, by comparing the production of primary Si wafer to recycled Si wafer, the energy used could be reduced by 70% if recycled materials are used (Deng et al., 2019; Vellini et al., 2017).

As assessed in this study, comparing different end-of-life scenarios produces lower environmental impacts or footprint for upcycling and downcycling when compared to direct landfill although the recycling process involves the use of chemicals and energy (Huang et al., 2017; Stolz, 2017). Furthermore, Lunardi et al. (2018) in their studies revealed that upcycling achieved a lower environmental footprint in all the categories (resources, ecosystem and human health) when they assessed and compared LCIA scenarios of chemical recycling, mechanical recycling, thermal recycling, reuse, incineration and landfilling. Thus, high value recycling processes developed and assessed in this study is very necessary towards achieving a sustainable management of EoL PV modules.

Again, the recycling of end-of-life PV modules are associated with high categorical impacts pertaining to transport (Dias et al., 2021). Transport is therefore very essential to collecting and recycling of PV waste. This issue is mostly ignored in several studies, assumptions are mostly used to assess the distances covered throughout the process. This study addresses the issue by developing an optimised system and assessing the LCA of the process. The optimised process showed a net environmental benefit for GWP as compared to the other two scenarios. This is particularly important because of the significant contributions transport have on climate change when it comes to recycling solar PV panels.

4.2 Policy, control measures and practices of PV waste management

To prevent environmental pollution, the government must take the necessary steps to prevent EoL solar panels from being disposed of in landfills. The European Union (EU) enacted the WEEE Directive, which governs EoL solar panels through extended producer responsibility. This ensures that hazardous or valuable materials in the panels are recovered or recycled, reducing landfill waste (Ramos-Ruiz et al., 2017). Other countries outside the EU market are still working on developing appropriate regulations for managing solar PV waste. Although the United States lacks a federal policy, states such as California, Washington, New Jersey, and North Carolina have passed bills to recycle EoL solar PV, with states such as Hawaii and Rhode Island still pending (Curtis, Buchanan, Heath, et al., 2021; Curtis, Buchanan, Smith, et al., 2021). The United States, Japan, China, India, and Australia are among the countries that lack specific policies (Oteng et al., 2022b; Xu et al., 2018). The majority of these countries are currently developing policies to regulate PV waste. The Australian government is developing a national product stewardship programme to govern the management of PV waste which is expected to be operational from 2023.

These policies should lead the process of creating an avenue for manufacturers to recycle through these regulations to prevent hazardous materials from going into landfills. The extended producer responsibility is yet to be adopted and mandated (mandatory product stewardship) to aid in the collection, tracking and recycling of panels by manufactures (Mahmoudi et al., 2019; Oteng et al., 2022a; Sharma et al., 2021). The government should provide incentives for industry led initiatives to also come up with innovative recycling technologies. Without proper control measures, the broken panels in the landfills may percolate and leach into the ground water (Nain & Kumar, 2020a, 2020b) which will cause several environmental and health issues.

5 Conclusions

Significant amount of solar PV waste, reaching their 25-30 years lifetime, is expected to overwhelm the industry in the coming years. These panels may end up in landfills due to lack of effective polices for regulating waste PV modules. This study therefore discusses the environmental impacts of three different policy options, sensitivity analysis and the impact of transport on recycling of EoL PV models.

The global warming potential for the non-existence of a product stewardship or policy was 1E+05 $kgCO_{2}$-eq for both PV modules which is a significant shift from the mandatory product stewardship or extended producer responsibility considering the -1E+06 $kgCO_{2}$-eq and -2E+06

$kgCO_{2\text{-}}eq$ for mono and multi c-Si modules, respectively. The credits attributed to the avoided products under the EPR such as aluminium, solar glass, copper, silicon, silver, lead, and tin goes back to the production stream creating significantly lower environmental footprint. This also reveals the significant environmental impact of the multi-Si panels when disposed in landfills but comparatively better than the mono-Si panels when recycled. Consequently, the comparison of different recycling and landfilling scenarios were assessed. The results revealed that, collecting and recycling most of the mono and multi c-Si panels were not effective (-365.00 kg $CO_{2\text{-eq,}}$ -698.40 kg $CO_{2\text{-eq,}}$ -1032.00 kg $CO_{2\text{-eq}}$) compared to keeping them away from the landfills and fully recycling (-2E+06 kg $CO_{2\text{-eq}}$) them especially when it comes to climate change.

The transportation impact of the recycling process was also assessed. Scenario three (-28722.19 $kgCO_2eq$) which was the shortest distance from the transfer stations to the recycling centres had the least environmental impact (global warming potential) on the recycling process. The highest impact (1E+06 $kgCO_2eq$) regarding global warming was the scenario of one recycling centre serving around 107 transfer stations. The optimised collection centre which is the second scenario had an environmental impact (5E+05 $kgCO_2eq$) between the baseline scenario and the third scenario. The methodology serves a s a first LCA assessment using a developed transport distance for the recycling process which can be replicated in other states and other countries. To further reduce the significant impact of transport distance on the PV recycling process, low-impact modes of transportation using renewable energies may be used in the transportation of the PV waste volume. It suggested that, using this model assessment, the social and economic aspects of the policy options may be assessed.

Chapter 7. Discussions

7.1 Introduction

This chapter highlights the comparative assessment of results from previous chapters and critically discuss them in light of existing literature. PV waste management stakeholders' views are analysed in Chapter 4. The PV waste management practice in SA has been discussed and the resulted waste generation from previous installations to the year 2050 considering a 30-year EoL is estimated in Chapter 5. Moreover, the impact of travel distances from transfer stations to recycling centres are also discussed. The various scenarios according to different policy options are assessed through environmental lifecycle analysis in Chapter 6. This was achieved using the framework developed through the fuzzy Delphi results created from the interviews. The estimated travel distances in Chapter 5, was also used to evaluate the environmental impacts of different scenarios. This chapter brings together all these findings to form policy recommendations for the optimisation of PV waste management practices in South Australia.

7.2 Current practices of end-of-life solar photovoltaic panels in Australia

The volume of PV waste continues to increase around the world and there are strategies that should be immediately considered to identify how to safely treat this waste stream. These include marketing strategy (Islam et al., 2020; Schmela et al., 2018), awareness (Mahmoudi et al., 2021), standardisation, legislation, monitoring systems, technologies, and infrastructure (Islam et al., 2020; Xu et al., 2018), sustainable treatment methods (Masoumian & Kopacek, 2015; Tao & Yu, 2015) and collection network (Islam et al., 2020). The following sections discusses the various practices associated with EoL PV in Australia.

7.2.1 Fast growing market for solar photovoltaic technologies worldwide

The benefits that come with the use of solar energy has seen the technology employed in several applications from residential use to production. The reduction in the cost of production through the use of solar photovoltaics has seen a huge installation of solar PV in many countries including Australia on a larger scale (Schmela et al., 2018). The discussion from chapter 3 highlights the market growth of solar technologies in Australia compared to other countries. It shows 95% share of the global dominance of c-Si panels that is reflected in Australia. Apart from the recent manufacturing of solar panels in Australia, it has always received its supply from Europe, US, and China.

Developments in solar technologies have seen a reduction in the prices of solar technologies leading to the high deployment of solar modules across the world. In the year 2017, the capacity of solar power deployed in China constituted 50% of the world's power generation with 30% going to Europe because of the slower rate of adoption in that year (IEA-PVPS, 2021). Nonetheless, it is estimated that, the power generated from solar will exceed 1TW (TWh) with the global capacity growing to 1270.5 GW in the generation of solar energy in 2022 (Chowdhury et al., 2020). The market for solar continues to grow in countries like the UK, Italy, Germany, United States, Japan, and China who are leading the world when it comes to the most installed capacity on solar PV generation (Padoan et al., 2019). India has seen a surge in the use of solar PV power recently. Moreover, as discussed in chapter 4 and 5, Australia leads the world when it comes to the installation of rooftop solar photovoltaics (Nain & Kumar, 2022; Oteng et al., 2021). This will continue to grow in the coming years as it provides a sustainable option through its use phase for users and an affordable choice for many.

7.2.1.1 Type of solar photovoltaic installation technologies in Australia

The first generation of PV technologies represents the highest market share and most popular among the three worldwide. The monocrystalline and polycrystalline silicon panels are the most common panels under the first generation with a respective market share of 41% and 51% (IRENA, 2019). The aforementioned is linked to the data in Australia because of its supply from the global market. However, the discussion in chapter 4 highlights the first generation as the most installed technology type in Australia. The second generation mostly the thin film technology also occupying the second largest share in the market, with CdTe and CIGS technologies being the common among them. These two generations have commercially available recycling technologies with the others still under research. The recycling technologies differ from each technology as their module structure are different (Dias et al., 2018; IEA-PVPS, 2021; IRENA, 2019). The results from chapter 4 revealed that, the installation of the first generation especially the mono and poly crystalline silicon modules constitute a very large share of the Australian photovoltaic market. Because there is no proper monitoring of these panels, it was difficult to confirm the percentage of the various technologies on the market. The percentages are aligned with the research conducted by the international energy agency (IEA-PVPS, 2021), this is because most of the technologies on the market are not produced in Australia. They are mostly imported from China and Europe and installed in Australia. There is currently a manufacturer (Tindo Solar) in South Australia that started the production of the first solar photovoltaics modules manufactured in Australia.

7.2.2 Australian policies and regulations on solar photovoltaic waste management

The estimated waste from solar panels in Australia in 30 years' time will be around 653,173 tonnes by 2047 (Mahmoudi, Huda, & Behnia, 2019). Moreover, it is estimated that around 100,007 tonnes of PV waste will be generated by 2050 in South Australia alone as discussed in chapter 5. The release of harmful chemicals such as cadmium and lead in the solar panels when not properly treated would be detrimental to the environment and humans (Heath et al., 2020). Without a sound regulatory framework for the management of this waste stream, there are huge environmental risks and costs to be incurred among governments around the world (Mahmoudi et al., 2021).

The lack of mandatory product stewardship on WEEE is a big problem in several countries because of the disposal of the waste materials in landfill (Blake et al., 2019). The European Union established the EU WEEE directive to mandate the treatment of solar PV waste by manufacturers. Countries like the UK and Germany started the process with the others joining later. Other countries outside the EU are still developing appropriate policies to govern end of life solar panels (Curtis, Buchanan, Smith, et al., 2021). Australia is among the countries without a specific regulatory policy on the management of PV waste. United States also lacks a federal policy. However, states like North Carolina, Washington, New Jersey, and California have passed a pill to recycle the PV waste. Japan, China, and India also lack specific policies to manage PV waste. nonetheless, majority of these countries are developing appropriate regulations to manage EoL panels (Curtis, Buchanan, Heath, et al., 2021; Xu et al., 2018).

The Australian government recently emphasised the need to treat EoL solar panels effectively as they are becoming one of the primary waste streams in the country. The are several states who have already banned the waste stream from landfills (Australian Government, 2019), however, there is no currently active policy to manage the solar photovoltaic waste stream. The interviews revealed in this study identified from stakeholders the need for a policy or regulation to aid in the effective management of PV waste in the country. With previous stewardship schemes considering PV waste under WEEE (Australian Government, 2019), efforts have been made to create an appropriate product stewardship for the PV waste stream in Australia (Majewski et al., 2021). This will involve dedication from manufacturers and recyclers to help create an effective product stewardship for the country.

7.2.3 Treatment pathway of solar photovoltaics waste management in Australia

As discussed earlier in chapter 4, the crystalline silicon modules are the panels mostly installed to date. Thus, most of the waste coming from solar panels will be associated with this technology in the coming years. There is therefore the need to develop appropriate means of treating the end-of-life waste stream coming from this technology (Fiandra et al., 2019). The large amount of waste estimated at around 800,000 tonnes in the year 2047 (Mahmoudi, Huda, & Behnia, 2019) could be detrimental to the environment if effective management strategies are not developed to treat the PV panels (Daljit Singh et al., 2021).

The panels may end-up in landfills releasing potentially hazardous materials into the soils through leaching. There are some valuable resources that could also be recovered from the treatment of the panels (Ardente et al., 2019). Several treatment scenarios were highlighted and assessed through the interviews. Even thou, some states have banned this waste stream from going into landfills, the panels still ended up going to landfills. Big recycling companies were turning the panels back because they did not have the infrastructure to treat these panels. The companies who were collecting the panels for recycling were also at the pilot study, meaning these panels were being kept until the recycling process being developed was complete.

7.2.3.1 Landfilling and disposal of EoL PV in Australia

The simplicity of the landfill process makes it the easier choice for Australia and globally in terms of waste disposal. The absence of a policy and a dedicated large scale PV recycling plant in Australia has seen a lot of the panels going to landfills (Daljit Singh et al., 2021). This was confirmed by most of the interviewees. The other issue was the economic feasibility of the recycling process, as there are not a lot of the PV waste in the system making it difficult recyclers to approach it as a good business model (Lunardi et al., 2018). However, landfilling is considered as the worst strategy or pathway for solar panels because of the harmful substances found in the panels. This might cause serious environmental and health issues when they leach into the ground (Masoumian & Kopacek, 2015). Effective policies and regulations directing solar PV waste from landfills will be appropriate to curb this current problem. Nonetheless, if the panels are not recycled, the policies may not be effective.

7.2.3.2 Recycling and recovery of EoL in Australia

The recycling of end-of-life PV far outweigh the disposal of the panels to landfills. Aluminium, copper, glass, and other materials are some of the significant components derived from the recovery of the panels. Over 85% of these components could be recovered through full recovery of the EoL panels (Omar et al., 2022). Many stakeholders are of the view that, Australia can benefit from the recovery of the panels through the supply of recovered components which may not be on the Australian market and currently relies on imports from other countries. Recovery becomes beneficial if the cost of the processes is lower than the expenses on the imports (Faircloth et al., 2019; Mahmoudi et al., 2020). The recovery and reuse of solar panels have become an important global option for solar PV waste because of the environmental burdens of disposing of solar panels in landfills. This also aids in the reduction of depleted valuable minerals and resources, and most importantly the reduction of the solar PV waste stream (Berger et al., 2010; Latunussa et al., 2016).

7.2.3.3 Other treatment options

There are other known options like incineration, reconditioning, and exportation. The impact of incineration starts with the complete disintegration of the panels without a chance to recover precious materials. This process also comes with the release of gases into the atmosphere which may cause long term effects on flora, fauna and human health (Lunardi et al., 2018). According to the experts, this practice is not common in Australia. However, exportation of some of the old panels are common, where panels are sent to developing countries without testing. This in turn may generate another waste stream of the same panels but in other countries. Recondition is barely practices in Australia. There is therefore the need for a holistic management strategy for end-of-life solar PV waste (Mahmoudi, Huda, & Behnia, 2019) in Australia. This will be possible if national regulations and policies are in line with the state and local levels.

7.3 Optimisation of solar photovoltaic reverse logistics in South Australia

The geographical dispersion of the installation of solar panels makes it difficult to collect and recycle (Masoumian & Kopacek, 2015; Padoan et al., 2019). Logistics plays an important part in the management of PV waste as it adds to the environmental emissions through the collection of EoL panels from their waste sources to transfer stations and then to the recycling centres.

The movement and monitoring of the panels are essential to the treatment as it covers the registration and data inventory of the panels to make appropriate decisions on the components and substances used in its production (Mahmoudi et al., 2021). This creates a good database for waste management and recycling because of the recycling technologies involved in recovery the different components of the panels.

The quantity of the waste also needs to be comprehensively assessed as the economic feasibility of the whole process may rely on it. The collection channels need to be properly planned as well as minimising the transport distance associated with the recycling and recovery of solar PV waste modules (Islam et al., 2020). Several researchers have discussed the need for more holistic and optimal reverse logistic approach to the collection and transport of PV waste from their sources to the treatment centres (Goe et al., 2015; Molano et al., 2022; Oteng et al., 2022a). This thesis has identified the need to develop and the impact of a holistic reverse logistic approach to the collection of PV waste from transfer stations to recycling centres.

The recent increase in the installation of solar panels has made it the highest adopted renewable energy sources throughout the years in Australia. However, the useful life of solar panels ranges from 25-30 years, which will see a rapid growth of solar panels reaching their end-of-life. This amount is estimated to reach over 60 million tonnes by the year 2050 worldwide

(IEA-PVPS, 2022), and around 960 to 1300 kilotons in Australia (200-folds of existing volume) (IRENA, 2019). The current market of PV technologies is dominated by the silicon-based models accounting for 92% of the market share (Sica et al., 2018; Xu et al., 2018). It is therefore imperative that, measures are put in place to effectively manage the waste at their end of life. Australia has the highest number of rooftop panels around the world. These panels will be coming to their end of life in the coming years. Because of that, chapter 5 of this thesis focuses on the quantification of the rooftop solar panels and their management in Australia.

7.3.1 Forecasting of end-of-life solar photovoltaic panels in South Australia

South Australia has the only manufacturer for solar PV panels in Australia, and the pioneers of the recycling process which is Reclaim PV as highlighted in chapter 4. Mahmoudi, Huda and Behnia (2019) forecasted the waste generation of Australia from 2017 to 2047 using the Weibull distribution. Islam et al. (2020) also forecasted the generation of PV waste in Australia to develop a reverse logistic network for New South Wales but did not use the Weibull distribution. In both cases, they forecasted the waste using the entire installation of the solar panels across the country and at council levels.

Rooftop or small-scale solar panels often find themselves in the municipal waste stream. This study estimates the waste generation at the postcode level that is a major contribution when it comes to developing an inventory data for environmental assessment on the local level. From chapter 5, the results show the postcodes with the highest and lowest waste generation for a 30-year period, highlighting the early and regular loss scenarios. The study again develops a hotspot analysis that other studies overlook (Islam et al., 2020; Mahmoudi, Huda, & Behnia, 2019) to ascertain the postcodes that would generate the highest amount of PV waste and how these would be treated. Chapter 5 discusses postcodes such as 5275, 5267, 5223, 5270, 5220, 5302, 5304, 5606, 5266 and 5303 which are among the highest hotspot areas for solar PV waste generation. This gives a good indication to aid the development of a holistic reverse logistic network for recycling solar PV waste.

7.3.3 Influence of an optimised reverse logistics on EoL PV in South Australia

According to Mahmoudi et al. (2020), the assessment of the environmental impacts on the recycling of solar PV waste is essential and needs to be critically evaluated. To get more accurate results, they noted that the selection of the recycling plant and collection points and its specification depends on the design of an advanced reverse logistic and route-finding analysis to serve as data inputs for the environmental assessment.

The assessment conducted by Molano et al. (2022) investigated the reverse supply chain between the recycling centres and PV installations using a case study. They estimated the minimum optimal distances between these points to improve the environmental gains and economic feasibility. Compared to this study, their study did not incorporate the hotspot of the generated waste as well as postcode waste generation data in the study creating a gap which this study fills. The need to identify the highly waste-generated postcodes is relevant to the design of a comprehensive logistic system that is effective and efficient in dealing with the management of the PV waste flow.

The scale of installations in particular areas have a significant impact on designing an efficient reverse logistic network for PV waste recycling. The transport distances of PV waste transfer from waste sources and transfer stations to recycling centres can greatly reduce the potential environmental impacts within a well-structured reverse logistic network (Mahmoudi, Huda, & Behnia, 2019). It is useful to have developed a comprehensive and holistic reverse logistic network in South Australia for the management of solar PV waste.

The successful recycling of end-of-life solar panels can be achieved through the development of an efficient logistic system (Cucchiella et al., 2015) which has a great influence on the recycling program. The design should be tailored to each region because of the different characteristics of local factors (Molano et al., 2022; Oteng et al., 2022a). The results clearly highlight the benefits of an optimised network system by minimising the travel distance and pollutant emissions generated by the trucks.

Chapter five has detailed the importance of the optimised system compared to the baseline scenario set for the recycling program. Compared to other studies (Molano et al., 2022) the network is tailored to the postcode hotspots that generate a lot of PV waste in South Australia that brings it down to the regional level, creating an inventory data for environmental analysis. The emissions such as PM, NO_x, CO_2 and CO were also assessed by the distance covered by the trucks to the recycling centres. For the first scenario which was one recycling centre serving 107 transfer stations, the emissions released was the highest (PM - 5.70kg, NO_x - 78.60kg, CO_2 – 7440.17kg and CO – 23.85kg) compared to the optimised system and the introduction of an additional recycling centre. According to Schröder and Cabral (2019), to achieve climate change related objectives the environmental impacts from road transport needs to be minimised. The study through an optimised system reduces the emissions created by the transport of solar PV waste to the recycling centres.

7.4 Environmental impacts of end-of-life solar photovoltaic panels

To reduce the carbon footprint that comes with the usage of solar photovoltaic power, solar panels can be reused after the recovery of raw materials from the recycling of end-of-life PV modules (Mahmoudi et al., 2020). This can be achieved if the global and local assessment of PV waste are explored in terms of the available policies and regulations in place (Mahmoudi, Huda, Alavi, et al., 2019; Oteng et al., 2021). The environmental impacts of PV waste have been analysed by many researchers, however, most of the studies make assumptions on the treatment pathway and travel distances for the recycling process. This study bridges the gap by evaluating the secondary data and collecting primary data to assess the environmental impact of the recycling process using a case study in South Australia. Furthermore, regional data are used to model transport distances covered by trucks from transfer stations to the recycling centres.

The evaluation of the life cycle assessment of the EoL panels uses industry data from Reclaim PV recycling process. The current operation of the plant is still in its pilot stages. Therefore, a comprehensive process for the recovery of solar PV waste (FRELP) was adopted and modified to cater for the missing data in the case study process. However, that process omits the credits given to the production of the secondary materials (Latunussa et al., 2016). This study incorporates these credits as the interview from the plant indicated the secondary materials going back into the production process and PV market.

7.4.1 Environmental impacts of treating EoL solar PV modules in South Australia

The environmental impact assessment is conducted under three policy and regulatory arrangements with a further sensitivity analysis. This system boundary used is derived from the results achieved through the assessment of stakeholders on the treatment pathway and management of end-of-life solar panels in Australia using fuzzy Delphi methodology. Even with the national ban of electronic waste, some are still going to landfills (Mahmoudi et al., 2020). EoL panels are among those that are still disposed in landfills as confirmed by the participants in Chapter 4.

The countries with policies in place such as the members of the European Union require manufactures and importers under a product consent scheme to register all incoming panels and also accept the responsibility of treating these panels at the end-of-life stages. The first country under the EU directive was the United Kingdom followed by Germany (Chowdhury et al., 2020; Jain et al., 2022). Failure to follow the regulations attract large fines. In order to satisfy the waste management policy, these obligations such as the collection, recycling and reuse of PV waste needs to be fulfilled (WEEE Directive, 2012). Australia can take a page from this comprehensive process, but the regional characteristics requires a tailored policy and regulation to the national case. The following policy options obtained through chapter 4, as well as the transport distances estimated earlier in Chapter 5 are analysed and discussed under the lifecycle assessment. Two technologies are considered under this assessment, these are the monocrystalline and multicrystalline silicon based solar panels. The assessment provides a national and regional evaluation of the policy scenarios and process to make an informed decision.

As discussed in Chapter 6, the table 7.1 highlights the LCA of various policy options together with additional scenarios created under the voluntary product stewardship. The scenarios were assessed against 13 impact categories: Global warming - GWP100a (GWP), Abiotic depletion - elem., econ. reserve (ADE), Abiotic depletion - Fossil fuels (ADF), Ozone layer depletion (ODP), Photochemical oxidation (POCP), Acidification (AP), Eutrophication (EP), Particulate matter (PMF), Human toxicity, cancer (HTC), Human toxicity, non-cancer (HTN), Freshwater ecotoxicity (FET) Ionizing radiation HH (IOR), and Water Scarcity WS).

The Australian Government (2022) defines product stewardship as "an approach to reducing environmental and other impacts of a product by encouraging or requiring manufacturers, importers, distributors and/or other persons to take responsibility for that product". Under the directive of the WEEE, European countries are guided by the extended producer responsibility when it comes to the management of solar PV waste (WEEE Directive, 2012). The impacts are analysed using five scenarios as described. Scenario one is no policy in place (panels end up in landfills). Scenario two evaluates the voluntary product stewardship (with 30% of the panels being recycled and the rest going to landfills). Scenario three looks at the voluntary product stewardship (with 50% of the panels being recycled and the rest in landfills). Scenario four identifies the impact categories of voluntary product stewardship (with 70% of the panels being recycled and the rest in landfills). The last one, that is, the mandatory product stewardship highlights the recycling of all the panels under this policy.

Table 7.1: Environmental impacts of various policy scenarios

Impact category	**Unit**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	1E+05	-298.6	-571.4	-844.2	-1E+06
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	4.393	-0.026	-0.046	-0.066	-95.94
Abiotic depletion (Fossil fuels)	MJ NCV	1E+06	-3310	-6418	-9525	-1E+07
Ozone layer depletion (ODP)	kg CFC-$11_{\text{-eq}}$	0.005	-3E-05	-5E-05	-7E-05	-0.104
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	26.72	-0.12	-0.218	-0.316	-463.2
Acidification	kg $SO_{2\text{-eq}}$	1713	-1.511	-3.661	-5.811	-9035
Eutrophication	kg $PO_{4\text{-eq}}$	401	0.2984	0.23	0.161	58.81
Particulate matter	kg $PM_{2.5}$	38.86	-0.31	-0.542	-0.774	-1123
Human toxicity, cancer	CTUh	3E-04	-2E-07	-5E-07	-8E-07	-0.001
Human toxicity, non-cancer	CTUh	0.002	-9E-06	-2E-05	-2E-05	-0.035
Freshwater ecotoxicity	CTUe	3E+08	-2E+05	-5E+05	-8E+05	-1E+09
Ionizing radiation HH	kBq $U235_{\text{-eq}}$	11.7	-13.3	-22.17	-31.04	-44354
Water Scarcity	$m^3H_2O_{\text{-eq}}$	99.07	-1.714	-2.922	-4.131	-5943

- Global warming (GWP100a)

For indicator GWP, the results show values of 1E+05 kg $CO_{2\text{-eq}}$ for scenario 1, -298.6 kg $CO_{2\text{-eq}}$ for scenario 2, -571.4 kg $CO_{2\text{-eq}}$ for scenario 3, -844.2 kg $CO_{2\text{-eq}}$ for scenario 4, and -1E+06 kg $CO_{2\text{-eq}}$ for scenario 5. Scenario 1 shows a significant environmental burden as against the other scenarios. The net environmental benefits for GWP starts with scenario 2 to 5. However, scenario 5, shows a significant environmental benefit. This is significantly high because of the high environmental impacts associated with the disposal of EoL panels in landfills. Disposal in landfills is responsible for high climate impacts.

- Abiotic depletion (elem., econ. reserve)

For ADE, the environmental impacts include 4.393 kg SB_{-eq} for scenario 1, -0.026 kg SB_{-eq} for scenario 2, -0.046 kg SB_{-eq} for scenario 3, -0.066 kg SB_{-eq} for scenario 4, and -95.94 kg SB_{-eq} for scenario 5. There is a significant environmental benefit associated with recycling PV waste as compared to landfilling as shown in the table. Scenario 1 significantly affects resource depletion due to loss of rare and critical metals being sent to the landfill without the opportunity to recycle and recover them.

- Abiotic depletion (Fossil fuels)

For indicator ADF, the results show 1E+06 MJ NCV for scenario 1, -3310 MJ NCV for scenario 2, -6418 MJ NCV for scenario 3, -9525 MJ NCV for scenario 4, and -1E+07 MJ NCV for scenario 5. The net environmental benefit is lower for scenario 2, 3, and 4. The reason for the high environmental benefit for scenario 5 is the credit given to the recycling process as critical minerals goes back into the production process for new solar PV panels. Scenario 1, however, records a very high resource depletion impact which stems from disposing the waste panels in landfills.

- Ozone layer depletion (ODP)

The ODP indicator shows environmental impacts including 0.005 kg CFC-11_{-eq} for scenario 1, -3E-05 kg CFC-11_{-eq} for scenario 2, -5E-05 kg CFC-11_{-eq} for scenario 3, -7E-05 kg CFC-11_{-eq} for scenario 4, -0.104 kg CFC-11_{-eq} for scenario 5. The environmental burdens accounted for in scenario 1 is relatively small. This is due to ODP mainly caused by transportation and chemicals which is mostly related to recycling. These are however accounted for through the credits rewarded to the recovery of the rare metals.

- Photochemical oxidation

The impact category POCP highlights 26.72 kg $C_2H_{4\text{-eq}}$ for scenario 1, -0.12 kg $C_2H_{4\text{-eq}}$ for scenario 2, -0.218 kg $C_2H_{4\text{-eq}}$ for scenario 3, -0.316 kg $C_2H_{4\text{-eq}}$ for scenario 4, and -463.2 kg $C_2H_{4\text{-eq}}$ for scenario 5. Scenarios 1 shows some environmental burdens associated with landfilling the waste panels. The environmental benefit values for scenarios 2, 3, and 4 are relatively close. There is however significant environmental benefit exhibited by scenario 5.

- Acidification

The AP indicator shows values such as 1713 kg $SO_{2\text{-eq}}$ for scenario 1, -1.511 kg $SO_{2\text{-eq}}$ for scenario 2, -3.661 kg $SO_{2\text{-eq}}$ for scenario 3, -5.811 kg $SO_{2\text{-eq}}$ for scenario 4, and -9035 kg $SO_{2\text{-eq}}$ for scenario 5. Sulphuric acid, sulphur oxides, nitrogen oxides and ammonia are the most commonly substances accounted for in AP. They deposited into aquatic and terrestrial environments when their emission to air reacts with moisture in the atmosphere to for acidic compounds. This is clearly seen in the impact category of scenario 1, as it shows a negative environmental impact. The rest of the scenarios show relative environmental benefits with scenario 5 showing a significant net environmental benefit.

- Eutrophication

401 kg $PO_{4\text{-eq}}$ for scenario 1, 0.2984 kg $PO_{4\text{-eq}}$ for scenario 2, 0.23 kg $PO_{4\text{-eq}}$ for scenario 3, 0.161 kg $PO_{4\text{-eq}}$ for scenario 4, and 58.81 kg $PO_{4\text{-eq}}$ for scenario 5. The values for EP, are all negative environmental impacts on humans and ecosystem, even with the full recycling of the PV waste. The is due to the fuel combustion associated with the transportation and recycling processes which releases elements like nitrogen compounds into the air.

- Particulate matter

The impact category for PM includes, 38.86 kg $PM_{2.5}$ for scenario 1, -0.31 kg $PM_{2.5}$ for scenario 2, -0.542 kg $PM_{2.5}$ for scenario 3, -0.774 kg $PM_{2.5}$ for scenario 4, and -1123 kg $PM_{2.5}$ for scenario 5. PM is mostly influenced by transport and other supply chain processes. Scenario 5 shows an environmental benefit which is relatively small. Transport accounts for a very high environmental burdens from recycling process.

- Human toxicity, cancer

The impact category HTC includes, 3E-04 CTUh for scenario 1, -2E-07 CTUh for scenario 2, -5E-07 CTUh for scenario 3, -8E-07 CTUh for scenario 4, and -0.001 CTUh for scenario 5. The impact of chemicals is very relevant considering how their fate and exposure may affect humans and the environment. The most burden on the environment is recorded by scenario 1 whiles scenario 5 show a net environmental benefit under HTC.

- Human toxicity, non-cancer

For HTN the indicator shows, 0.002 CTUh for scenario 1, -9E-06 CTUh for scenario 2, -2E-05 CTUh for scenario 3, -2E-05 CTUh for scenario 4, and -0.035 CTUh for scenario 5. The effects of HTN are highly influenced by the recovery of glass, copper, and semiconductors. This is represented in the scenario 5, which has a lower net environmental benefits compared to to scenarios 2, 3 and 4. The exhibition of a lower value for scenario 1 is justified even thou, the environmental impacts are negative.

- Freshwater ecotoxicity

For FET the environmental impacts include, 3E+08 CTUe for scenario 1, -2E+05 CTUe for scenario 2, -5E+05 CTUe for scenario 3, -8E+05 CTUe for scenario 4, and -1E+09 CTUe for scenario 5. The main negative contributor to FET is waste disposal. Scenario 1 records a high environmental impact. However, there are similarities among scenario 2, 3, and 4 as they show relatively similar values. Scenario 5 has the highest environmental benefits among the rest.

- Ionizing radiation HH

The IOR impact category values include, 11.7 kBq $U235_{-eq}$ for scenario 1, -13.3 kBq $U235_{-eq}$ for scenario 2, -22.17 kBq $U235_{-eq}$ for scenario 3, -31.04 kBq $U235_{-eq}$ for scenario 4, and -44354 kBq $U235_{-eq}$ for scenario 5. The environmental burdens recorded are associated with scenario 1. Scenario 5 reports some environmental benefits associated with recycling of the waste panels.

- Water Scarcity

The indicator WS shows, 99.07 $m^3H_2O_{-eq}$ for scenario 1, -1.714 $m^3H_2O_{-eq}$ for scenario 2, -2.922 $m^3H_2O_{-eq}$ for scenario 3, -4.131 $m^3H_2O_{-eq}$ for scenario 4, and -5943 $m^3H_2O_{-eq}$ for scenario 5. The environmental impact of scenario 1 is very high considering the other scenarios. Accessibility to freshwater is very important for human health and ecosystem. Even thou the other scenarios highlights environmental benefits for recycling most of the panels, there still remains a question of preventing chemicals from recycling and leaching from landfills into freshwater bodies.

7.4.1.1 No policy in place (ends up in landfilling)

The amount of waste improperly disposed into landfills needs to be minimised to prevent the leaching of toxic substances such as cadmium and lead into soils causing detrimental impacts on human health and the environment. This will also aid in the recovery of rare metals from the panels avoiding the loss to landfills (Masoumian & Kopacek, 2015). Compared to the other policy options, this scenario assumed all the solar panels generated annually were going to landfill.

The global warming potential for full landfilling for both the mono and multi crystalline silicon models were very high (1E+05 kg CO_{2-eq}) compared to the voluntary (-298.64 kg CO_{2-eq}) and mandatory (-1E+06 kg CO_{2-eq}) approaches. The significant change between the options gives a clear indication of the severe impacts of the EoL panels going to landfills. This is made more prominent in the eutrophication (401 kg $PO_{4\text{-eq}}$), human toxicity-cancer effects (3E-04 CTUh) and freshwater ecotoxicity (3E+08 CTUe) of the landfill option and how severe its impacts are on the environment. The results are peculiar to this study because of the different nature of this study compared to other studies (Ardente et al., 2019; Dias et al., 2021; Latunussa et al., 2016; Lunardi et al., 2018).

7.4.1.2 Voluntary regulatory approach (percentage to recycling and landfill)

A voluntary program such as the PV CYCLE created in the year 2017, was committed to the enforcement of the WEEE regulations taking responsibility to collect and recycle solar PV waste in Europe (Padoan et al., 2019; WEEE Directive, 2012). Voluntary approach towards the management of PV waste does not critically mandate the recycling and recovery of PV waste in the country. Blake et al. (2019) posits that, voluntary approach to regulating e-waste was not the best and recommended the use of a mandatory product stewardship (MPS) or an extended produce responsibility (EPR).

This study as discussed in chapter 6 has compared the voluntary product stewardship (VPS) to the MPS to identify the regulatory policy with the least environmental impact when it comes to the management of solar PV waste. The results revealed that, the MPS had a lesser impact on the environment to the VPS. The global warming potential for the VPS was -298.64 kg $CO_{2\text{-eq}}$) and the MPS around -1E+06 kg $CO_{2\text{-eq}}$. The negative sign shows the credits achieved through the use of the recovery materials back into the production process. Even thou the VPS is beneficial compared to full landfilling (1E+05 kg $CO_{2\text{-eq}}$) for both mono and multi crystalline silicon panels, the MPS was the best choice out of the three.

7.4.1.3 Mandatory approach (full recycling and recovery)

Extended producer responsibility is seen as the best regulatory approach as it allows for the full recovery of solar PV panels. Australia is expected to deliver a policy management regulation on EoL PV in the year 2023 (Majewski et al., 2021). The detail of the policy is still under discussion. The right information and assessment are needed for government to make the right choice towards the implementation of this policy. With a full recovery process, carbon dioxide could extensively reduce lessening the negative impact of the waste stream on the environment (Chowdhury et al., 2020). Moreover, this will require a comprehensive assessment of the processes and different options to make an informed decision.

The recycling process of the mono and multi crystalline silicon panels revealed a more sustainable option compared to the others. The global warming potential (-1E+06 kg $CO_{2\text{-eq}}$), ozone layer depletion (-0.104 kg CFC-$11_{\text{-eq}}$), eutrophication (58.81 kg $PO_{4\text{-eq}}$) particulate matter (-1123 kg $PM_{2.5}$) human toxicity-cancer (-0.001 CTUh) and freshwater ecotoxicity were all relatively better in terms of the impacts on the environment and humans as compared to the VPS and full landfilling. These results consider the credits allocated to the recovery of raw materials throughout the process. The results confirm the positive impact of recycling especially when all panels are regulated through mandatory product stewardship.

7.4.2 The influence of transport on the recycling of EoL PV in South Australia

To get a more accurate results on the recycling processes. An optimised holistic reverse logistic network was developed for the transportation of PV waste from transfer stations across South Australia to the recycling centre. Previous studies on life cycle assessment (Dias et al., 2018; Latunussa et al., 2016; Lunardi et al., 2018) lacks the inventory data on the transport distances covered by the PV waste to the recycling plant. This research developed the distances covered by the PV waste from transfer stations to the recycling centres as well as optimising the process to reduce the emissions that comes with. This is necessary because of the significant influence of transport on the life cycle assessment of solar PV waste recycling.

An analysis was conducted on three different scenarios for the LCA. The travel distances were estimated in Chapter 5 for the assessment. The baseline scenario which required trucks to collect waste from all transfer stations to the recycling centre was the worst scenario with significant impact on the recycling process. The GWP for the baseline scenario, scenarios two and three were 1E+06 kg $CO_{2\text{-eq}}$, 5E+05 kg $CO_{2\text{-eq}}$ and -28722 kg $CO_{2\text{-eq}}$, respectively. The third optimal reverse logistic proposal produced less environmental impact. Developing an optimal logistic network has the potential to reduce environmental impacts through the reduction of transport distance in the network (Molano et al., 2022). The impact of the process may also change according to the method of transportation (Lunardi et al., 2018). This should be emphasised as this study used two different trucks for the analysis.

7.5 Recommended strategies (policies and practices) for managing EoL PV in South Australia

There are eleven policy strategies and management practices that are recommended based on the findings from Chapter 2, 4, 5 and 6 of this study to manage EoL PV modules in Australia. The national, state, and local government may bare some responsibilities when it comes to the treatment of solar PV waste in Australia. Again, other PV waste stakeholders such as manufacturers, recyclers, distributers, installers, and consumers will be subject to any policy and regulatory effects and should be aware of the management practices associated with solar PV waste.

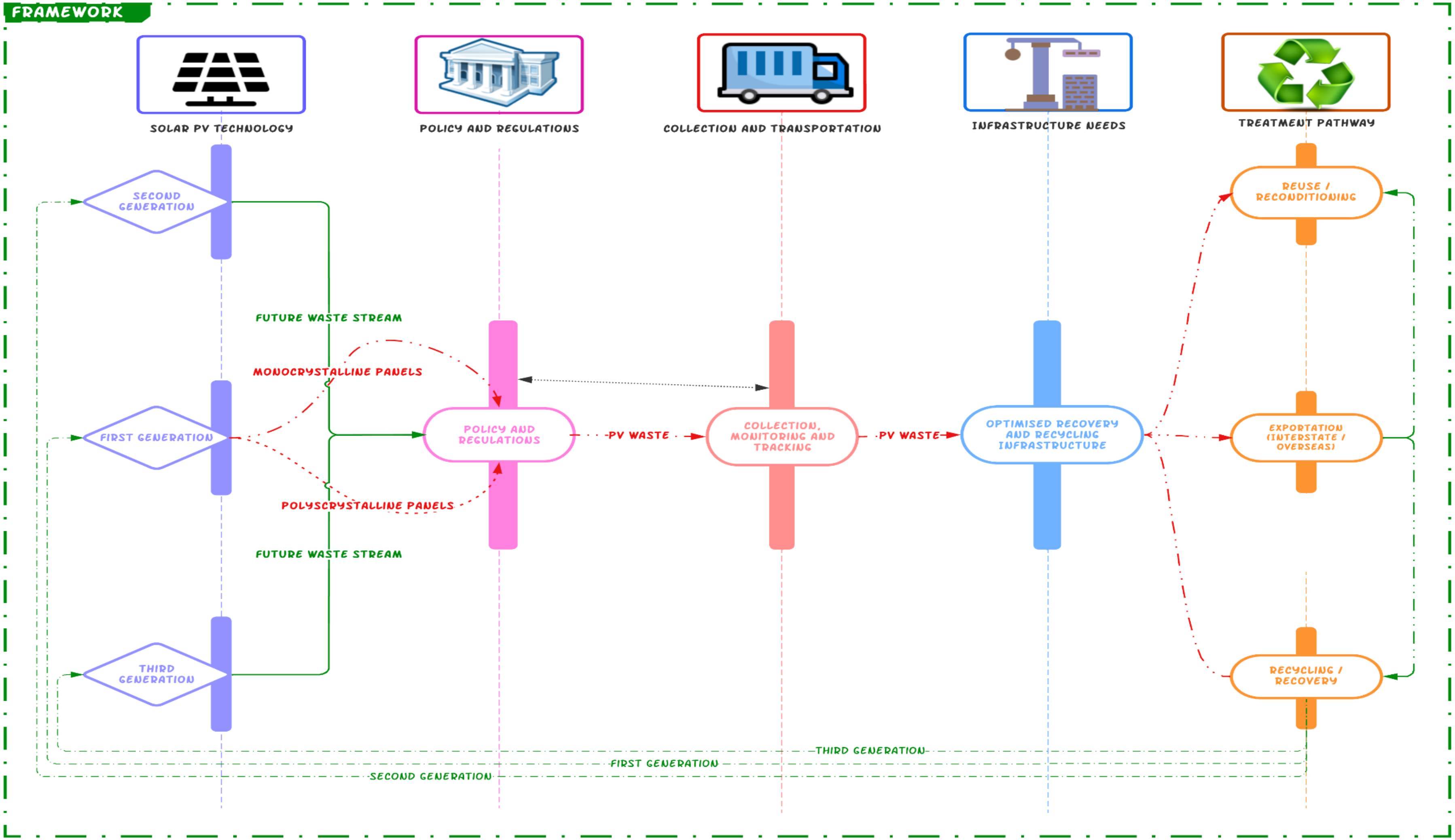

Figure 7.1: recommended practical framework for EoL PV management

Managing the supply market of solar PV technologies

The recommended establishment of a monitoring and tracking scheme to identify the solar panels from manufacturers, installers, and importers highlighted in Chapter 4, will aid in monitoring the movement of PV waste modules from installation to end-of-life. Several solar PV modules in Australia are imported into the country. Therefore, the state should establish means for producers to register and trademark their products for easy tracking and identification from installation to end-of-life. Establishing legislative decrees should not only consider the manufacturers in the country but the importers and suppliers of the panels from other countries as well. There should be material passports (such as materials used, module types) and standardised labelling to make panels easier to sort for effective recovery process when it reaches the end-of-life.

Creating collection centres for EoL PV modules in South Australia

Based on the finding from chapter 4, there are no collection centres available for EoL solar PV modules in South Australia. It is revealed that, the "*whichbin*" initiated by Green Industries SA does not provide a bin for the collection of EoL solar PV modules. Consumers are referred to their councils or installers to deal with the waste. Companies like Reclaim PV collect EoL PV for recycling, but you have to call for their services. The local councils should provide central EoL PV collection and sorting centres or transfer stations for consumers. This is a good step in the right direction towards an optimised reverse logistic network.

Developing a logistic network to for the collection of EoL PV modules

According to the optimised reverse logistic network developed in Chapter 5, transport distance is severely reduced when an optimised approach is adopted. This also reduces carbon emissions associated with transporting EoL PV from transfer stations to recycling centres. The best way to reduce carbon footprint is to create an optimised central collection point. Moreover, collection can be managed through distributors or installers where the PV panels were purchased. The state should develop an efficient reverse logistic network for the collection, transporting and recycling of solar PV waste modules.

- *Creating and enhancing the PV recycling market for recovered materials*

Chapter 4 highlights the need for Australia to recycle and recover precious metals from EoL PV modules. According to the survey, the PV recycling market was good but not perfect. Materials like glass and aluminium already has a relatively good market in Australia. However, there need to be a high value recycling approach to deliver high end recycled materials from the solar panels to make it better for the market. The legislations could be introduced that requires the need to use a percentage of recycled materials, so to create market for recycled EoL PV materials.

- *Issuing a regulatory landfill ban for EoL solar PV module in South Australia*

Based on the results from Chapter 4, most PV waste are currently landfilled. This is because of the absence of a regulatory and policy direction in South Australia. A legislative decree should be issued, mandating the banning of PV waste going into landfills. This will create avenue for recyclers to collect and stockpile the panels for recovery.

- *Developing a mandatory product stewardship for PV waste in Australia*

This study as discussed in Chapter 6, suggests the implementation of hard-line policies by the government that mandates manufacturers, installers, and importers to collect and recycle their solar panels after its end-of-life. The introduction of the PV waste stream in the annual priority product list under the product stewardship act is a good step by the government in establishing a product stewardship for the waste stream. The ongoing attempt to introduce a product stewardship for the management of solar PV waste, can learn from the findings of this study. legislation should be enacted to require producers (installers, distributors, manufacturers etc) to operate their own take-back system under an extended producer responsibility for EoL PV modules. Important responsibility should be placed on producers to recycle their own PV waste under a mandatory product stewardship. Australia is aiming to implement a National Product Stewardship for PV systems by June 2023, led by the Product Stewardship Centre for Excellence who have been working on this scheme for some time.

- *Promoting and providing financial incentives to current and future infrastructure for PV recycling*

Based on the findings from Chapter 4, there is only one recycling company in South Australia that collects PV waste for recycling. The company is still developing effective treatment processes as discussed in Chapter 6, to aid the recycling of the already accumulated waste panels at their warehouse. The state can aid financially by supporting the company with enough capital for various recycling machinery. The state can also build the capacity of the recyclers to efficiently recycle the PV waste.

- *Minimising the exportation of PV waste overseas and interstate*

The exportation of discarded PV panels is predominant in South Australia as confirmed in the discussion from Chapter 4. There are individuals who collect these discarded panels and export them overseas, sometimes without even testing them. This creates a new waste problem for the new destination of the panels if appropriate recycling opportunities are not present there. There is therefore the need to enhance the possibility of reuse and repairs of used PV panels by improving circularity and minimising illegal exports.

- *Encouraging industry led research on new innovations to improve the recovery of different PV technology families*

Based on the results from Chapter 5, the emission from the recycling process was significant. Chapter 6 also emphasised on the dominance of the first-generation PV panels. There is therefore a lot of research on recycling the first-generation panels. However, the recycling process could be improved, and new processes developed for new PV generations. The state should collaborate with industry and research institutions to develop innovative and cost-effective approaches to recycling current and future EoL PV technologies. This will improve the revenue for recycled materials and decrease the cost of recycling.

- *Developing sustainable measures to cut emissions for recycling through research and development in South Australia*

According to the findings from Chapter 6, there are a lot of burdens that comes with recycling of PV waste. The highest emission is associated with the transport covered by trucks. There are chemicals used in the recycling process that are also harmful to the environment. The state should invest in green supply chain and harmless treatment recycling processes through research and development.

- *Build the capacity and promote awareness on the benefits of PV recycling*

The diversion of solar PV waste from landfill are achieved if consumers and the industry understand the benefits thereof. Chapter 4 highlights the non-participation of industry when it comes to the collection and recycling of PV waste, which was delivered by some industry participants. There is a lack of knowledge on where and how to dispose of EoL PV modules. The state should create public awareness and training for consumers and build the capacity of industry to increase the rate of participation and help divert panels from landfills.

7.6 Chapter Summary

The chapter discussed the results from the previous chapters in light of existing Australian and global scholarship. The first section looked at the current practice of solar photovoltaic waste management in Australia, through the identification of experts and culminating in the establishment of a conceptual framework for the study. The main highlight under the discussion is the currently improper disposal of PV waste panels in landfills even with the mandated regulatory ban of PV waste to landfills. The second section explained the optimal reverse logistic network developed for the transport of solar PV waste to recycling centres in South

Australia. The last discussion established the policy option that had less environmental impact considering the waste management currently in place and what it could be in the years to come.

Chapter 8. Conclusions

The need to develop a policy on PV waste has never been greater. Previous chapters have presented the necessary options taken to develop an effective evaluation of the impacts of treating solar PV waste In South Australia. This chapter summarises the findings of the previous chapters and addresses the contribution and limitations of the study.

This chapter consists of four sections. The first section revisits the research objectives and present the main findings under each objective including how they were achieved in the study. The original contributions to the theory and practice of PV waste management are described in the second section. The limitations of the study are presented with future research opportunities in the third section. The last section gives a closing remark on this thesis.

8.1 Revisiting the research objectives

This study is conducted to ascertain the environmental impacts associated with the management of solar PV waste in Australia. Literature suggests that by 2050, 200 times as many rooftop solar panels as today will come to their end-of-life. Such significant relatively new waste stream contains hazardous substances and should be prevented from going to landfills. However, to date, there is no active regulatory policy on how to manage EoL solar photovoltaic panels in Australia. Moreover, there is a lack of monitoring and inventory data to assist government and industry practitioners on the appropriate disposal of the PV waste stream. Therefore, this study aimed to assess the environmental impact of rooftop solar photovoltaic waste management practices in Australia. The outcome of each objective under the research aim are presented below:

8.1.1 Objective 1:

To explore the current practices of managing end-of-life rooftop solar photovoltaic panels in Australia.

There has been on-going research on end-of-life PV waste management in the literature. Especially the generation of the waste to recycling practices across the globe. However, a gap still exists on the national and regional management of this waste stream because of the different characteristics associated with each region. In Australia, there have been recent studies on the management of PV waste, but these studies lack the focus on monitoring, transport, and treatment pathways for rooftop solar photovoltaic panels.

Applying a comprehensive methodology (presented in Chapters 2 and 4), this study has explored the various technologies related to solar photovoltaic panels, examined the alternative strategies and initiatives of EoL treatment pathways, and develop an assessment framework for managing end-of-life solar photovoltaic panels in South Australia.

The findings revealed that, the first-generation technology including monocrystalline and multi-crystalline silicon-based panels were the most installed panels in Australia and are the ones flooding the e-waste stream in the next 20 to 30 years. In relation to policies and regulations, participants were not aware of any policy or product stewardship which was currently in operation to regulate the management of the PV waste in Australia. Nonetheless, a few were aware of the national ban of solar panels to Australian landfills. A further probe revealed that, the ban did not stop individuals from dumping PV waste in municipal waste bins that ended up in landfills.

The main reason for the inappropriate dumping of PV waste into landfills was the lack of monitoring and tracking of the panels as implemented in other countries mostly in the European

Union. The ineffective tracking, collection, and transport of PV waste from waste sources to authorised treatment stations are some of the findings from the survey.

The unavailability of proper infrastructure to treat the PV waste was also a major issue. Many companies are now developing effective treatment options for the EoL panels that may need support from national and state government. Finally, there was a consensus from most of the experts on the best treatment pathway for Australia: Recycling of the panels will help deviate toxic substances from the landfills and produce secondary materials for the PV recycling market. Consequently, a framework was proposed to address proper environmental assessment of the recycling and landfill processes through the lens of current and proposed policy options.

8.1.2 Objective 2:

To develop an optimised system approach in dealing with solar photovoltaic waste in Australia.

A great deal of managing EoL PV modules is associated with the collection, movement and reverse logistic network of the treatment process. Several researchers have confirmed the need to properly estimate the distances covered when treating solar PV waste as it contributes significantly when conducting a life cycle assessment of the recycling process. Again, knowing the specific amount of generated PV waste to be treated is very essential. Existing scholarship attests that, conducting case studies for particular treatment processes is the best option to gather inventory data for accurate analysis. Australia has the highest users of rooftop solar photovoltaic panels in the world. With the first manufacturers and recyclers of solar PV waste situated in South Australia. The State became the best case to study for this research.

A robust and comprehensive methodology (see Chapters 3 and 5) was adopted to quantify the amount of waste generated from the decommissioning of rooftop solar photovoltaic panels, to investigate the influence of reverse logistics and infrastructure needs on the management of solar PV waste. Furthermore, it optimises a system network for the collection and transport of EoL rooftop solar PV panels for recycling and recovery in South Australia.

Primary data recodes and projections revealed that, around 1009,007 tons of PV waste would be generated in the next 30 years using the postcode installations of solar panels across South Australia. Suburbs such as Wyomi; West Range; Wangolina; Tilley Swamp; Taratap; Sandy Grove; Rosetown; Reedy Creek; Pinks Beach; Mount Benson; Kingston SE; Keilira; Cape Jaffa; Boatswain Point; and Blackford recorded the highest PV waste generation in the coming decades. These suburbs can become the hotspots for solar PV waste generation. It is imperative to develop a network for the transport of the generated waste from the suburbs to an appropriate treatment centre.

Using the recycling centre Reclaim PV as the treatment centre and 107 transfer stations across South Australia as the case study, an optimised system was developed to reduce the transport distance of trucks from the transfer stations to the recycling plant. The results show that, the second optimised network that is the scenario 3 covered a lesser distance culminating to a 30% reduction in pollutant emission compared to the baseline scenario and scenario 2. The analysis created an inventory data for the environmental life cycle assessment.

8.1.3 Objective 3:

To assess the environmental impacts of end-of-life rooftop solar photovoltaic panels in Australia within the developed assessment framework.

The influence of solar PV waste on the environment is important because of the health and environmental issues associated with its disposal and recycling. Extensive literature has been conducted on the environmental impacts of PV waste on the recycling and landfilling scenarios, but none captures the contextual transportation issue (mostly assumed fixed values) and policy.

Moreover, because of the spread of population centres and different characteristics associated with regional areas, the situation in Australia is quite different from that of other countries.

The lifecycle assessment boundaries developed through the fuzzy Delphi methodology in Chapter 4 and extended to the transport logistics in Chapter 5 is adopted to assess the environmental impacts of rooftop solar PV waste in South Australia. Specifically, Chapter 6 looks at comparing the environmental impacts of different policy options in the management of end-of-life solar photovoltaic panels, investigates the environmental influence of transport on the recycling of end-of-life solar photovoltaic panels, and provides policy suggestions for the management of solar photovoltaic waste in Australia. The data for the analysis was collected from background and foreground data sources such as, expert interviews, field study, literature review, Australian lifecycle inventory datasets, and the ecoinvent database found in the SimaPro software.

The two technologies mono and multi crystalline silicon based solar panels were used for the lifecycle analysis. Results show the impact of the different policy options which are no policy (full landfilling), voluntary product stewardship (percentage of waste going to landfill and the rest to recycling) and mandatory product stewardship (full recycling) on the environment. The full recycling option showed a great improvement on the impact on the environment compared to the voluntary and no policy approach. There is a significant variation in environmental impact (For indicator GWP, the results show values of 1E+05 kg $CO_{2\text{-eq}}$ for scenario 1 which is an environmental burden against scenario 5 showing a value of -1E+06 kg $CO_{2\text{-eq}}$ which is identifies environmental benefits from the recycling process) which highlights the preferred option that can promote a sustainable PV treatment pathway for South Australia.

The results from Chapter 5 are used as inventory data to calculate the impact of the optimised reverse logistic network on the environment. It is posited that the optimised system especially the optimised transfer station with an addition recycling centre (scenario 3) leads to a significant decrease in all the environmental impact categories (GWP -28722 kg $CO_{2\text{-eq}}$; ADE -81.725 kg $SB_{\text{-eq}}$; ADF 1E+07 MJ NCV; ODP 0.1501 kg CFC-$11_{\text{-eq}}$; POCP -750.16 kg $C_2H_{4\text{-eq}}$; AP -13106 kg $SO_{2\text{-eq}}$; EP 1662.3 kg $PO_{4\text{-eq}}$; PMF -1906.7 kg $PM_{2.5}$; HTC 0.0149 CTUh; HTN 0.0167 CTUh; FET 1E+10 CTUe; IOR -97796 kBq $U235_{\text{-eq}}$; and WS -5731 $m^3H_2O_{\text{-eq}}$) as compared to the other two. The study therefore recommended the use of a mandatory product stewardship approach in South Australia and adopt the optimised reverse logistic network in achieving a sustainable waste management policy in the state.

8.2 Contributions of the research

The study has contributed both theoretically and practically to the end-of-life solar photovoltaic research field. The theoretical implications of this research leans towards the broader PV waste literature and sustainable perspective on the management of the waste stream. The development of an innovative methodology to optimise the logistics network contributes to distance calculation for recycling processes in lifecycle analysis. Practically, it provides recycling practitioners with the knowledge of the generated waste in the coming years and how to approach it. In addition, it provides a sustainable policy pathway for national and state government on how to effectively manage the PV waste stream through the introduction of hard-line product stewardship approaches. This also creates a heathier environment for the public through the application of the results from the study.

8.2.1 Theoretical contributions

This research contributes to the body of knowledge on solar PV waste management. Existing literature has discussed PV waste from the lens of waste flow, environmental assessment, recycling of different technologies, and leaching of materials into landfills. In Australia, other researchers have investigated the waste generation and impact assessment without incorporating the local factors that contributes the results of the impacts especially the transport distance and the influence of current and future policy in the management of the PV waste stream. This study is the first to develop a conceptual framework through expert opinions on the current practices of PV waste in the country and developing a holistic logistic network for the transportation of PV waste.

Secondly, the methodological contribution of this study lies with the innovative approach in developing a reverse logistic network for the management of PV waste from transfer stations to recycling centres around the country. The methodology offers an innovative way for researchers to use to develop contextual logistic network for the management of PV waste in other states in the country.

Thirdly, the study provides primary inventory data for life cycle assessment. The study develops fundamental primary data from field studies and expert interviews on a pilot plant in South Australia for the analysis. The data collected can serve as a dataset for other studies. The transported distance estimated offers real inventory data for the calculation of environmental impacts from recycling process, which is the first of its kind. This allows to inculcate transport distances to the EoL recycling process for LCA analysis.

8.2.2 Practical contributions

First and foremost, the practical recommendations of various stakeholders involved in the management of solar PV waste in Australia provides potential policy suggestions for government departments on the best policy pathway for the treatment of solar PV waste in Australia. It generates a forecast in the next three deacades how the solar PV waste stream will behave in South Australia to aid in the development of a waste management plan for the state and the country.

In addition, the data provided for the environmental impact assessment can aid the state and local governments, and other stakeholders to forecast other impacts such as economic feasibility and social impacts that comes with choosing any of the policy options. The data provides a detailed inventory for the assessment of recycling and landfilling scenarios by government departments to help in waste prevention strategies to protect the environment and human health.

Lastly, the information provided serves as knowledge database for recyclers to plan their collection routes to minimise environmental emissions. It provides manufactures and suppliers with necessary information on how best to manage their installations and whether future operations like recycling can boost their sales, and how the enacted policies may affect them when it comes into force.

8.2.3 Global and national implications and generalisation

On a national scale, the results of this study can serve as a guide for policy makers to process the introducing of a product stewardship scheme for Australia.

- The methodology can serve as a way to estimate the PV generation in other states and develop an optimised reverse logistic network for recycling.
- Data from the research can serve as inventory data for other recycling plants across the country when conducting LCA on solar PV waste in Australia.
- The development framework extends beyond South Australia and can be used a system boundary for the assessment of environmental impacts on end-of-life solar PV modules.

Globally, this research is the first of its kind when it comes to the development of an optimised system network for a particular locality using postcode data and GIS. Several studies across the globe when conducting LCA assumes specific distances from the waste source to the recycling centre. This study bridges that gap by using an estimated regional transport distance in the LCA simulation within the solar PV waste recycling processes.

Due to relative similarity in standards, manufacturing, usage, transportation, and cost in South Australia to other states, the result of the study may extend to all other states including Australia Capital Territory, New South Wales, Victoria, Queensland, Western Australia, Norther Territory and Tasmania). However, spatial care has to be taken regarding availability of local or national collection centres, their practice norms and state regulatory barriers and intensives.

8.3 Limitations and suggestions for future research

There are limitations to this research driven from the nature of this study:

- First of all, due to the limited resources and budget and to some large extent the impact of the Covid-19, the field study was only conducted in South Australia using one recycling plant as a case study. This however was compensated with online communications with other recyclers from other states to make an inform decision on the data to collect for this study. it is suggested that future studies can compare different processes from other recycling plants in the other states to suggest alternatives.
- Secondly, the development of the reverse logistic network considered only trucks as the means of transport for this study. Other transport options may have different impacts on the environmental emissions. Using an electric vehicle, trains, or plane may have a different result to what has been established. In the future, a more sustainable means may be adopted for the assessment of the environmental emissions.
- Finally, the recycling plant used for this research was at the pilot stage of testing its recycling processes. Therefore, data from literature and the Ecoinvent database were used to support the inventory data for the life cycle assessment. The life cycle assessment can be undertaken again after the plant goes on full recycling scale.

- Moreover, the economic and social aspects of the chosen options may be conducted to get a full picture of the impacts associated with the treatment of solar PV waste in Australia.

8.4 Closing remarks

To conclude, this study stems from the need to manage the increasing volume of solar PV waste in Australia and around the world. It is imperative that we understand the growth of PV waste generation in the coming years to make an informed decision on their disposal. The toxic and hazardous substances found in PV waste requires the appropriate disposal or treatment of the waste stream, to prevent health and environmental issues due to leaching of the materials into the soil. Australia has defined PV waste under the WEEE and has banned all end-of-life solar panels from sending to landfills. However, this ban does not appropriately regulate the management of the waste stream. This has resulted in illegal dumping of the panels into the landfills. Effective policies should be enacted and implemented to curb the increasing dumping of end-of-life solar panels into the landfills as these may create environmental and health effects when they leach into the ground soil and water. This study suggests the development of a mandatory product stewardship to control the monitoring and movement as well as the treatment of solar PV waste in South Australia and Australia in general.

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Appendices

Appendix A – Manuscript: A scientometric review of trends in solar photovoltaic waste management research

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A scientometric review of trends in solar photovoltaic waste management research

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ABSTRACT

Solar photovoltaic (PV) systems, are effective measures to reduce the greenhouse gas emissions related to the generation of power. However, the large exploitation of solar PV modules, leads to undesirable waste accumulation, impacting the environment. Solar PV waste management research is an emerging field which has received more attention recently, affected by the increase volume of solar PV disposal. However, only a few studies have reviewed the current trends in solar photovoltaic waste management. This study reviewed the emerging trends in solar photovoltaic waste management research from 1974 to 2019 using the scientometric review techniques. A total record of 4683 articles were retrieved from the Web of Science database on solar PV waste. The co-word, co-citation and co-author analysis of the retrieved articles were conducted to determine the emerging trends in the PV waste management research. The results revealed that, with a gradual growth in the PV waste management research, performance and efficiency of polymer solar cells have been the centre of recent research due to its light weight, flexibility, environmentally harmless materials and lower cost over the silicon based solar cells. However, it will be years before they are ready for commercialization for specific applications. Thus, the silicon-based modules are the most installed to date and will be coming to their end-of-life very soon. The results also show that, little attention was given to areas like recycling, recovery, policies and regulations on solar PV module waste management. Future research should focus on assessing the recycling potential and emissions from current solar PV modules and the easy remanufacture, recovery and reuse of future solar PV modules.

1. Introduction

Photovoltaics is a renewable source of energy that converts solar radiation to electricity, which provides a perfect alternative to traditional fossil fuels as the world transitions to a renewable energy-based economy. The application of this technology has been in existence since the 1980s, but the 1990s has been recorded as the year of the first appreciable application of power from solar photovoltaics (Padoan et al., 2019; Tao and Yu, 2015). Solar energy is non-polluting, efficient, reliable and safe. There is a global interest recently in solar energy particularly PV technology. This has seen the use of solar PV modules climb sharply because of government's effort to achieve clean energy globally. PV technology is to become one of the main energy sources worldwide because of its expectation to significantly produce a portion of the world's energy consumption (Xu et al., 2018).

The awareness of the effects of greenhouse gas emissions has trigged an upsurge in the need for clean energy. The need is much evident in the current drifts into photovoltaic installation. The International Energy Agency in their 2021 preliminary market report, revealed that the global market for PV grew significantly despite the COVID-19 pandemic. This shows an installation of at least 139,4 GWdc of installed and commissioned PV systems worldwide last year. They further reported that, the relative global capacity has cumulatively reached 760,4 GWdc at the end of 2020 (IEA-PVPS, 2021). The use of Photovoltaic power generation can be considered a favourable technology because it can be used at any location to produce clean energy (emission free) during the day and night times if the power system has some storage technology incorporated in it. The implementation of the PV technology is being promoted by some governments from a worldwide perspective. These governments incorporate the use of incentives and target setting in making PV technology occupy a significant proportion of their energy needs (IEA-PVPS, 2017).

The application of PV system for solar energy becomes a viable choice for power production to decrease greenhouse gas (GHG) emission

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and life cycle energy use. Studies have identified that an abuse of this could however lead to unwanted environmental impacts in relation to disposal of waste and material availability (Fthenakis, 2004; Fthenakis and Moskowitz, 2000; Kannan et al., 2006; Nieuwlaar et al., 1996; Phylipsen, 1995). The exponential increase in the PV panel waste is anticipated to reach over 60 to 70 million tonnes by 2050 (Ardente et al., 2019; IRENA and IEA-PVPS, 2016). Moreover, PV modules contain dangerous materials that poses serious human health risk as well as risk to the environment (Mahmoudi et al., 2018). These dangerous materials can be found in PV modules such as Copper Indium Gallium Selenide (CIGS) which contains Cadmium (Cd), Lead (Pb) and Selenide (Se); Cadmium Telluride (CdTe) which contains Cd and Pb; and Crystalline Silicon (c-Si) which contains Pb (IRENA, 2016; Bang et al., 2018; Podoan et al., 2019; Mahmoudi et al., 2021) Workers who are exposed to these harmful waste materials and gases such as poly/brominated flame retardants, heavy metals, and Chlorofluorocarbons (ozone depleting carbons) are prone to severe health impacts, where some wider population may be affected by the exposures as well (Fiandra et al., 2019). The production of semiconductors springs up the most heath concerns in solar panel use because it contains potentially dangerous materials (Moss et al., 2014). Moreover, hazardous wastes are generated by the panels after their useful life which is also another environmental problem. Due to their life expectancy of 25 years, the reuse and recycling of these panels was not of much concern at the development stages, but, presently, an appreciable number of these already installed solar panels are entering their end-of-life stage. Therefore, an effective management of these retiring panels are now becoming an environmental issue of much concern (Aman et al., 2015; Xu et al., 2018).

1.1. *Knowledge gap and research objectives*

Photovoltaics is a broad research area because of its multidisciplinary application in various research fields. However, previous reviews on photovoltaics has leaned towards general application, capacity building and recycling. The waste management and end-of-life aspect is an emerging field and has received little attention when it comes to reviews, a gap this research tends to bridge. Solar panel waste recycling status by Xu et al. (2018) discussed the processes of the retrieval and dismantling of waste solar panels with an in-depth discussion of various recycling techniques and methods. Another review by Sica et al. (2018) addressed the end-of-life management of PV modules focusing on technology, life cycle, production, environmental issues and their end-of-life explained into details. The study ended with suggestions and future directions on how the PV industry is becoming a big player in circular economy and how it is being shaped through the lens of natural systems in providing services and goods. Both studies adopted a qualitative review of the literature without necessary going through database searches.

Similarly, a review by Salim et al. (2019a) highlighted drivers, barriers and enablers of battery energy storage and photovoltaic systems when it comes to their end-of-life. They identified some drivers clustered under economic, social and environmental. The barriers were also grouped under policy and economic, recycling infrastructure, environmental, market and social clusters. With the final which is the enablers falling under recycling technology and infrastructure, behavioural, policy and economic, market and social. A discussion of the current research trend was also highlighted, finally ending up with the development of a conceptual framework for solar energy systems when it comes to the circular supply chain. The study was limited to the years 2000 to 2018. In a recent systematic literature review carried out by Mahmoudi et al. (2019a), they discussed the trend analysis, bibliometric details and treatment procedures of end-of-life PV modules. Their review considered all published research available in Web of Science (WoS), Scopus and Science direct upto 2018. With both using the WoS database in addition to Scopus and Science direct respectively.

Moreover, Salim et al. (2019a) and Mahmoudi et al. (2019a) analysed 817 and 70 journal papers respectively as compared to the number of papers that is used in this study (4683 articles). Most importantly, waste and end-of-life solar PV panel management research is an emerging field and needs to be constantly reviewed as new articles emerge (Xu et al., 2018; Chowdhury et al., 2020; Mahmoudi et al., 2021). Furthermore, none of the previous studies on solar photovoltaics and waste have mapped out the co-author relationship and analysis linking authors and their institutions. Again, these studies have not further studied into details the co-citation, co-author and co-word analysis. This research is relevant because, bibliometrics review using the aforementioned analysis is a valuable complement to traditional ways of reviewing literature, thus, it creates more understanding through the relationship that exists (Fonteyn et al., 2020) within the full structure of the solar PV waste research domain. It presents a broader perspective on solar PV through the collaborative ties that links various researchers within the domain, links and maps out similar research elements as well as identifying information flow and influential researchers within the field of solar photovoltaics research.

From the above, this study differentiates itself by bridging the gap in literature on solar PV waste research through scientometric analytical review. This study provides an in-depth understanding of the current research trend on solar photovoltaic waste research through all the years till now. It also identifies future research agenda and the gaps in literature. It aims at highlighting the emerging trends of solar photovoltaic waste research through i) co-word analysis, ii) co-citation analysis, and iii) co-author analysis using the retrieved data from the WoS database.

This paper consists of five sections: The *first* section gives an introduction and the reason for the research as previously explained. The *second* section explores the methods that is adopted in analysing the study. The selection of the database, keywords and tools as well as the scientometric techniques used are explained in this section. The *third* section describes the analysis and the results from the research. It discusses the co-word, co-citation and co-author analysis of the study. The discussion of the results is elucidated in the *fourth* section of this paper. The *last* section finally lays down the conclusions.

2. Methodology

Data analysis in this paper is based on the science mapping methodology. According to Chen (2017), science mapping represents a “generic process” of domain analysis and visualisation. This process includes several components within a scientific literature that enables the exploration and interpretation of significant trends and patterns highlighted by visual and scientometric analytical indicators, metrics and tools. Bibliometric or Science mapping is a spatial representation relating specialities, fields, disciplines and individual authors and documents to each other showing their relative locations and physical proximities (Cobo et al., 2011). Science mapping overlaps between scientometric, bibliometric and informatics in its analysis yet they are independent techniques on their own (Hood and Wilson, 2001). Studies based on science mapping typically applies either a scientometric or bibliometric analysis technique (Hosseini et al., 2018).

Scientometric analysis compared to bibliometrics delivers a broader approach when it comes to measuring and analysing bibliometric tools and data, to reveal potentially insightful trends and patterns whiles bibliometrics predominantly focuses on the literature per se (Hood and Wilson, 2001). Several studies employ different scientific methods when reviewing literature such as systematic literature reviews (Curtin et al., 2019; Wassie and Adaramola, 2019; Wu, H.Y. et al., 2019), bibliometric technique (Chen et al., 2017), scientometric analysis (Chen et al., 2014; Montoya et al., 2014; Shi and Liu, 2019), and content analysis (Herbes and Ramme, 2014) within areas like renewable energy, sustainability, construction and diseases. This study therefore employs scientometric techniques in its analysis as it broadly covers bibliometric data, tools and methods.

2.1. Database and keyword selection

The quality of a scientific review depends on the selection of appropriate databases and the methodology used. Retrieval of data from bibliometric sources such as Scopus, WoS, Medline, Science Direct and Google Scholar (Cobo et al., 2011; Mongeon and Paul-Hus, 2016), are relevant in collecting information within several scientific fields. However, results may vary depending on the database used as their coverage differs in each database when it comes to research disciplines (Mongeon and Paul-Hus, 2016). Clarivate Analytics uses the Web of Science citation database, consisting over 155 million records in 34,000 journals having over 1.7 billion cited references across several disciplines (Clarivate Analysis, 2020), and is mostly used by the scientific research community due to its quality (Niñerola et al., 2019). This study employs the WoS database because of its scientific robustness and comprehensiveness (Neto et al., 2016; Olawumi and Chan, 2018). The search is conducted within the Web of Science Core Collection (including Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Emerging Sources Citation Index (ESCI), Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH), Conference Proceedings Citation Index- Science (CPCI-S), and Arts & Humanities Citation Index (A&HCI)) database on 10th December 2019. Many articles would have been under review or published after the database search which means publication number may increase at the end of the year. These articles are not analysed in this paper but may be cited in the discussion.

The keywords for this study are within the waste research studies conducted by several researchers on solar or photovoltaic cells. Therefore, these keywords were adopted (Mahmoudi et al., 2019a; Salim et al., 2019a; Shubbak, 2019; Sica et al., 2018) and modified (keywords from the waste hierarchy (Parto et al., 2007) formulated by Ad Lansink) through expert opinions to suit the purpose of this study. A search criterion was then developed to select the required articles needed for the studies. Keywords such as *"solar panels" OR photovoltaic OR "photovoltaic cells" OR "pv panels" AND "End-of-life" OR waste OR recycl* OR reus* OR recover* OR dispos* OR treatment,* were combined with the Booleans ("AND" and "OR") and used as the search query in the WoS database. These keywords needed to occur within the topic search of the Web of Science Core Collection.

An initial search produced 6520 records, among these were academic literature consisting of 4857 articles, 1724 proceedings papers, 274 reviews, 16 early access, 7 editorial materials, 7 meeting abstracts, 3 letters, 1 note, 1 book chapter, 1 retracted publication and 1 correction from 13 different languages. This search was then limited to articles which were written in English in all years. All the other documents were also excluded with the exception of the articles and reviews because of the comprehensiveness and reputability of these sources as "certified knowledge" (Olawumi and Chan, 2018). Thus, 4683 total records were retrieved for analyses. The records were then downloaded and imported into EndNote version X9 reference manager for analysis.

2.2. Tool selection

The selection of an appropriate visualisation tool for analysis is very critical when it comes to scientometric analysis. There are several existing science mapping tools such as VOSviewer (van Eck and Waltman, 2009), VantagePoint (Porter and Cunningham, 2004), Sci^2 Tool (Chen et al., 2012), Network Workbench Tool (Börner et al., 2010), Leydesdorff's Software (Leydesdorff and Schank, 2008), IN-SPIRE (Wise, 1999), CoPalRed (Bailón-Moreno et al., 2005), CiteSpace II (Chen, 2006), Bibexcel (Persson et al., 2009), Gephi (Bastian et al., 2009) and HistCite (Garfield, 2004) for visualising and analysing temporal, dynamic and structural trends and patterns within a scientific literature. Moreover, analytical methods such as network, temporal (burst detection) and geospatial analysis are conducted using these software tools (Cobo et al., 2011). The various tools perform differently according to each of their abilities and strengths when it comes to bibliographic data analysis.

Thus, choosing an appropriate tool is critical when thoroughly analysing your data. A careful analysis of the various software established the need for the use of CiteSpace, Gephi and VOSviewer for this research. This is because Citespace facilitates the detection of abrupt changes and emerging trends within scientific literature (Chen et al., 2012), Gephi is used to explore and manipulate networks (Bastian et al., 2009) whiles VOSviewer explores, visualises and produces bibliometric maps and networks (Van Eck and Waltman, 2018).

2.3. Scientometric techniques

Establishing a relationships and links between units such as authors, cited references, documents and journals through co-word analysis, co-citation analysis, co-author analysis and bibliographic coupling are the analysis involved in scientometric techniques (Cobo et al., 2011). Processing the data retrieved required the use of three scientometric techniques for this study, and among them are 1) co-word analysis: involves keyword co-occurrence and clusters as well as burst detection of the top keywords, 2) co-citation analysis: deals with the co-cited author, documents and journal visualisation and relationships within downloaded papers from the WoS database, and 3) co-author analysis: compares the occurrences and linkages between authors, countries and institutions. Table A1 in the appendix shows the details and description of the techniques used.

3. Analysis and results

The 4683 retrieved articles were analysed using CiteSpace, Gephi and VOS viewer software to establish the emerging trends of solar photovoltaic waste research. According to Cobo et al. (2011), critical information can be extracted through network, temporal and geospatial analysis. The aforementioned analysis was performed using the software explained earlier. This section therefore explains the various analysis applied to the data retrieved from the database.

3.1. Publication distribution

Research on solar photovoltaics was first referenced as back as 1974 in the journal of applied physics (Fahrenbr.Al and Bube, 1974), where Fahrenbr and Bube researched on the effects of heat treatment on copper sulphide/cadmium sulphide (Cu_2S-CdS) heterojunction photovoltaic cells. Research concerning photovoltaics was also cited by (Lawrence et al., 1984; and Miyata et al., 1987) in 1984 and 1987. From these years, photovoltaic research has received a study interest since 1991. A look at Fig. 1 shows the growth of solar photovoltaic module waste research through the years till now. Particularly in 2014 where there was a sharp climb of about 438 documents within the year. This shows the attention solar photovoltaics (PVs) waste research is receiving and will continue to receive because of the retirement of old solar PV modules in the coming years. This upward increase and interest in this area of research has propelled several researchers (Salim et al., 2019b; Sica et al., 2018) to look into the end-of-life management of solar PVs. A significant record of 636 publications on solar photovoltaic waste module research occurred in 2018 only. This shows the gradual interest waste research is receiving recently and how best researchers can steer towards new innovation and creativity when it comes to solar photovoltaic modules.

3.2. Distribution of articles in journals

Among the articles retrieved, journals that produced 45 and more articles were selected making up the top 20 journals within the field. Table 1 illustrates the distribution of the publications within the top 20 journals selected. Their characteristics such as the number of articles

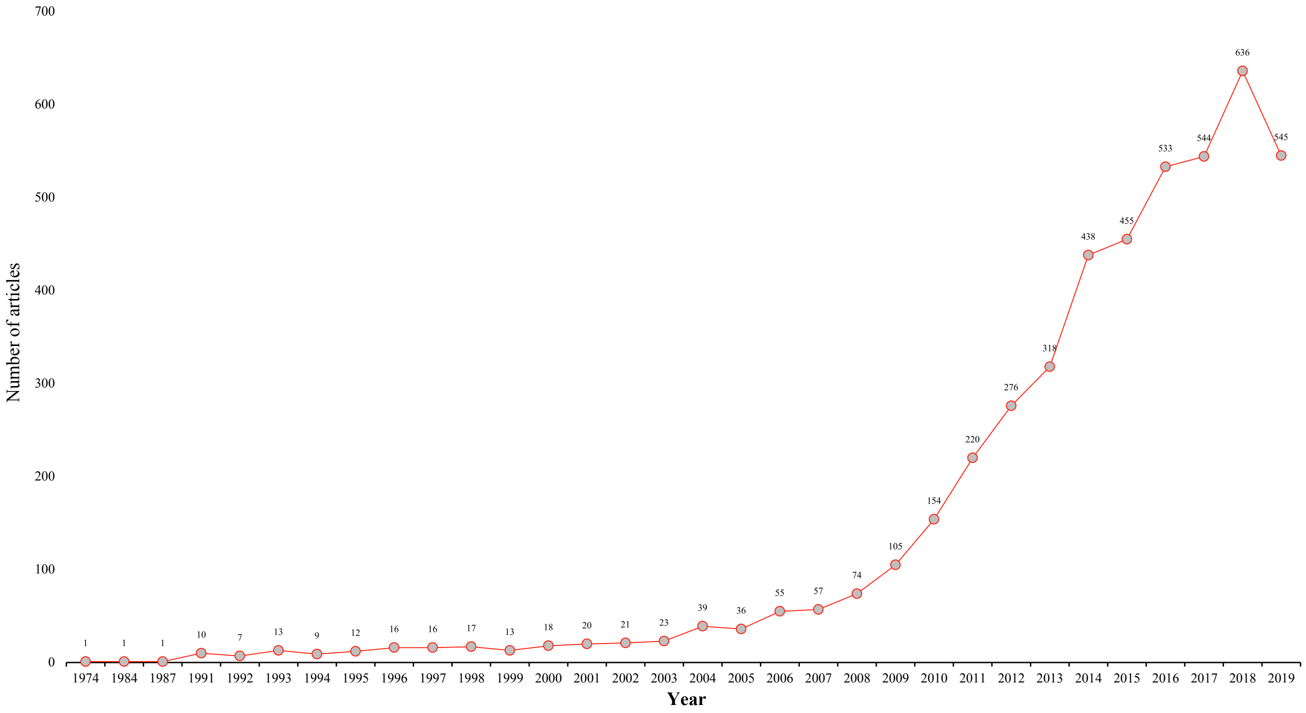


Fig. 1. Annual publication distribution of Solar PV waste research.

produced, number cited, journal impact factor (JIF) and their Scimago Journal and Country Ranking (SJR) were accessed. Among the 20 journals, Solar Energy Materials and Solar Cells, ACS Applied Materials and Interfaces, Solar Energy, Journal of Materials Chemistry A and Journal of Physical Chemistry C produced more than 100 articles related to solar photovoltaics waste research.

InCites Journal Citation Report from Clarivate analytics indicates that Advanced Energy Materials (25.245), Advanced Functional Materials (16.836), Renewable and Sustainable Energy Reviews (12.110), Journal of Materials Chemistry A (11.301) and Applied Energy (8.848) are the top five journals with the highest impact factor in 2019 citation report with Advanced Functional Materials having the highest number of citations (7266) followed by Solar Energy Materials and Solar Cells (6171). The SJR was also compared with the JIF to reconcile the impacts these journals have on photovoltaic waste research. The results were similar when it comes to how the journals were ranked and the impact they had on photovoltaic research.

3.3. *Co-word analysis*

The analysis of the main concept and conceptual structure extracted from a research field is termed as co-word analysis (Cobo et al., 2011). The keywords extracted from the WoS database search through the title, abstract and keywords are analysed to obtain the term co-occurrences of the documents. This section explains the analysis of the network of co-occurring keywords and co-occurring subject categories.

3.3.1. *Network of co-occurring keywords*

The analyses of keywords are essential in determining key research areas (Shrivastava and Mahajan, 2016) across a field of study. Thus, keywords characterise the core research of a published paper and shows the boundaries within which a research area is depicted (Su and Lee, 2010). The network of a keyword provides a good picture of the knowledge area of a research giving insight into the association and organisation of topics within a research domain. This is calculated on the basis of publications within which both these keywords appear together through the weight of their links (van Eck and Waltman, 2014). The network of co-occurring keywords was explored using the VOSviewer and CiteSpace software. Using all the keywords such as the author's keywords and keywords plus (indexed terms from journals) from the database, the relationship and patterns of the keywords were established. Fig. 2 shows a visualisation of the frequency or count of the keywords as well as the co-occurrence between them.

From a combination of over 14,561 keywords analysed, 207 nodes surpassed the threshold of minimum thirty occurrences for the analysis in VOSviewer. The visualisation in Fig. 2 shows the keyword counts, where "performance" and "efficiency" received the highest frequency of 813 and 702 respectively. "solar cell" was the third highest with 647 counts. The others are "thin film" (470), film (418), morphology (332), photovoltaic cell (296), system (224), layer (243), polymer solar cell (225), energy (224), design (223), nanoparticle (218), photovoltaic (213), recombination (202), polymer (196), fabrication (194), open circuit voltage (168), conjugated polymer (159) and photovoltaics (158). Other keywords such as renewable energy, dye-sensitized solar cells, silicon, solar energy were also predominant. The visualisation clearly shows the trend of photovoltaic waste research, has leaned towards solar performance and efficiency for the past few years. Studies such as (Li, F. et al., 2012; Shen et al., 2013) looks at enhancing the performance of solar cells which could reduce the amount manufactured in volume needed for residential and commercial installation therefore reducing the amount of waste produced at the end-of-life of the PV panel. Moreover, there is gradual shift into environmental sustainability as old solar cells come to the end of their service life. There is therefore research into new ideas on how best these solar cells may become environmentally friendly whiles producing less waste.

3.3.1.1. Keyword clusters. Analysing keywords in clusters helps establishes emerging trends in literature. Clustering group keywords together establishing a link within the same field of research. CiteSpace supports the selection of cluster labels based on Latent Semantic Indexing (LSI), Log-Likelihood Ratio Test (LLR) and Mutual Information (MI). Moreover, thematic labels of each cluster include terms selected by either LLR which highlights the unique themes or LSI which identifies common themes (Chen and Song, 2019). These two selections can indicate

Table 1
Characteristics of top 20 journals.

S/N	Journal name	No. of articles	Citations	JIF	SJR	*JIF ranking*
1	*Solar Energy Materials and Solar Cells*	204	6171	6.984	1.83	*10*
2	*ACS Applied Materials & Interfaces*	154	3405	8.758	2.57	*6*
3	*Solar Energy*	108	2142	4.608	1.54	*12*
4	*Journal of Materials Chemistry A*	104	2864	11.301	3.43	*4*
5	*Journal of Physical Chemistry C*	102	3964	4.189	1.48	*13*
6	*Organic Electronics*	90	1743	3.310	0.90	*16*
7	*Renewable & Sustainable Energy Reviews*	78	2756	12.110	3.63	*3*
8	*RSC Advances*	70	588	3.119	0.74	*17*
9	*Applied Physics Letters*	68	2832	3.597	1.34	*14*
10	*IEEE Journal of Photovoltaics*	67	885	3.052	1.00	*18*
11	*Applied Energy*	63	1585	8.848	3.61	*5*
12	*Journal of Applied Physics*	61	1784	2.286	0.73	*19*
13	*Journal of Cleaner Production*	61	754	7.246	1.89	*9*
14	*Renewable Energy*	59	1252	6.274	2.05	*11*
15	*Thin Solid Films*	58	1016	2.030	0.51	*20*
16	*Advanced Functional Materials*	57	7266	16.836	5.88	*2*
17	*Progress in Photovoltaics*	53	1359	7.690	1.86	*8*
18	*Energy Conversion and Management*	51	807	8.208	2.92	*7*
19	*Advanced Energy Materials*	49	1670	25.245	9.51	*1*
20	*Physical Chemistry Chemical Physics*	45	1002	3.430	1.14	*15*

InCites Journal Citation Report /Scimago Journal and Country Ranking (2019).

different or similar themes. This study therefore uses the LLR in analysing the keywords. In giving a sound interpretation of the results, the silhouette and modularity has to be taken into consideration (Chen, 2016). The average homogeneity of the clusters, thus, the clustering configurations quality is measured using the silhouette value (Chen et al., 2010). The modularity, however, measures the degree with which a group of nodes in a network can be divided such that they are closer and tighter within the same group than in another different group (Chen et al., 2012). The modularity and silhouette representing the results of this analysis are Q = 0.330 and 0.587 respectively. The details of the twenty highest LLR labels are presented in the appendix Table A2. The clusters are solar cell, dye-sensitized solar cell which appeared twice, Cadmium telluride (CdTe) solar cell and single-walled carbon nanotube. Table 2 gives the details of the characteristics of the clusters.

Cluster #0 is the largest cluster with 64 members and a silhouette value of 0.78 and is labelled "solar cell" by LLR. Other alternative labels are polythiophene and polymer nanoparticle. The most active citer in cluster #0 is Xi et al. (Xi et al., 2010), who did experimental research on improving the performance of organic solar cells. This cluster indicates the considerable research that has gone into organic solar cells in recent years and how researchers are still finding ways to make organic solar cells more efficient and productive. Organic solar cells in comparison with other types of solar PV modules, create a number of possible applications because they are potentially environmentally friendly, variable in colour, lightweight, flexible and cheap. Unfortunately, there are a lot of research being conducted on organic cells before they are ready for commercialization (Yin et al., 2020). Cluster #1 is the second largest cluster with 52 members and a silhouette value of 0.696 and is labelled "dye-sensitized solar cell (DSSC)" by LLR. The silhouette value of the five clusters are all above 0. 65, indicating a robust and meaningful results.

The alternative names are organic sensitizer and phenylenevinylene copolymer. The most active citer in the cluster is Yang et al. (Yang et al., 2013), followed by cluster #2 with 45 members and a silhouette value of 0.760 that is labelled "dye-sensitized solar cell" by LLR. Alternative names are solar cells, photovoltaic modules and crystalline silicon. Cluster #3 is the fourth cluster with 38 members and a silhouette value of 0.765 and is labelled "CdTe solar cell" by LLR. Alternative names are solar cells electrodeposition and chalcopyrite thin film. Cluster #4 has the least members (12) and a silhouette value of 0.866 and is labelled "single-walled carbon nanotube" by LLR the alternative labels are solar cells, open circuit voltage and enhancement. Dye-sensitized solar cells have been under extensive studies due to its ease of production, low toxicity and low cost since the early 2000s (Sharma et al., 2018). Cluster #1 and #2 clearly shows the efforts of researchers that has gone into the studies on dye-sensitized solar cells. The occurrence of mean year of both clusters between 2007 and 2009 depicts that, over the decade a lot of attention has gone into the performance and efficiency of DSSC. The mean years of all the clusters shows that, they have been formed relatively around old documents as the mean year ranges from 2003 to 2007.

3.3.1.2. Citation bursts and betweenness centrality. The rate of change throughout a field is measured by its burstness. Through a period of time, a sudden change in the frequency of an entity at a specific time shows its burstness. Burstness can be analysed through the use of CiteSpace. When a node shows a strong burst (showed by the red colour) as shown in Fig. 3, it signifies the attention the work has received within a short period of time (Chen, 2016). The burstness of the keywords were measured within year groups. The keyword with the strongest burst (23.195) is "light emitting diode" which receive a lot of attention within the 2003 to 2012-year period. This is followed by "solar cell" with a strength of 17.448 through the years of 1993 to 2004. It was realised that within the year 2006 to 2009 the keyword "plastic solar cell" was very prominent with a burst strength of 5.492. This shows the attention given to research on new technologies as alternatives, in achieving efficient improvements and more stable performance in its operation.

The betweenness centrality of the keywords indicates the transformative potential of a contribution or the importance of that node in the network (Chen et al., 2012). Looking back at Fig. 2., the following shows the betweenness centrality of the keywords with Performance (0.12) having the highest value, and the second being efficiency (0.10), and the others are solar cell (0.19), thin film (0.08), film (0.06), morphology (0.06), photovoltaic cell (0.08), system (0.08), layer (0.02), polymer solar cell (0.03), energy (0.10), design (0.03), nanoparticle (0.05), photovoltaic (0.06), recombination (0.04), polymer (0.04), fabrication (0.06), open circuit voltage (0.02), conjugated polymer (0.06) and photovoltaics (0.05). Performance and efficiency as explained previously has been an important part of photovoltaic research and will continue to be, because of the quest to find better and more efficient solar photovoltaics to prevent harmful waste to humans and the environment.

3.3.2. Network of co-occurring subject categories

The subject category came up with a modularity of Q = 0.4676 and silhouette of 0.8723. Among the research subject categories discovered were Materials Science; Materials Science, Multidisciplinary; Physics; Physics, Applied; Chemistry; Energy and Fuels; Science and Technology; Engineering; Chemistry, Physical; Nanoscience and Nanotechnology; Chemistry, Multidisciplinary; Physics, Condensed Matter; Engineering, Electrical and Electronic; Green and Sustainable Science & Technology; Environmental Sciences and Ecology; Environmental Sciences;

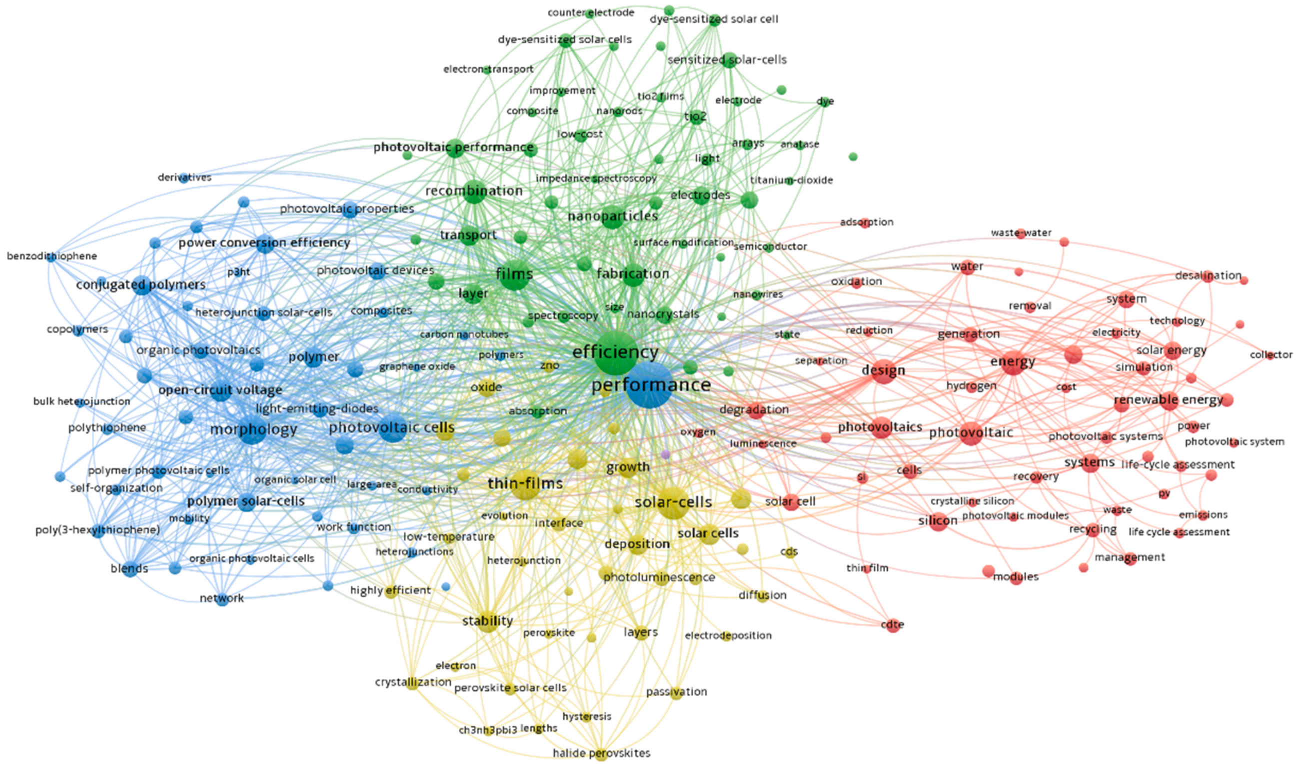


Fig. 2. Visualisation of co-occurring keywords.

Table 2
Keywords cluster characteristics.

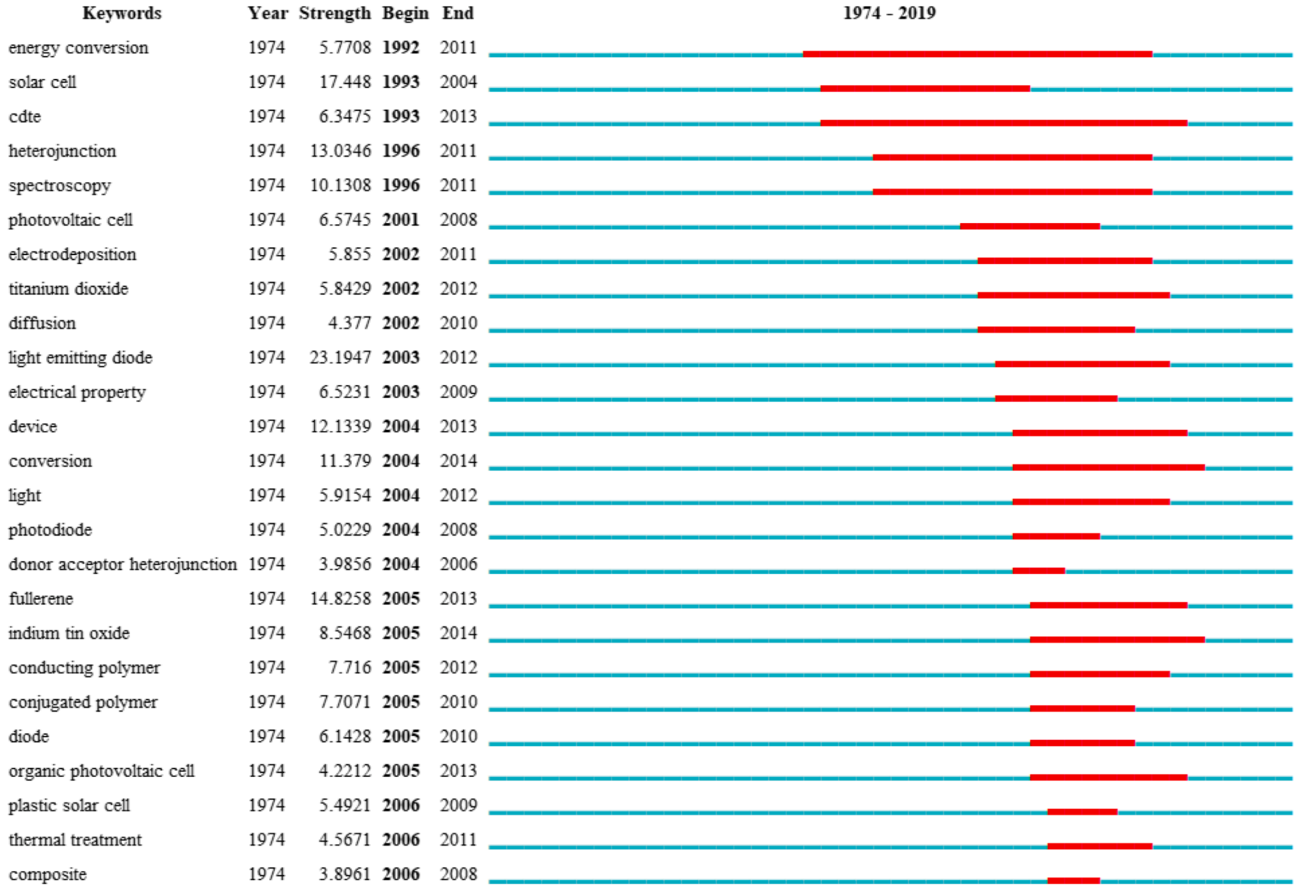
Cluster ID	Size	Silhouette	Mean (Year)	Cluster label (LLR)	Other labels	Articles
0	64	0.780	2007	solar cell	polythiophene, polymer nanoparticle	(Nelson et al., 2009; Po et al., 2010; Yang et al., 2011)
1	52	0.696	2007	dye-sensitized solar cell	organic sensitizer, phenylenevinylene copolymer	(Wang et al., 2013; Yu et al., 2011; Zhao et al., 2010)
2	45	0.760	2009	dye-sensitized solar cell	solar cells, photovoltaic modules, crystalline silicon,	(Friedel et al., 2009; McDonald and Pearce, 2010; Yoon et al., 2010)
3	38	0.765	2003	CdTe solar cell	solar cells electrodeposition, chalcopyrite thin film	(Heath et al., 2004; Lincot et al., 2004; Lupan et al., 2010)
4	12	0.866	2005	single-walled carbon nanotube	solar cells, open circuit voltage, enhancement	(Mistry et al., 2011; Stevens et al., 2009; Szeifert et al., 2009)

Engineering, Chemical; Engineering, Environmental; Electrochemistry; Materials Science, Coatings and Films; Polymer Science; Thermodynamics; Optics; Physics, Atomic, Molecular and Chemical; Water Resources; Mechanics; Multidisciplinary Sciences; Metallurgy and Metallurgical Engineering; Environmental Studies; Engineering, Mechanical; Construction and Building Technology; Physics, Multidisciplinary; Engineering, Civil; and Instruments and Instrumentation.

The highest citation count is related to Materials Science, with 2178 citation followed by Materials Science Multidisciplinary with 2028, Physics with 1671, Physics Applied with1408, Chemistry with 1342, Energy & Fuels with 1274, Science & Technology (2000) with 1095, Engineering with 895, Chemistry, Physical with 892 and Nanoscience and Nanotechnology with 698 citation counts. The field of material science has received a major boost in terms of citation as well as physics and chemistry as these research areas lead the studies on solar photovoltaics waste management research. Thus, the emergence and production of new materials for solar panels that are more efficient and effective are constantly researched to better perform when it comes to carbon emissions during production and after its end-of-life. Their recycling and recovery capabilities are also significant areas of research.

3.3.2.1. Citation bursts and betweenness centrality. The highest ranked item by bursts is Physics (1991–2005), with burst score of 34.26. This explains the attention physics as a subject area has received in the area of solar photovoltaics from 1991 to 2005. The second one is Physics, Applied (1992–2005), with bursts of 31.83. It can be realised that, applied physics also receive the same attention around the same year as physics, this shows the collaborative work between these two disciplines on the work of solar photovoltaic waste research. The third is Polymer Science (2005–2013), with bursts of 11.05. The 4th is Physics, Multidisciplinary (2006–2012), with bursts of 7.02. The 5th is Materials Science, Coatings and Films (1991–2010), with bursts of 6.00. The 6th is Physics, Condensed Matter (2006–2008), with bursts of 5.18. The 7th is Energy and Fuels (2001–2002), with bursts of 4.87. The 8th is Engineering, Electrical & Electronic (1999–2001), with bursts of 4.87.

From Fig. 4, the pink ring around the nodes depict the centrality of each node. The bigger the ring the higher the centrality which shows the importance of that node to the group. The highest ranked item by centrality is Engineering, with centrality score of 0.52, followed by Energy and Fuels, Chemistry, Environmental Studies and Materials Science with respective centrality values of 0.26, 0.18 and 0.14. Science and



Keywords	Year	Strength	Begin	End
energy conversion	1974	5.7708	**1992**	2011
solar cell	1974	17.448	**1993**	2004
cdte	1974	6.3475	**1993**	2013
heterojunction	1974	13.0346	**1996**	2011
spectroscopy	1974	10.1308	**1996**	2011
photovoltaic cell	1974	6.5745	**2001**	2008
electrodeposition	1974	5.855	**2002**	2011
titanium dioxide	1974	5.8429	**2002**	2012
diffusion	1974	4.377	**2002**	2010
light emitting diode	1974	23.1947	**2003**	2012
electrical property	1974	6.5231	**2003**	2009
device	1974	12.1339	**2004**	2013
conversion	1974	11.379	**2004**	2014
light	1974	5.9154	**2004**	2012
photodiode	1974	5.0229	**2004**	2008
donor acceptor heterojunction	1974	3.9856	**2004**	2006
fullerene	1974	14.8258	**2005**	2013
indium tin oxide	1974	8.5468	**2005**	2014
conducting polymer	1974	7.716	**2005**	2012
conjugated polymer	1974	7.7071	**2005**	2010
diode	1974	6.1428	**2005**	2010
organic photovoltaic cell	1974	4.2212	**2005**	2013
plastic solar cell	1974	5.4921	**2006**	2009
thermal treatment	1974	4.5671	**2006**	2011
composite	1974	3.8961	**2006**	2008

Fig. 3. Top 25 keywords with the strongest citation burst.

Technology, Environmental Sciences and Ecology and Engineering, Chemical had a similar centrality value of 0.11; Biotechnology and Applied Microbiology, had centrality value of 0.10 and Engineering, Electrical and Electronic had centrality value of 0.09.

3.4. *Co-citation analysis*

Co-citation explains the citation of two scholarly items such as journals, references, documents and/or authors by the same article (Olawumi and Chan, 2018; Wu, J. et al., 2019). The intellectual structure within a scientific field can be analysed via co-citation (Cobo et al., 2011). The VOSviewer, Gephi and CiteSpace software was used to analyse the co-citation networks of the authors, documents and journals as explained in this section.

3.4.1. *Author co-citation network*

Author co-citation explores the frequently cited authors in a research field (McCain, 1991). Author co-citation network is visualised with the aid of the VOSviewer software. The colours in Fig. 5 shows the pattern and network of authors who are indirectly cited together whether collaboratively or individually.

The highest ranked author is Li et al. (Li et al., 2006), with citation counts of 631, followed by Green and Wenham (Green and Wenham, 1994) with 563, Krebs et al. (Krebs et al., 2005) 430, Brabec et al. (Brabec, 2003) with 380, Gratzel (Grätzel, 2004) with 356, Yu (Yu et al., 2003) with 337, He et al. (He et al., 2012) with 323, Fthenakis and Wang (Fthenakis and Wang, 2006) with 285, Ma et al. (Ma et al., 2005) with 257, and Kim et al. (Kim et al., 2005) with 246 citation counts. The most cited paper, Li et al. (Li et al., 2006), looks at efficient inverted polymer solar cells. The second most cited paper by Green and Wenham (Green and Wenham, 1994) explored novel parallel multijunction solar-cells.

3.4.2. *Citation bursts and betweenness centrality*

The highest ranked item by bursts is Ma et al. (Ma et al., 2005) with bursts of 43.83, followed by Kojima et al. (Kojima et al., 2015) with bursts score of 42.41, Yang et al. (Yang et al., 2015) with 39.50, You et al. (You et al., 2013) with 35.21, Padinger et al. (Padinger et al., 2003) with 34.00, Zhang et al. (Zhang et al., 2016) with 33.79, Jeon et al. (Jeon et al., 2014) with 33.60, Kim et al. (Kim et al., 2005) with 33.33, Shaheen and Ginley (Shaheen and Ginley, 2004) with 32.98, and Zhao et al. (Zhao et al., 2017) with 32.97 bursts scores.

3.4.3. *Document co-citation network*

The document co-citation is visualised in Fig. 6. CiteSpace recorded a modularity of 0.6947 and a Silhouette of 0.4812 during the mapping of the document co-citation network. The highest ranked item by citation counts is Li et al. (Li et al., 2005) in Cluster #1, with citation counts of 185, followed by Ma et al. (Ma et al., 2005) in Cluster #1 with 162 citation counts, Burschka et al. (Burschka et al., 2013) in Cluster #2 with 148, Lee et al. (Lee et al., 2012) in Cluster #2 with 129, He et al. (He et al., 2012) in Cluster #0 with 120, Liu et al. (Liu et al., 2014) in Cluster #2 with 116, Li et al. (Li, G. et al., 2012) in Cluster #4 with 113, Jeon et al. (Jeon et al., 2014) in Cluster #2 with 112, Stranks et al. (Stranks et al., 2013) in Cluster #2 with 111, and Li (Li, 2012) in Cluster #0 with 104 citation counts.

Cluster #0 is the largest cluster with 83 members and a silhouette value of 0.761 and is labelled “efficient polymer” by LLR. Xin et al. (Xin et al., 2010) is the most active citer to cluster #0 with his work on “polymer nanowire/fullerene bulk heterojunction solar cells: how nanostructure determines photovoltaic properties”. Cluster #1 (the second largest) has 80 members and a silhouette value of 0.764, and is labelled “fullerene bulk heterojunction” by LLR. The most active citer to the cluster is Liu et al. (Liu et al., 2010) on their paper “the mechanisms

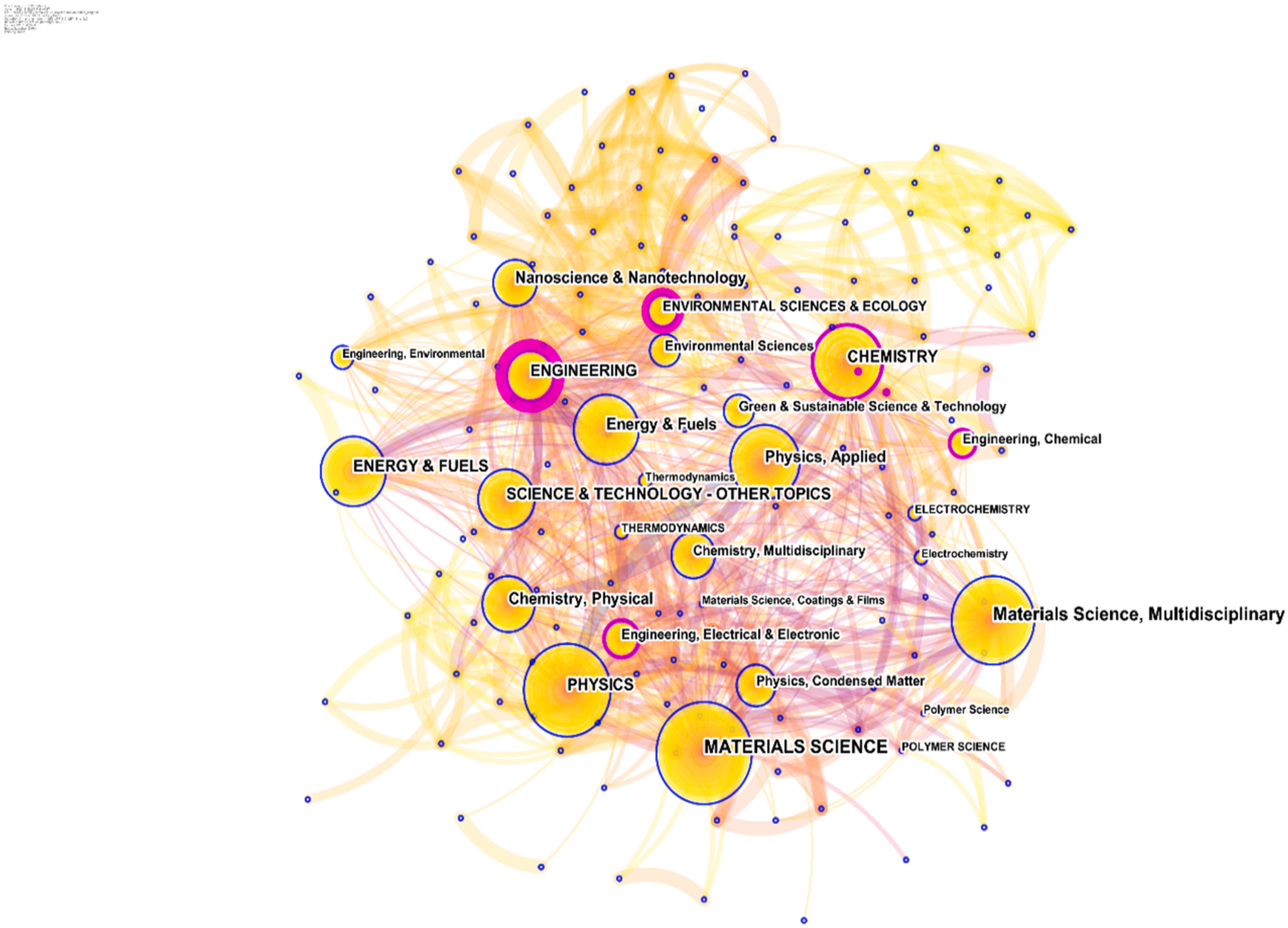


Fig. 4. An overview of the subject category co-occurring network.

for introduction of n-dodecylthiol to modify the P3HT/PCBM morphology”. Cluster #3 is the third largest cluster with 45 members and a silhouette value of 0.85, and is labelled “device architecture” by LLR. The most active citer to the cluster is Kwong et al. (Kwong et al., 2004) on “CuPc/c-60 solar cells-influence of the indium tin oxide substrate and device architecture on the solar cell performance”.

Cluster #0 and #1: The first and second clusters (#0 and #1) focus on the polymer solar cells performance especially the fullerene bulk heterojunction solar cells. The search for a more efficient and low-cost solar cells is trending in the photovoltaic waste research field as old panels reach their end-of-life and the need to create less harmful and environmentally friendly solar cells. Research such as that of Xin et al. (Xin et al., 2010), experimented on bulk heterojunction solar cells through the use of solvent and thermal annealing to vary the morphology of fullerene composites. The work of Po et al. (Po et al., 2010), delved into the current approaches and achievement in polymer solar cells. They realised that the cost, durability and efficiency are the critical elements to pivot the success of polymer solar cells. Other researchers (Canli et al., 2010; Hains et al., 2010; Liu et al., 2010; Tang et al., 2010) have also examined different treatment and properties of polymer solar cells to make it more efficient and low cost. A look at the five strongest citation burst (*see* Fig. 7) reveals that the emerging trend on photovoltaic modules waste management research has been centred on polymer solar cells (Coakley and McGehee, 2004; Li et al., 2005; Padinger et al., 2003; Shaheen et al., 2001; Yang et al., 2005) from the year 2004 to 2013. But a critical look at the research on photovoltaic waste has been a gradual process through the years. Even thou most of the earlier research is centred on polymer solar cells as the alternative to the old PV technologies because of the less harmful effect on the environment, its effectiveness and efficiency is still an ongoing study. That means, many of the silicon and cadmium based solar panels will be installed by the time other new technologies hit the market. There is therefore the need to intensify the research on how to properly manage the waste from the old PV technologies.

Cluster #3, #4 and #5: These three clusters examines the characteristics and properties of polymer solar cells. The article with the highest coverage in the fourth cluster (#3) which is Kwong et al. (Kwong et al., 2004) investigated the performance of organic solar cells through the application of different indium tin oxide surface treatment and device architecture. The performance of the organic solar cell, they realised will be greatly improved through the use of a three-layer architecture having a co-deposited mixed layer. Exploration and application of multi-layer photodetectors (Xue and Forrest, 2004), oligo derivatives (Nierengarten, 2004; Nierengarten et al., 2004), and nanoscale morphology (Hoppe et al., 2004) to organic solar cells are some of the of the characteristics and properties that several researchers are studying to improve the performance and efficiency of organic solar cells. This cluster (#4) describes the improvement made within the small molecule based organic solar cells. Patil et al. (Patil et al., 2016) and Wang et al. (Wang et al., 2015) are some of the most referenced researchers on small molecule based organic solar cells. Their studies investigate the improvement of small molecule based organic solar cells through experimental tests. The sixth cluster (#5) demonstrates how solar cells perform through different treatments (Olson et al., 2007; Uhlrich et al., 2009a; Uhlrich et al., 2009b). The three clusters explained in this paragraph also looks at polymer solar cells. The trend in a past couple of years has been centred on polymer solar cells, its characteristics and advantages compare to the silicon based solar cells. Their characteristics

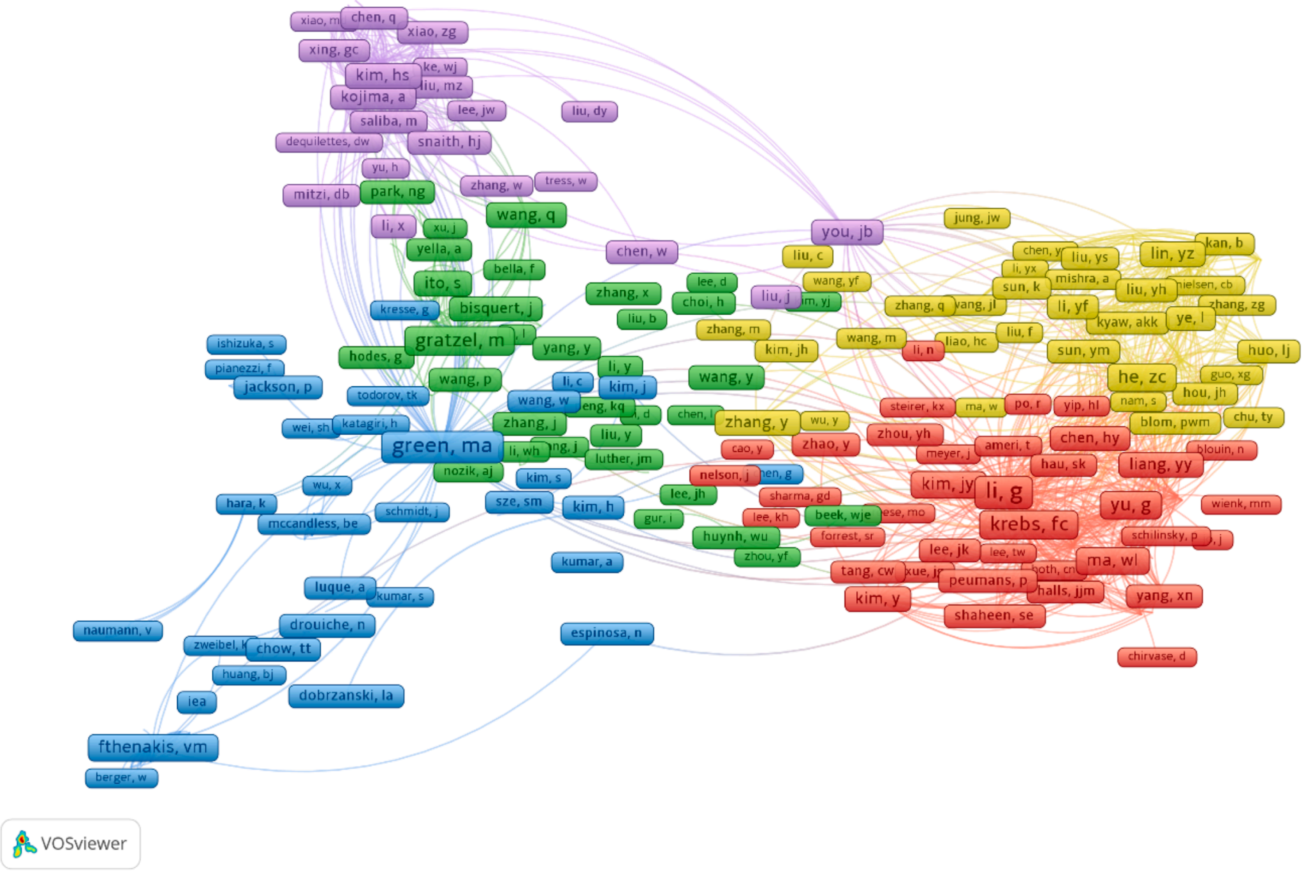


Fig. 5. Author co-citation visualisation network.

such as its lightweight, low cost and its low impact to the environment has made it the alternative solar technology compared to the old technologies.

Cluster #6, #15 and #22: The last three clusters examines sensitized, inverted and hybrid solar cells. As research progresses, experts are finding new ways and methods to improve the performance and efficiency of solar cells as well as make them environmentally friendly. An increase in the performance and efficiency of photovoltaics has been recorded through the use of quantum dot sensitized solar cells (Jin et al., 2012; Pan et al., 2012). The same case is recorded in inverted polymer solar cells through the modification of its cells (Cho et al., 2011; Sun et al., 2011). The last cluster (#22) discusses the improvement and treatment of hybrid solar cells. The studies conducted by Zhou et al. (Zhou et al., 2011) describes the enhancement of hybrid solar cells through acid treatment. The last batch of clusters also look at different PV technologies that might serve as an alternative to the current installed ones. It is important to establish new innovations that are environmentally friendly and can help with reducing waste from solar PV technologies.

3.4.4. Citation bursts and betweenness centrality.

The highest ranked item by bursts is Li et al. (Li et al., 2005) in Cluster #1, with bursts score of 57.17 followed by Ma et al. (Ma et al., 2005) in Cluster #1 with 48.98 bursts, Padinger and Rittberger (Padinger et al., 2003) in Cluster #1 with 31.37, Kojima et al. (Kojima et al., 2009) in Cluster #2 with 29.58, He et al. (He et al., 2012) in Cluster #0 with 28.36, You et al. (You et al., 2013) in Cluster #0 with 27.85, Yang et al. (Yang et al., 2015) in Cluster #2 with 26.49, Jeon et al. (Jeon et al., 2014) in Cluster #2 with 26.29, Liu et al. (Liu et al., 2014) in Cluster #4 with 24.08, and Burschka et al. (Burschka et al., 2013) in Cluster #2 with 23.10 bursts scores.

The burst within the years as visualised in Fig. 7, shows the citation burst (showed by the red colour) of the references as sorted by years. The beginning year 2004, 2005, 2006 and 2007 showed (indicated by the deep blue colour) the most strength in its burstness. From the years of 2004 to 2011, Shaheen et al. (Shaheen et al., 2001), recorded the highest burst strength of 20.93. The year 2005 to 2009 saw the highest burst strength of 6.30 from Brabec et al. (Brabec et al., 2001). With a burst strength of 31.37, 21.58 and 16.95 the references Padinger et al. (Padinger et al., 2003), Yang et al. (Yang et al., 2005) and Coakley (Coakley and McGehee, 2004) respectively received one of the highest strengths in the year period 2006 to 2013. Li et al. (Li et al., 2005), received the highest burst within all the year groups with a burst of 57.17. in its year group from 2007 to 2010. The research on the articles that received the highest burst were on polymer solar cells. For the past decade, attention of researchers has shifted towards the performance and efficiency of polymer solar cells. This is because of the quest to fight the harmful impact of waste from old solar panels and to easily produce new and low-cost solar panels.

3.4.5. Journal co-citation network

According to McCain (McCain, 1991), journal co-citation networks establishes frequently co-cited journals. This shows the network of documents that are mostly cited in these journals. The CiteSpace and Gephi software were used in analysing and visualising the networks between the journals. The journal co-citation network has 216 nodes, the journals with the most cited papers are discussed. Table 1 as explained earlier describes the number of articles that were published in some of these journals and their characteristics. Fig. 8 shows the connection and links between the journals. The bigger and deeper the colour of the node and edges the higher and stronger the frequency and connection between the citation of the journals.

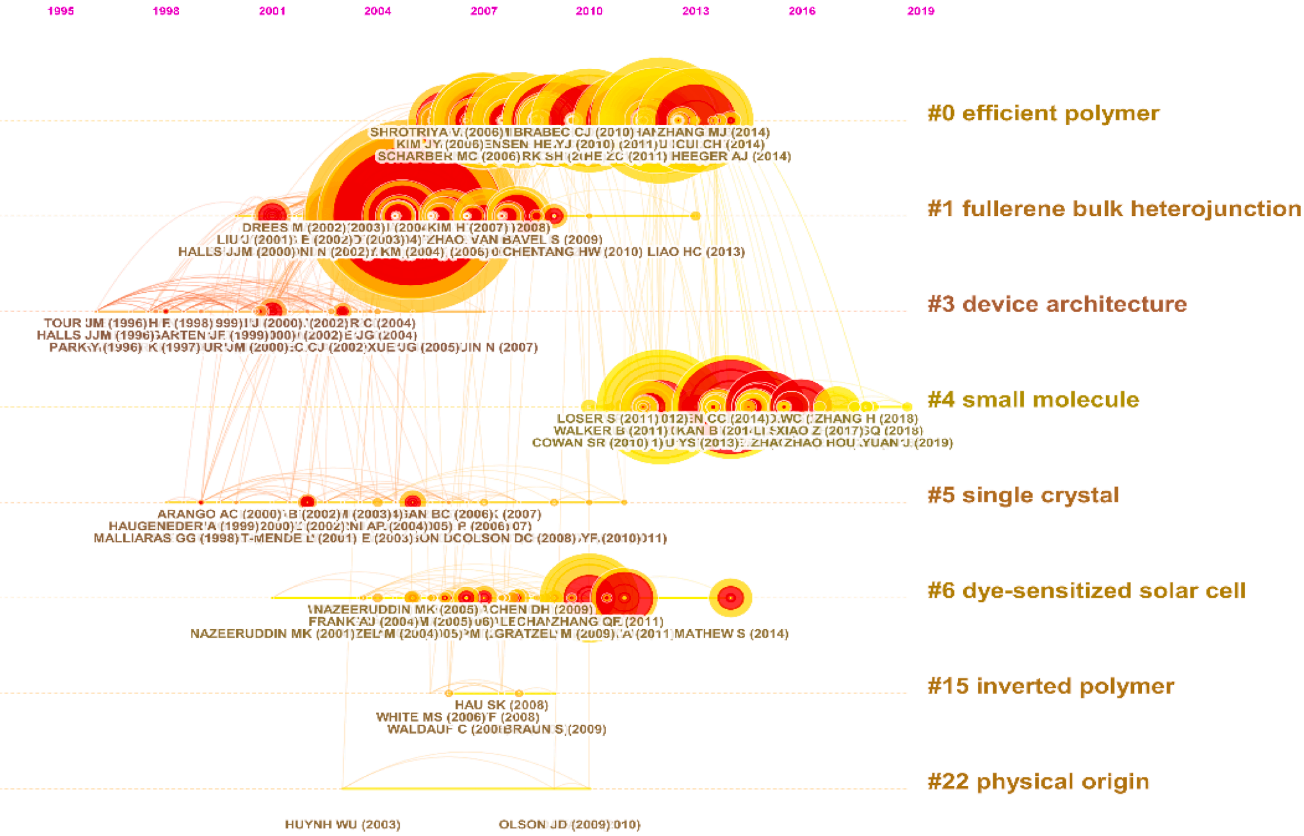
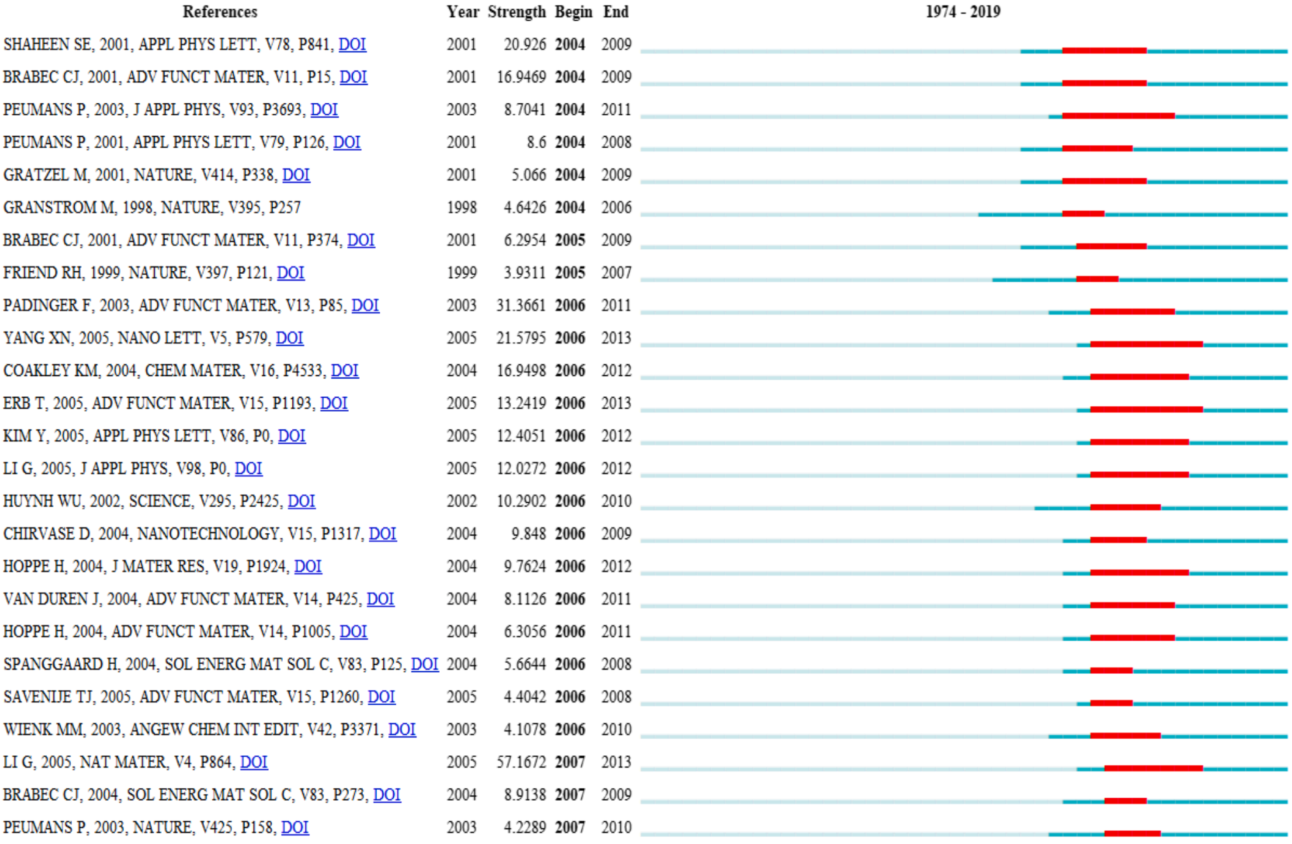


Fig. 6. Network of document co-citations.



References	Year	Strength	Begin	End
SHAHEEN SE, 2001, APPL PHYS LETT, V78, P841, DOI	2001	20.926	**2004**	2009
BRABEC CJ, 2001, ADV FUNCT MATER, V11, P15, DOI	2001	16.9469	**2004**	2009
PEUMANS P, 2003, J APPL PHYS, V93, P3693, DOI	2003	8.7041	**2004**	2011
PEUMANS P, 2001, APPL PHYS LETT, V79, P126, DOI	2001	8.6	**2004**	2008
GRATZEL M, 2001, NATURE, V414, P338, DOI	2001	5.066	**2004**	2009
GRANSTROM M, 1998, NATURE, V395, P257	1998	4.6426	**2004**	2006
BRABEC CJ, 2001, ADV FUNCT MATER, V11, P374, DOI	2001	6.2954	**2005**	2009
FRIEND RH, 1999, NATURE, V397, P121, DOI	1999	3.9311	**2005**	2007
PADINGER F, 2003, ADV FUNCT MATER, V13, P85, DOI	2003	31.3661	**2006**	2011
YANG XN, 2005, NANO LETT, V5, P579, DOI	2005	21.5795	**2006**	2013
COAKLEY KM, 2004, CHEM MATER, V16, P4533, DOI	2004	16.9498	**2006**	2012
ERB T, 2005, ADV FUNCT MATER, V15, P1193, DOI	2005	13.2419	**2006**	2013
KIM Y, 2005, APPL PHYS LETT, V86, P0, DOI	2005	12.4051	**2006**	2012
LI G, 2005, J APPL PHYS, V98, P0, DOI	2005	12.0272	**2006**	2012
HUYNH WU, 2002, SCIENCE, V295, P2425, DOI	2002	10.2902	**2006**	2010
CHIRVASE D, 2004, NANOTECHNOLOGY, V15, P1317, DOI	2004	9.848	**2006**	2009
HOPPE H, 2004, J MATER RES, V19, P1924, DOI	2004	9.7624	**2006**	2012
VAN DUREN J, 2004, ADV FUNCT MATER, V14, P425, DOI	2004	8.1126	**2006**	2011
HOPPE H, 2004, ADV FUNCT MATER, V14, P1005, DOI	2004	6.3056	**2006**	2011
SPANGGAARD H, 2004, SOL ENERG MAT SOL C, V83, P125, DOI	2004	5.6644	**2006**	2008
SAVENIJE TJ, 2005, ADV FUNCT MATER, V15, P1260, DOI	2005	4.4042	**2006**	2008
WIENK MM, 2003, ANGEW CHEM INT EDIT, V42, P3371, DOI	2003	4.1078	**2006**	2010
LI G, 2005, NAT MATER, V4, P864, DOI	2005	57.1672	**2007**	2013
BRABEC CJ, 2004, SOL ENERG MAT SOL C, V83, P273, DOI	2004	8.9138	**2007**	2009
PEUMANS P, 2003, NATURE, V425, P158, DOI	2003	4.2289	**2007**	2010

Fig. 7. Top 25 references with the strongest citation burst.

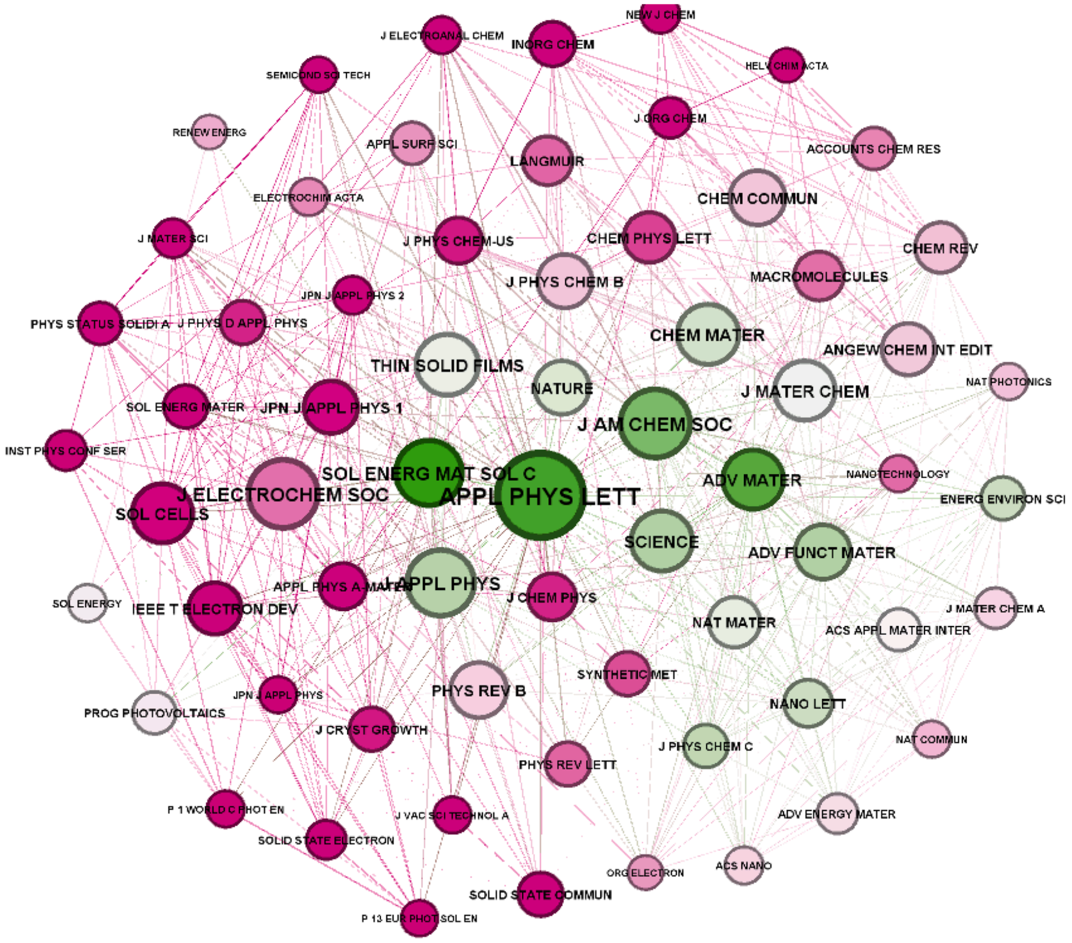


Fig. 8. Co-citation network of journal sources.

The highest ranked item by citation counts is “Solar Energy Materials and Solar Cells” with 2091 citations followed by “Applied Physics Letters” with 2029, Advance Materials with 1938, “Journal of the American Chemical Society” with 1747, “Advanced Functional Materials” with 1452, “Science” with 1441, “Journal of Applied Physics” with 142, “Journal of Physical Chemistry C” with 1363, “Nano Letters” with 1295, and “Energy and Environment Science” with 1292 citation counts. Table A3 in the appendix shows the details of twenty journal sources with the highest citation count. This result shows the significant contribution these journals have made in the area of photovoltaic waste research.

3.4.6. *Citation bursts and betweenness centrality*

The highest ranked item by bursts is “Nano Energy” with bursts of 102.83. The second one is “Synthetic Metals” with bursts of 80.43. The third is “Nature Energy” with bursts of 74.00. The 4th is “Chemical Physics Letters” with bursts of 65.44. The 5th is “Energy Policy” with bursts of 64.74. The 6th is “Scientific Reports” with bursts of 60.42. The 7th is “IEEE Journal of Photovoltaics” with bursts of 58.26. The 8th is “Journal of Materials Chemistry A” with bursts of 51.91. The 9th is “Nanotechnology” with bursts of 51.64. The 10th is “Journal of Materials Chemistry C” with bursts of 50.47.

The highest ranked item by centrality is “Applied Physics Letters” with centrality of 0.26. The second one is “Solar Energy Materials and Solar Cells” with centrality of 0.18. The third is “Journal of the Electrochemical Society” with centrality of 0.16. The 4th is “Solar Energy” with centrality of 0.10. The 5th is “Renewable Energy” with centrality of 0.10. The 6th is “Solar Cells” with centrality of 0.09. The 7th is “Journal of the American Chemical Society” with centrality of 0.09. The 8th is “Journal of Applied Physics” with centrality of 0.08. The 9th is “Japanese Journal of Applied Physics” with centrality of 0.08. The 10th is Physical Review B with centrality of 0.08.

3.5. *Co-author analysis*

Glänzel and Schubert (2005) argues that, the lack of scientific collaboration or co-authorship is seen as lower research productivity within the scientific community. Thus, publications produced through collaboration serves as enough evidence as they receive more citations and are published in higher impact journals. This section explains the scientific collaboration between authors through their publication, countries and institutions using the VOSviewer, CiteSpace and Gephi software with an explanation of the publication distribution using mapchart.net. The sections therefore explain the co-authorship networks, network of countries/regions and the network of institutions/faculties.

3.5.1. *Co-authorship network*

The author to author publication network starts with researchers such as Li, Yongfang who has had about fifty-three collaborations, which is the highest, collaborating with authors like Zou, Yingping; Zhang, Zhiguo (4th highest); Shen, Ping; Yuan, Jun; Sun, Chenkai; Cui, Chaohua; Brabec, Christoph J.; Liu, Feng; and Chen, Yiwang (2nd highest). Another prominent researcher Cao, Yong (3rd highest) has also made collaborations with several researchers among them are Kim, Jin Young (5th highest); Wang, Jian; Woo, Han Young; Wang, Jing; Russell, Thomas P. and Liu, Feng. The colours in Fig. 9 represents the research communities of the authors within the photovoltaic waste research field.

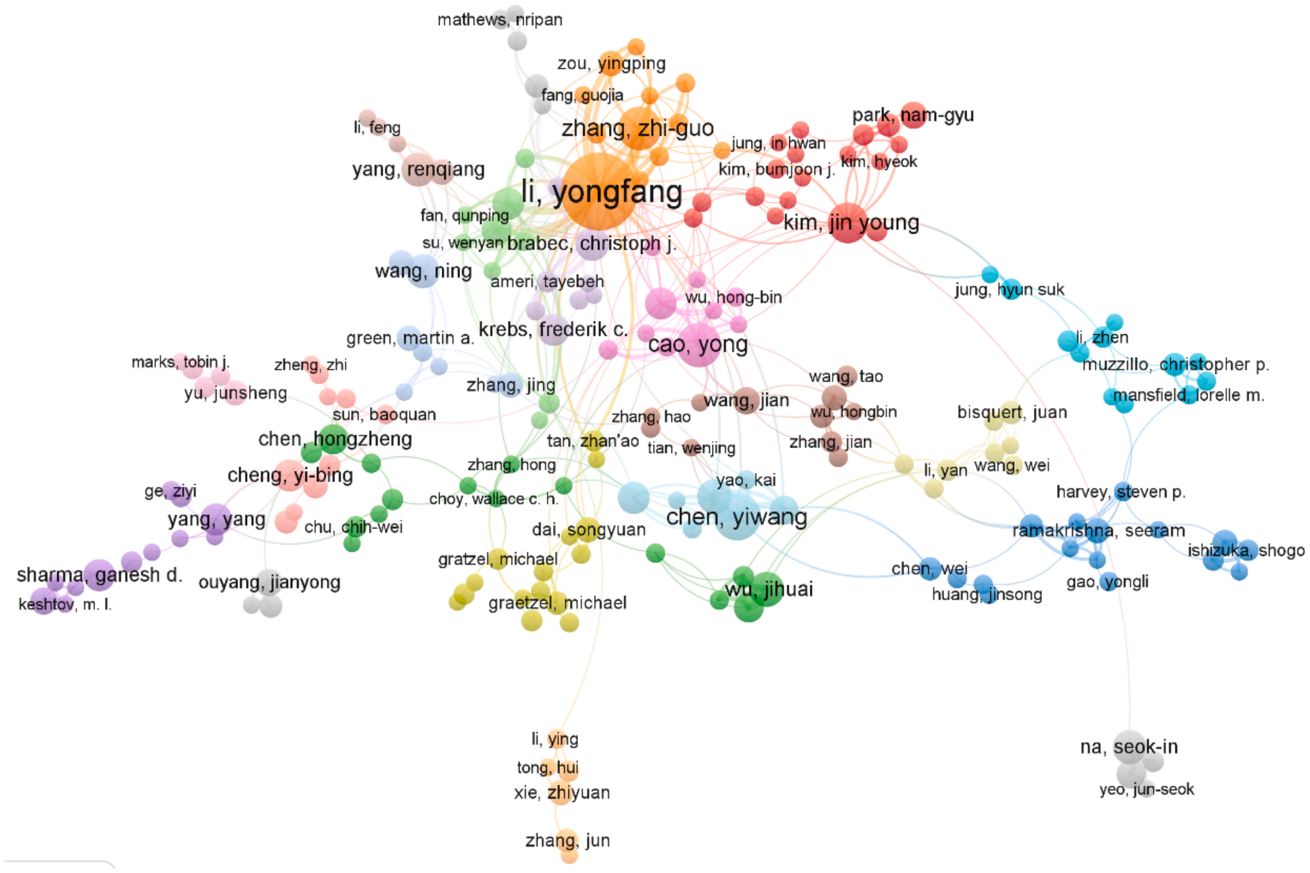


Fig. 9. Author collaboration network.

The top ten collaborators by the number of articles produced are Li, Yongfang (53) with 2085 citations; Chen, Yiwang (24) with 373 citations; Cao, Yong (22) with 702 citations; Zhang, Zhi-gou (21) with 279 citations; Kim, Jin Young (19) with 1914 citations; Chen, Lie (15) with 246 citations; Wu, Jihuai (15) with 250 citations; Brabec, Christoph J. (14) with 2185 citations; Yang, Renqiang (14) with 238 citations; and

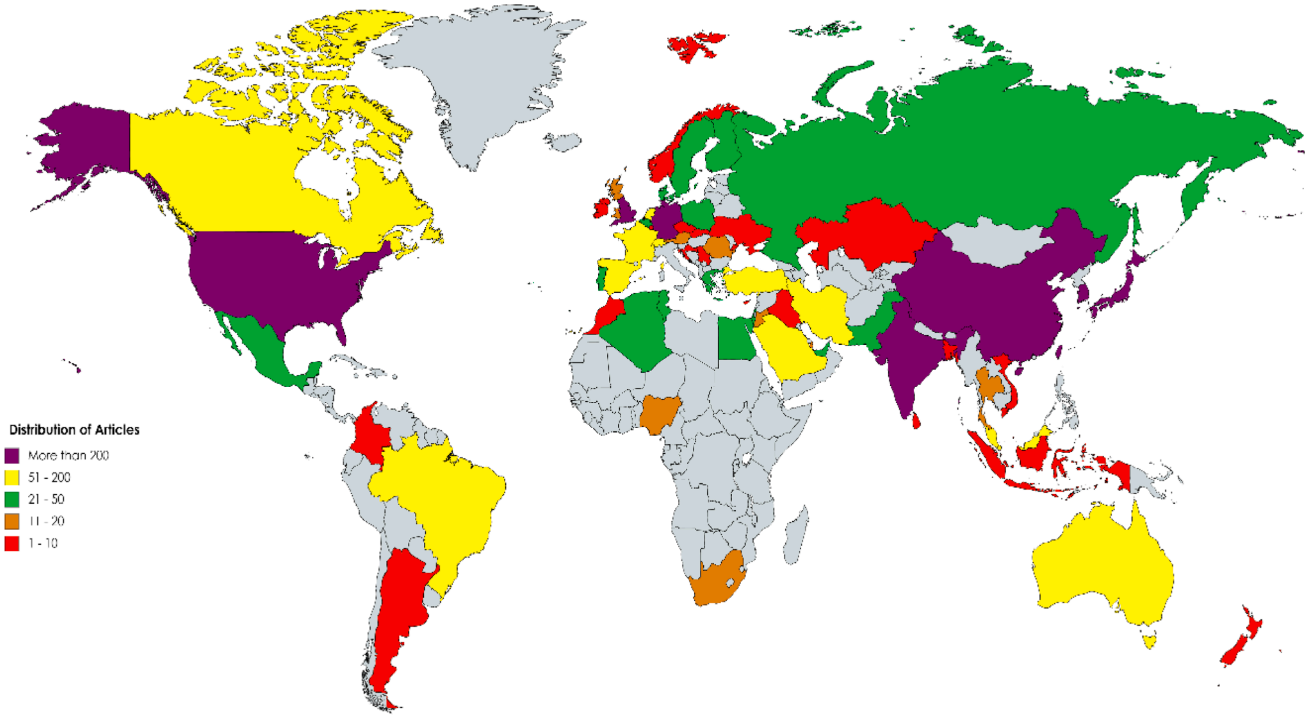


Fig. 10. Distribution of articles across countries.

Na, Seok-in (14) with 635 citations.

3.5.2. *Network of countries/regions*

Fig. 10 shows the distribution of the number of published researches by country worldwide. Countries like USA., China, England, Germany, Japan, South Korea, India all had more than 200 published articles on photovoltaic waste research. Canada, Spain, France, Australia, Iran, Turkey, Malaysia, Netherlands and Brazil were among the countries with about 51 to 200 documents. The rest of the countries including Algeria, Egypt, Russia, Poland, South Africa and the others shown on the map produced 50 articles or less. This establishes the seriousness and contribution of countries like the USA and China on the fight against photovoltaic waste through research and innovation.

The highest ranked item by frequency is China with documents of 1150 and a citation count of 25571, followed by the USA with 819 documents and 36,444 citation counts. Next is South Korea with 451 documents and 10,768 citation counts, Japan with 280 documents and 7243 citation counts, India with 258 documents and 3035 citation counts, Germany with 240 documents and 7075 citation counts, Italy with 229 documents and 8859 citation counts, Taiwan with 222 documents and 4144 citation counts, England with 217 documents and 9086 citation counts, and France with 183 documents and 6621 citation counts. The details are documented as Table A4 in the appendix section of this paper.

3.5.2.1. Citation bursts and betweenness centrality. The highest ranked item by bursts is France with bursts of 21.71, followed by Japan with bursts of 20.63, the USA with bursts of 17.73, Singapore with bursts of 10.91, Germany with bursts of 8.25, Taiwan with bursts of 6.16, and Austria with bursts of 4.08. France showed a lot of productive research from 1996 through to 2008. Fig. 10 shows a lot of productive research being done across the globe. The links and collaborations between the countries are very strong and very productive. Table 3 shows the burstness and betweenness centrality of the countries through the years and at what point they have been productive.

The highest ranked item by centrality is USA with centrality of 0.29, followed by England with centrality of 0.25, Germany with centrality of 0.17, France with centrality of 0.16, Spain with centrality of 0.13, China with centrality of 0.11, Australia with centrality of 0.08, Japan with centrality of 0.07, Saudi Arabia with centrality of 0.07, and India with centrality of 0.06.

3.5.3. *Network of institutions/faculties*

Collaboration between institutions are very important in the growth of research and development through the sharing of ideas and expertise within the same and different fields. Thus, collaborations between various researchers both in the same field and interdisciplinary has grown recently. This has seen various institutions collaborating with others due to similar interest in several research fields. To reveal these characteristics, CiteSpace was used to analyse the data retrieved from the WoS database. The results of the analysis revealed a modularity score of 0.663 and a mean silhouette of 0.2719. This is visualised in Fig. 11.

The highest ranked item by citation count is Chinese Academy of Sciences with citation counts of 251, followed by National Renewable Energy Laboratory with citation count of 84, the University of the Chinese Academy of Sciences with a citation count of 52, Soochow University with citation counts of 50, Sungkyunkwan University with a citation counts of 48, National Taiwan University with a citation count of 43, North China Electric Power University with a citation count of 41, Nanyang Technology University with a citation count of 39, Zhejiang University with a citation counts of 37, and the National University of Singapore with a citation count of 35. Table A5 in the appendix shows the details of twenty institutions with the highest citation count.

Table 3
Burstness and centrality of collaborative countries.

No.	Country	Burst	Centrality	Span
1	France	21.71	0.16	1996–2008
2	Japan	20.63	0.07	1998–2010
3	USA	17.73	0.29	1991–2009
4	Singapore	10.91	0.00	2011–2012
5	Germany	8.25	0.17	2000–2005
6	Taiwan	6.16	0.01	2008–2011
7	Austria	4.08	0.00	2011–2012

3.5.3.1. Citation bursts and betweenness centrality. The highest ranked item by bursts is the South China University of Technology with bursts of 7.76. The second one is National University of Singapore with bursts of 6.98. The third is Nanyang Technology University with bursts of 5.08. The 4th is National Taiwan University with bursts of 4.96. The 5th is Industrial Technology Research Institute with bursts of 4.95. The 6th is University of California, Los Angeles with bursts of 4.89. The 7th is Pusan National University with bursts of 4.80. The 8th is the Beijing Jiaotong University with bursts of 4.56. The 9th is Massachusetts Institute of Technology (MIT) with bursts of 4.56. The 10th is the Delft University of Technology with bursts of 4.48.

The highest ranked item by centrality is the Chinese Academy of Sciences with centrality of 0.37. The second one is National Renewable Energy Laboratory with centrality of 0.17. The third is National Chiao Tung University with centrality of 0.13. The 4th is Sungkyunkwan University with centrality of 0.10. The 5th is Soochow University with centrality of 0.09. The 6th is National University of Singapore with centrality of 0.08. The 7th is Nanyang Technology University with centrality of 0.08. The 8th is Seoul National University with centrality of 0.06. The 9th is Yeungnam University with centrality of 0.06. The 10th is Ecole Polytechnique Federale de Lausanne with centrality of 0.06.

4. Discussion of emerging trends and future directions

Recently, the PV market has seen the dominance of Si-crystalline (mono or poly) panels, which has become the most used PV technology worldwide because of its high efficiency and low cost of production. Alternative technologies such as Hybrid and organic cells, CdTe and CIGS have been developed and others still under research. However, Si-crystalline (mono or poly) panels, remains the most profitable (Padoan et al., 2019). The usage of toxic elements (Cd in CdTe) and rare/critical substances in the production of these PV modules are the main concern to their use extensively. Furthermore, the waste generation from the PV module is being tagged as potentially harmful, similar to e-waste, and is liable to the European WEEE (Waste Electrical and Electronic Equipment) Directive (2012). This has generated a lot of debate around the policies and regulations, performance and efficiency, recovery and recycling and end-of-life assessment of solar PV module waste management. Drawing from the aforementioned analysis, the emerging trends and future directions are discussed under four themes.

4.1. *Policies and regulations*

Several countries have been early promoters of solar energy. They have focused on providing financial and investment aid in supporting initial policies and regulations. The introduction of feed-in tariffs (FiTs) in Australia, United Kingdom, Portugal, Italy, Germany, France, Japan and other countries has caused an increase in the installation of solar PV panels in the residential sector (Pereira da Silva et al., 2019). There are other policies by governments which also provided incentives for the increase in the use of solar PV worldwide, aiming to achieve intergovernmental sustainability targets. This has informed many to turn to renewable and sustainable energy sources. With photovoltaics as an important solar energy generator, world leaders developed interest in this particular source of energy and started initiating policies and

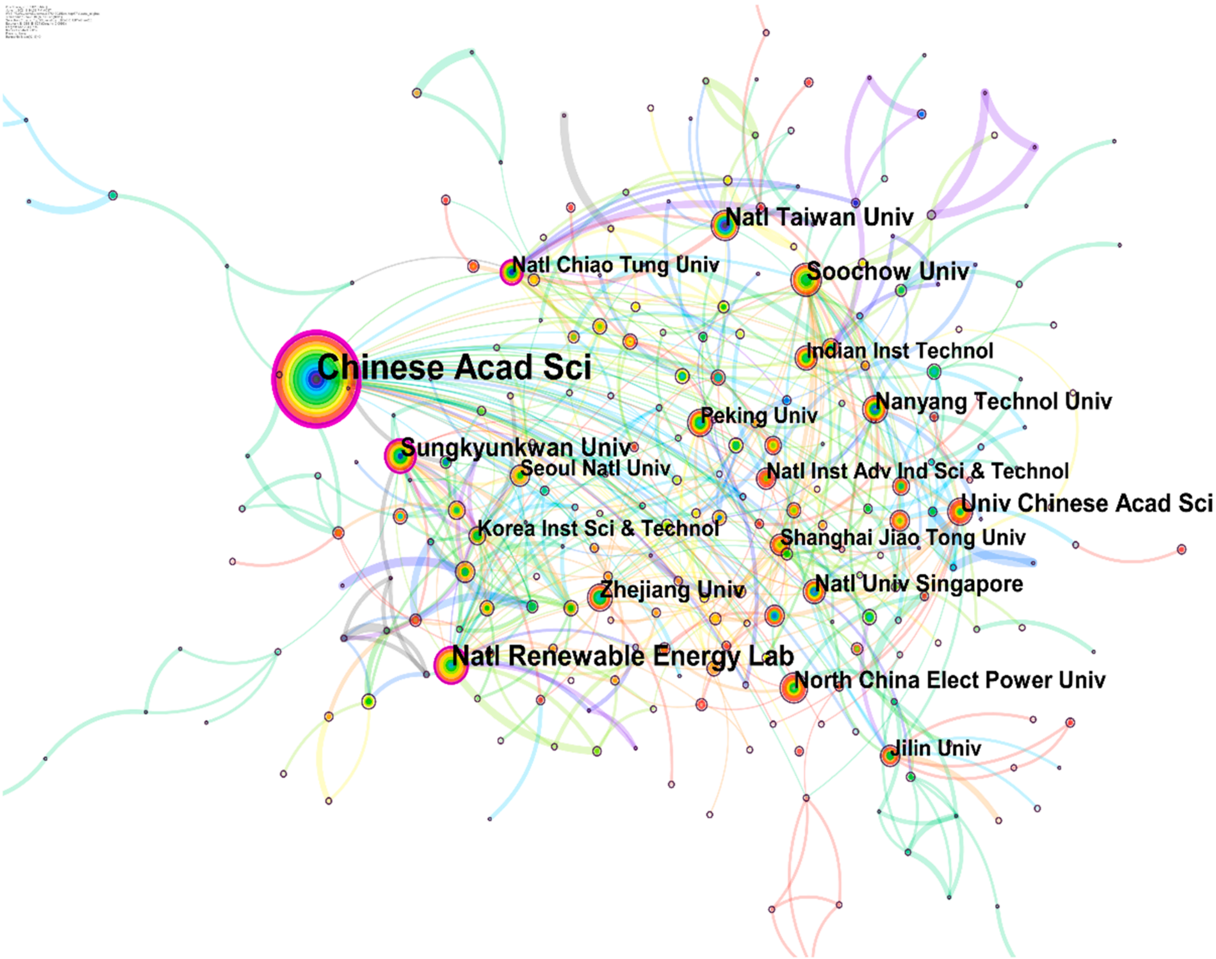


Fig. 11. Network of collaborations between institutions.

regulations for its use. However, the current problem to this is the harm it can cause if not properly disposed at the end of its life. The attention generated by this threat has again brought governments together to search for a solution. Since policies and regulations keep changing when it comes to the solar PV industry, several countries have started developing new policies or modifying others to help in achieving the sustainability goals. According to this analysis, the results clearly show the less attention that is given to policies and regulations when it comes solar PV waste research over the years. The analysis draws researcher's attention to the performance and efficiency of solar cells throughout the co-word and co-citation analysis. Nonetheless, recent research has emphasised the need to establish policies and standards for PV disposal (Nain and Kumar, 2020; Shubbak, 2019).

According to Xu et al. (2018) there should be an encouragement within government agencies in devising a recycling and safe disposal policy for solar PV module waste. This has informed several countries into developing policies that tackle solar PV waste at the end-of-life management. The European Union (EU) on their Waste Electrical and Electronic Equipment (WEEE) Directive outlined guidelines for the collection, recycling and recovery of solar PV waste. Reinforcing the responsibility of producers is an efficient approach in managing waste from solar PV known as the extended producer responsibility (Fthenakis et al., 2020). Many countries are introducing regulatory frameworks to guide the management of PV module waste. The WEEE directive has been a big influence in areas like Japan, South Korea, China and California in the establishment of similar policies and regulations. There is more to be done because of the potential waste that will come into the system in the years to come. Countries which produces most of these wastes are yet to establish safe guidelines in regulating solar PV module waste. Polices and regulations are needed to guide the safe disposal of these waste as well as the proper recycling and recovery of old panels. The results emphasised on the use of new materials such as organic cells which are more efficient and cheaper. Regulations should be made in the use of sustainable materials and easy to recycle materials after their end-of-life.

4.2. Performance and efficiency

Performance and efficiency have been the centre of research in photovoltaics for a very long time as the results suggests. This started with the development of the first-generation photovoltaics which were based mostly on silicon (i.e. solar cells which were either single-crystalline or multi-crystalline). The second generation focused more on thin-film modules and cells (i.e. amorphous silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS)). The third-generation technologies however in an innovative capacity integrates several organic, inorganic or hybrid-based solar cells. This has seen efficiency and technological development in the application of solar PV through technologies such as quantum dots solar cells (QDSCs), perovskite solar cells (PSCs), full organic PV solar cells (OPCs) and dye sensitized solar cells (DSSCs) (Parisi et al., 2020). This technological innovation and improvement have been seen throughout the years and in this analysis within the visualisation of the keyword clusters and citation bursts. The highest frequency within the keywords analysis was performance and efficiency. Solar PV performance has gone through several technological advancement and research through the use of different materials. Materials such as DSSCs was used a lot in these experiments. between 2003 and 2009, researchers studied the characteristics of DSSCs (Lupan et al., 2010; Xi et al., 2010; Yu et al., 2011), aiming to improve the performance and efficiency of these cells and also application of organic and hybrid solar cells. These research leads towards finding a more sustainable solar cell in the future. Researchers are encouraged to work on more sustainable an efficient solar cell to reduce the burden on waste from the end-of-life solar cell.

4.3. *Recycling and recovery*

The rapid growth in the installation of solar PV systems and its generation capacity has necessitated the implementation of recovery and recycling strategies of end-of-life PV panels by 2040. This action is anticipated to result in carbon dioxide emission reduction and therefore, positively address environmental sustainability targets. Solar module recycling has been the focus when it comes to research and development in the US, Europe and Japan recently. Recycling types such as the physical, thermal and chemical processes are the three types that are commonly applied to solar PV panels. Most importantly, the research focuses on the Si panels on how to recycle and recover the essential parts for remanufacture (Chowdhury et al., 2020). This has caused several researchers to patent their recycling procedures. There are other recycling processes such as the mechanical processes which has an advantage of being inexpensive but requires more elaborate treatment when recovering high value materials (Padoan et al., 2019). From Vargas and Chesney (2020), in 2018 a joint effort between PV Cycle France and Veolia lead to the installation of a recycling plant in France which was the first in Europe. The facility by 2022 is expected to recycle over 4,000 tons of solar PV waste.

The remanufacture of solar PV from recovered or recycled materials is gaining a lot of attention recently. The analysis of the keywords shows results of the clusters and citation burst mostly around the year 1992 to 2011, recycling and recovering was not covered by many researchers around these years. This is because, solar PV then and now are not concentrated neither by content nor geography, with many applications dominated by stand-alone residential installations as well as off-grid power systems application on industrial areas. The collection as well as the value of materials to be reclaimed are low (Fthenakis, 2000). However, the first-generation of the solar photovoltaic panels are coming to the end of their life. This has called for researchers to focus more on the end-of-life treatment and production of a safer and more efficient photovoltaic cells in the future. Over the years, researchers (Dominguez and Geyer, 2017; Salim et al., 2019a) have proven the harmful effect of waste from solar photovoltaics and the need to manage these wastes to help improve the environment. The research on environmental impact from solar photovoltaics have been conducted a lot with several recommendations on the need to properly manage the incoming influx of solar waste in the coming years. Options such as incineration, recycling, treatment and disposal has been some of the solutions up until now (Mahmoudi et al., 2019b; Shubbak, 2019). Recycling PV waste is beneficial to the environment and as well will become economically profitable with decreased initial investment cost as PV module waste flow rises (Faircloth et al., 2019). More research and development are needed in fighting negative impacts recycling processes have on the environment (Contreras Lisperguer et al., 2020). More so the economic and social aspects are very important in achieving sustainability.

4.4. *End-of-life assessment*

With emerging increase in the research and development of PV waste, there is still lack of data when it comes to waste from PV modules. There have been a lot of studies conducted by researchers to estimate the waste from PV panels in the years to come. This is to help with the forecasting of PV waste volumes necessary for designing a proactive strategy in treating and recycling waste (Dominguez and Geyer, 2019; Mahmoudi et al., 2019a). To do this, environmental and techno-economic analysis are needed to ascertain the impacts of the waste stream (Dominguez and Geyer, 2019) through assessment such risk and life cycle analysis. The results of these assessments inform governments and policy makers on the urgency of decreasing environmental impacts through the establishment of recycling and recovery facilities, especially with countries that do not have these facilities or regulations on PV waste but in highly use of PV technology (Contreras Lisperguer et al., 2020).

Many PV modules such as the silicon-based PVs are coming to their end-of-life in the near future, others like the CdTe PV modules as stated by Fthenakis et al. (2020) are not of an immediate concern because of their relatively low volume of installation and use. With their decommissioned time slated for 25 to 30 years, a considerable growth in CdTe PV waste is anticipated. However, to deal with the considerable amount of PV module waste in the near future (IRENA and IEA-PVPS, 2016), their end-of-life management must be understood today to prevent problems associated with sustainability in the coming years. There have been a lot of assessment on Solar PV waste ranging from Risk assessment, material flow analysis, circular economy, Chemical treatment and life cycle analysis. A clear indication of the earlier results of the analysis reveals that, early research was based more on the performance and efficiency of solar panels instead of its waste prospects. The term end-of-life was recently introduced within the solar PV research field because of the projection of PV waste in the coming years and the need for us to reach the sustainability goals and help protect the environment. Also, the issue of leaching and contamination of PV waste within the solar research field needs more attention as this research and others (Nain and Kumar, 2020) have shown.

5. Conclusions

Emerging waste streams such as that from the solar technologies are now becoming a problem because of the growth and the need to satisfy the housing and energy demands as well as produce clean energy. This has caused a quick rise in the installation of PV panels across the world. Solar photovoltaic waste research is an emerging research area which has received more attention recently due to the health and environmental impacts associated with its disposal. This study reviewed the emerging trends and patterns of PV waste research over the years. The study revealed that, research on solar photovoltaics was first referenced as back as 1974 in the journal of applied physics, also the study has seen a gradual increase in the interest of solar photovoltaic waste research since 1974. Moreover, Advanced Energy Materials, Advanced Functional Materials, Journal of Materials Chemistry A, Renewable and Sustainable Energy Reviews and ACS Applied Materials and Interfaces were ranked as the top five journals with the highest impact factor per the 2019 incites citation report.

The co-word analysis established the keyword co-occurrence and clusters as well as the subject categories which revealed performance and efficiency as the most frequent keywords, and this is because there is a considerable effort going into research on the performance and efficiency of alternative PV technologies to replace the old ones. A good mention is the polymer solar cell. The keyword clusters however produced five clusters and they are solar cell, dye-sensitized solar cell which appeared twice, Cadmium telluride (CdTe) solar cell and single-walled carbon nanotube. The co-citation analysis discussed the author co-citation, document co-citation and the journal co-citation networks. The discussion revealed the attention that has been given to polymer solar cells within the past few years as researchers continue to search for a more efficient and strong performing material to alternatively replace the old technologies. It was realised in the discussion that, waste research towards the end-of-life solar panels started within the decade and continues to grow. The collaborative efforts of the authors were also discussed with the USA and China proving to be the most collaborative countries as well as researchers on solar PV waste research. The results posit that, little attention was given to reuse, recovery and recycling of solar PV modules throughout the years and with the previous installations coming to their end-of-life, interest in its management has been one of the hot topics recently.

With most of the earlier research concentrating on the performance and efficiency of polymer solar cells, future research should aim at finding solar cells that are easily recycled or recovered after its end-of-life. Moreover, the commercialisation of organic solar cells should be prioritised because of its environmental benefits. Current research on PV module waste, needs improvement because of the slow development of policies and regulations in countries with a high number of solar PV installations. Furthermore, assessments (risk and life cycle analysis) should be conducted on waste disposal strategies and recycling technologies to meet the requirements of the old and new PV modules. Finally, future research should focus on assessing the emissions of current solar PV modules and the easy remanufacture, recovery and reuse of future solar PV modules.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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Supplementary Material (Appendix A)

A scientometric review of trends in solar photovoltaic waste management research

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Table A1: Details of Techniques

The table details the techniques (scientometric analysis) used in the paper and the description of the software analysis with their corresponding citations.

Technique	Technique	Software/Tool	Table/Figure	Section	Description	References
Co-word analysis	Co-occurring keywords	VOSviewer CiteSpace	Fig. 2, 3 Table 2, A2	3.3.1	The data was analysed using all the keywords such as the author's keywords and keywords plus (indexed terms from journals) from the database. Analysing keywords in clusters helps establishes emerging trends in literature. LLR which highlights the unique themes was used in analysing the keywords in CiteSpace and the Label view was used in VOSviewer.	(Chen, 2006; van Eck and Waltman, 2009)
	co-occurring subject categories	CiteSpace	Fig. 4	3.3.2	The data was uploaded to CiteSpace with the analysis set to Subject Categories to determine the main concepts or structure within the research field. The time slice was set to one year per slice with the nodes set to top 50 levels of most cited items from each slice.	(Chen, 2006)
Co-citation analysis	Author co-citation network	VOSviewer CiteSpace	Fig. 5	3.4.1	The data was uploaded to VOSviewer and the analysis set to author co-citation to visualise the most frequent clusters in label view. CiteSpace was used to determine the authors cited together frequently by setting the software to author co-citation analysis.	(Chen, 2006; van Eck and Waltman, 2009)
	Document co-citation network	CiteSpace	Fig. 6	3.4.2	Document co-citation construct networks of cited references using CiteSpace. A time series of network models are built using a time slicing technique to create an overview network through the synthesizes of individual	(Chen, 2006)

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					networks. The Link retaining factor and maximum links per node was set to three and five respectively for the analysis.	
	Journal co-citation network	CiteSpace Gephi	Fig. 8	3.4.3	The data was uploaded to CiteSpace and set to journal co-citation. The analysis resulted in journals that are frequently co-cited together. This data was then uploaded to Gephi to extract the visual representation of the reults.	(Chen, 2006; Bastian et al., 2009)
Co-author analysis	Co-authorship network	VOSviewer CiteSpace	Fig. 9	3.5.1	The data was uploaded to VOSviewer and co-authorship was selected for analysis. The default value 20 citations were used as the inclusion criteria for selection. The data was further analysed using CiteSpace to ascertain the citation burst and betweenness centrality.	(Chen, 2006; van Eck and Waltman, 2009)
	Network of countries/regions	CiteSpace	Fig. 10 Table 3	3.5.2	Data was uploaded into CiteSpace for the network of countries and institutions. Both node types were selected in CiteSpace for analysis. With one year per slice and levels of most cited items from each slice as 50, both nodes were analysed to arrive at the various clusters.	(Chen, 2006)
	Network of institutions /faculties	CiteSpace	Fig 11	3.5.3		(Chen, 2006)

Table A2: Detailed characteristics of keyword clusters

The table shows the details of the five keyword clusters, the twenty highest labels (LLR) and their characteristics are highlighted in the table.

Cluster ID	Cluster Name	Size	Silhouette	Mean (Year)	Label (LLR) (p-value)
0	Solar Cell	64	0.78	2007	solar cell (587.02, 1.0E-4); bulk heterojunction (498.54, 1.0E-4); solution-processed polymer (385.57, 1.0E-4); charge generation (382.26, 1.0E-4); fullerene bulk heterojunction (236.88, 1.0E-4); pcbm morphology (207.2, 1.0E-4); phenol liquid crystalline compound (203.9, 1.0E-4); dye-sensitized solar cell (200.68, 1.0E-4); optical probe (200.6, 1.0E-4); efficient organic photovoltaic device (197.31, 1.0E-4); colloidal nanocrystal hybrid (194.01, 1.0E-4); using ethanedithiol treatment (194.01, 1.0E-4); controlling hierarchy (190.72, 1.0E-4); crosslinked p3ht (190.72, 1.0E-4); organic solar cell (189.6, 1.0E-4); acceptor copolymer (187.42, 1.0E-4); high open-circuit voltage (187.42, 1.0E-4); salt-based molecule (184.12, 1.0E-4); enhanced performance (184.12, 1.0E-4); cathode interlayer (184.12, 1.0E-4).

1	dye-sensitized solar cell	52	0.696	2007	dye-sensitized solar cell (792.66, 1.0E-4); perovskite solar cell (642.27, 1.0E-4); solar cell (301.33, 1.0E-4); photovoltaic module (262.22, 1.0E-4); bulk heterojunction (230.78, 1.0E-4); photovoltaic performance (223.6, 1.0E-4); photovoltaic system (177.55, 1.0E-4); crystalline silicon (174.82, 1.0E-4); life cycle assessment (172.09, 1.0E-4); solution-processed polymer (155.73, 1.0E-4); charge generation (154.36, 1.0E-4); solar energy (139.37, 1.0E-4); thermoelectric device (132.57, 1.0E-4); solvent treatment (109.84, 1.0E-4); spatial distribution (109.84, 1.0E-4); synergistic amplification (109.84, 1.0E-4); temperature dependence (108.51, 1.0E-4); surface treatment (108.51, 1.0E-4); solar cell device (107.19, 1.0E-4); cspbi2br thin film (107.19, 1.0E-4).
2	dye-sensitized solar cell	45	0.76	2009	dye-sensitized solar cell (578.9, 1.0E-4); photovoltaic module (551.81, 1.0E-4); photovoltaic system (401.88, 1.0E-4); crystalline silicon (395.81, 1.0E-4); life cycle assessment (389.74, 1.0E-4); perovskite solar cell (367.92, 1.0E-4); solar energy (316.97, 1.0E-4); thermoelectric device (301.82, 1.0E-4); solar-powered rankine cycle (223.15, 1.0E-4); fresh water production (223.15, 1.0E-4); solar thermal-driven reverse osmosis desalination (220.12, 1.0E-4); recycling model (217.1, 1.0E-4); extended producer responsibility (217.1, 1.0E-4); two-stage parabolic trough (214.08, 1.0E-4); optical modeling (214.08, 1.0E-4); using spectral beam splitting technology (214.08, 1.0E-4); laser processes (211.06, 1.0E-4); photovoltaic silicon (211.06, 1.0E-4); chemical treatment (208.03, 1.0E-4); recovering pure silicon (208.03, 1.0E-4).
3	cdte solar cell	38	0.765	2003	cdte solar cell (258.62, 1.0E-4); cdte thin film (244.78, 1.0E-4); znse thin film (198.74, 1.0E-4); schottky barrier junction (198.74, 1.0E-4); well-aligned array (194.02, 1.0E-4); ito-coated glass (194.02, 1.0E-4); chalcopyrite thin film (189.31, 1.0E-4); using drive-level capacitance (184.59, 1.0E-4); metastable defect (184.59, 1.0E-4); cuin1-xgaxse2 thin film (184.59, 1.0E-4); scalable core-shell (179.89, 1.0E-4); tio2 solar cell (179.89, 1.0E-4); thin-film cu (175.19, 1.0E-4); photovoltaic cd (170.5, 1.0E-4); thin film layer (170.5, 1.0E-4); photoluminescence study (170.5, 1.0E-4); zn-rich cu2znsns4 film (165.81, 1.0E-4); formation mechanism (165.81, 1.0E-4); metallic stack (165.81, 1.0E-4); single-step sulfo-selenization method (161.13, 1.0E-4).
4	single-walled carbon nanotube	12	0.866	2005	single-walled carbon nanotube (106.89, 1.0E-4); polymer amine (106.89, 1.0E-4); n-type transparent conducting film (106.89, 1.0E-4); open circuit voltage (96.15, 1.0E-4); compact tio2 photovoltaic film (85.41, 1.0E-4); o-2 plasma treatment (85.41, 1.0E-4); si incorporation (85.41, 1.0E-4); nanocrystalline building block (74.69, 1.0E-4); crystalline mesoporous titania film (74.69, 1.0E-4); small molecule (67.35, 1.0E-4); incorporating ph-neutral pedot (63.98, 1.0E-4); hole transport layer (63.98, 1.0E-4); high purity silicon (53.29, 1.0E-4); rf plasma process (53.29, 1.0E-4); emitting diode (42.61, 1.0E-4); post-fabrication electric field (42.61, 1.0E-4); polymer light (42.61, 1.0E-4); titanium-doped

	indium oxide film (31.94, 1.0E-4); dye-sensitized solar cell application (31.94, 1.0E-4); using reactive rf magnetron (31.94, 1.0E-4).

Table A3: Citation count of journal sources

The table constitute the twenty highest citation count of journal sources from the analysis using CiteSpace.

Freq	Burst	Centrality	Sigma	PageRank	Year	Source
2091		0.18	1	0	1994	Solar Energy Materials and Solar Cells
2029	8.9	0.26	7.89	0	1991	Applied Physics Letters
1938		0.04	1	0	2002	Advance Materials
1747		0.09	1	0	1992	Journal of the American Chemical Society
1452		0.04	1	0	2004	Advanced Functional Materials
1441		0.04	1	0	1997	Science
1425	49.54	0.08	48.77	0	1991	Journal of Applied Physics
1363		0.01	1	0	2008	Journal of Physical Chemistry C
1295		0.03	1	0	2006	Nano Letters
1292		0.01	1	0	2010	Energy & Environmental Science
1247		0.06	1	0	2002	Chemistry of Materials
1211	7.21	0.02	1.18	0	1993	Nature
1141	6.69	0.02	1.15	0	2004	Nature Materials
1119	15.77	0.07	2.8	0	1993	Thin Solid Films
1079	7.63	0.05	1.49	0	2002	Journal of Materials Chemistry
1021	3.95	0.01	1.02	0	2011	ACS Applied Materials & Interfaces
990		0.1	1	0	1997	Solar Energy
988		0.05	1	0	1997	Progress in Photovoltaics
928		0	1	0	2012	Advanced Energy Materials
887	51.91	0	1.1	0	2014	Journal of Materials Chemistry A

Table A4: Citation count of countries/regions

The table shows twenty countries with the highest citation counts when it comes to publications using CiteSpace.

Freq	Burst	Centrality	Sigma	PageRank	Author	Year
1150		0.11	1	0	China	2003
819	17.73	0.29	95.78	0	USA	1991
451		0.04	1	0	South Korea	2000
280	20.63	0.07	4.17	0	Japan	1998
258		0.06	1	0	India	2006
240	8.25	0.17	3.66	0	Germany	2000
229		0.06	1	0	Italy	2001
222	6.16	0.01	1.05	0	Taiwan	2007
217		0.25	1	0	England	1998
183	21.71	0.16	24.23	0	France	1996

180		0.08	1	0	Australia	2002
160		0.13	1	0	Spain	2006
99		0.03	1	0	Canada	2007
98		0.01	1	0	Iran	2011
84	10.91	0	1.02	0	Singapore	2009
70		0.01	1	0	Brazil	2004
67		0.01	1	0	Switzerland	2011
59		0.01	1	0	Turkey	2008
59		0.02	1	0	Malaysia	2011
59		0.07	1	0	Saudi Arabia	2011

Table A5: Citation count of institutions/faculties

The table shows the highest citation count of twenty institutions/faculties publications using CiteSpace.

Freq	Burst	Centrality	Sigma	PageRank	Author	Year
251		0.37	1	0	Chinese Academy of Sciences	2007
84		0.17	1	0	National Renewable Energy Laboratory	1999
52		0.01	1	0	University of Chinese Academy of Sciences	2013
50		0.09	1	0	Soochow University	2013
48		0.1	1	0	Sungkyunkwan University	2009
43	4.96	0.05	1.26	0	National Taiwan University	2008
41		0	1	0	North China Electric Power University	2014
39	5.08	0.08	1.51	0	Nanyang Technological University	2011
37		0.02	1	0	Zhejiang University	2010
35	6.98	0.08	1.67	0	National University of Singapore	2011
32		0.13	1	0	National Yangming Jiaotong University	2010
32		0.03	1	0	Indian Institutes of Technology	2011
32		0.01	1	0	Peking University	2011
30		0.05	1	0	Jilin University	2010
29		0.03	1	0	Shanghai Jiao Tong University	2011
29		0.04	1	0	Korea Institute of Science and Technology	2009
28		0.06	1	0	Seoul National University	2011
28		0.04	1	0	National Institute of Advanced Industrial Science & Technology	2012
27	3.96	0.03	1.11	0	Xi'an Jiaotong University	2013
27		0.02	1	0	Tsinghua University	2011

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Appendix B – Manuscript: An expert-based evaluation on end-of-life solar photovoltaic management: An application of Fuzzy Delphi Technique

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Original Research Articles

An expert-based evaluation on end-of-life solar photovoltaic management: An application of Fuzzy Delphi Technique

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A R T I C L E I N F O

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Framework
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A B S T R A C T

The implementation of solar photovoltaic (PV) waste management options is of concern to international bodies, policymakers, and communities as it is not only related to life cycle environmental impacts but the preparation of a long-term plan and its successful implementation. There are insufficient options in Australia when it comes to the appropriate management of hazardous materials from solar PV waste. This study investigates the management of end-of-life (EoL) PV waste in Australia. A modified Fuzzy Delphi Method (FDM) is adopted in gathering data through interviews and questionnaires from experts in the field. The FDM analysis revealed the results showing the decisions made by the experts. The results show that, crystalline silicon panels were the most common panels on the Australian market and the ones that are being installed frequently. On policies, although the Australian government has banned PV waste from going to landfill since 2014, there were no regulations or action plans to manage PV waste. The absence of policies and regulations results in unregulated movement and tracking of solar PV waste in and out of Australia as well as within and across the states. The extent of the PV recovery and recycling is still under investigation. Moreover, infrastructure and logistics has been a significant problem because of the geographical spread of the country and how it affects transportation and the supply chain. Findings led to the establishment of a conceptual framework for the current treatment of solar PV waste in Australia.

Introduction

Solar photovoltaic (PV) energy is efficient, safe, and reliable. The interest in solar energy is at an all-time high because of the benefits mentioned. The global effort to achieve sustainable environmental goals has seen several government push for clean energy, which has seen the dramatical rise of solar energy use across the world (IEA-PVPS, 2021; IPCC, 2012). When it comes to green energy, increased adoption of solar PV delivers an effective solution (Dominguez and Geyer, 2019). Conventional power generation plants could be replaced or complemented by photovoltaic technology because of its current maturity. However, the upsurge in the global waste stream should be envisaged for the coming years. With old modules being replaced by new and some reaching their end-of-life (EoL), a significant amount of PV waste may end up in landfills if proper managerial steps are not considered and implemented (Khawaja et al., 2021).

Among the sources of electric energy generation, the amount of waste per unit energy attributed to solar PV waste is significantly high (Baldwin et al., 2015). This situation is alarming because of the installation year, 1990, for solar panels in most developed countries. Weckend et al. (2016) explains that, this will see an estimated global solar PV waste of 60 million tons being disposed into landfills in the year 2050. Dangerous elements like cadmium, chromium and lead in landfills could be harmful to the environment and human health if steps are not taken to curb the situation (Majewski et al., 2021). Landfilling is not sustainable long-term and is not an environmentally friendly option. With these heavy metals present in the panels, significant environmental issues may arise due to leaching or contamination in the soil or groundwater (Farrell et al., 2020).

According to Tsanakas et al. (2020), with the increase patronage in solar PV, value creation opportunities may be created through proactively adopting principles within a circular economy. The need for reuse of rare earth materials from end-of-life solar PV back into the supply chain and the avoidance of negative impacts to the environment and human health, associated with inappropriate hazardous material disposal (Salim et al., 2021), are key drivers for creating an effective sustainable policy for solar PV waste. The efficiency of new solar cells and their commercial supply have been the center of solar PV research in the past years. Currently, a significant body of research on solar PV waste is looking at the management and recycling of end-of-life solar PV across the world (Oteng et al., 2021; Xu et al., 2018).

According to Daniela-Abigail et al. (2022), the successful implementation of a long-term PV waste management plan which is tailored to a specific country is of concern to international bodies, policymakers

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and communities because of the environmental impacts associated with solar PV waste. Thus, to successful create a sustainable infrastructure for solar PV waste management, various stakeholders are required to contribute to achieving a long-term sustainability goal. Recently, a lot of countries are trying to ascertain effective ways to manage the PV waste stream, among them is Australia which has the highest adoption of rooftop solar PV in the world. Majewski et al. (2021) posits that, there are insufficient management options in Australia when it comes to the appropriate management of hazardous materials from solar PV waste. They also emphasize that; recyclers and recovery units currently lack the capability to recover valuable resources and materials from end-of-life solar PV.

There are existing studies on the drivers, barriers and enablers of solar PV waste (Curtis et al., 2021a; Mahmoudi et al., 2019; Salim et al., 2019) management, others, on the life cycle assessment of solar PV end of life in Australia (Mahmoudi et al., 2020, 2021) without necessarily investigating the current practices of solar PV waste management. Salim et al. (2021) also researched into the dynamic modeling of PV product stewardship transition in Australia. None of these studies in Australia, establishes the current managerial practices related to the movement, monitoring, and recycling of solar PV waste management through government and industry experts. This study bridges the gap by looking at the various practices associated with the management of end-of-life solar PV through expert interview and analysis. It adds to literature by conducting a comparative analysis between other countries in the management of PV waste. The study further develops a conceptual framework of the current PV waste management practices and suggests potential future directions in Australia.

Literature review

Technologies across solar photovoltaics and some of the practices related to the management of PV waste are reviewed in this section. A search criterion has been developed to ascertain the appropriate keywords for the review. Keywords include "treatment" OR "waste" OR "End-of-life" OR "dispos*" OR "recover*" "reus*" OR "recycl* AND "pv panels" OR "photovoltaic cells" OR "photovoltaic" OR "solar panels", were used as the search query using Booleans "OR" and "AND". This search was conducted in the Web of Science Core Collection occurring within the topic search. The search occurred on the 10th of December 2019 for the design of interviews for primary data collection and updated on the 31st of March 2022.

The keywords occur within the waste research studies conducted by researchers within the field of solar photovoltaics (Mahmoudi et al., 2019; Oteng et al., 2021; Salim et al., 2021). The Web of Science is used because of its quality and coverage of over 1.7 billion cited references within 155 million records in 34, 000 journals in different disciplines (Clarivate Analysis, 2020). A comprehensive literature review was conducted on solar PV waste research (Oteng et al., 2021) and a further classification was analyzed per the themes in Table 1. The classification consists of; solar panel technology: policies and regulations: monitoring, tracking and logistics: treatment pathway: and collection and infrastructure needs of solar PV waste. This formed the themes for the interview design and structure for primary data collection. Table A1 in the supplementary material shows the various themes involved in solar PV waste management literature and describes the process thereof.

Solar photovoltaic technologies

At the gigawatt scale of electricity production, solar photovoltaic technology is known to be the cleanest and safest among existing sources of renewable energy (IEA-PVPS, 2021). There has been a tremendous increase in the development of solar technology since its discovery in the 19th century. This development has seen dramatic changes to technological generation and efficiency, solar cell types, and technical fields within its mechanics, electronics, physics, and chemistry. Therefore, the production and application levels has dynamically improved on the market (Shubbak, 2019).

There are three classes of solar PV technology (Sundaram et al., 2016). These classes are known as the first, second and third generations of PV technology. The ones currently available on the market for consumers are the first and second generations. The first-generation technology are crystalline silicon (c-Si) wafer-based cells. Among the second generation are the single-junction Gallium Arsenide (GaAs) Cells, amorphous Silicon (a-Si) cells, Copper indium gallium di-selenide (CIGS) cells, and the Cadmium telluride (CdTe) cells which are also known as thin film technologies. These two technologies are available in several applications because of their mass production in the solar PV market. With a staggering 93% production capacity, c-Si cells dominate with 24% attributed to mono-crystalline and 69% attributed to the multi-crystalline technologies. The total production of the thin films forms 7% of the technologies. The amorphous Silicon, Cadmium telluride constitutes 3% and 2.5%, respectively, with less than 2% attributed to the Copper indium gallium di-selenide (Shubbak, 2019).

The third generation is still yet to reach the market (Farrell et al., 2020) with a lot of research being conducted for its commercialization. The third generation of PV technologies is emerging including the multijunction cells, Dye Sensitized Solar Cell (DSSC), perovskite solar cells (PSC) and organic solar cells (OPV) which are under research for commercialization. The aim is to make the manufacturing innovative to supply electricity at low cost (Oteng et al., 2021; Shubbak, 2019; Sundaram et al., 2016).

Policy and regulations governing solar PV waste

The production of electricity using solar panels has increased recently. Their end-of-life management is essential as these panels in the coming years will be sent to landfills if proper legislative directives and robust systems are not put in place to handle the collection and storage of solar PV waste (Dominguez and Geyer, 2019). Recycling and monitoring of PV waste stream and the implementation of innovative management technologies are critical to the reduction of environmental impacts associated with end-of-life solar PV (Majewski et al., 2021). According to Zou et al. (2017), there is a tremendous market growth of solar PV in countries like the USA, India, Australia, China, and Japan, however, they lack specific regulatory measure in the management of EoL solar PV (Oteng et al., 2021).

To minimize landfilling and optimize recycling of end-of-life solar PV, the European Union (EU) implemented the WEEE directive which includes an integrated approach to regulate the generation of PV waste in Europe (Jain et al., 2022). The EoL collection and recovery of solar PV is entirely the responsibility (financial and physical liability) of distributors and manufacturers under the Extended Producer Responsibility (EPR) as formulated in the WEEE EU/2012/19 directive (WEEE Directive, 2012). This is expected to aid in the devolvement of innovative recycling technologies from manufactures. The products life is expected to be extended and the reuse and recycling process will be easier (Khawaja et al., 2021). A recycling and recovery rate of 75–80% is required under the WEEE for PV waste panels when it was revised in 2012 through 2018 and expected to increase to 80–85% rate by mass (Majewski et al., 2021).

However, in countries like the USA, each state must introduce its own recycling regulations. There is no federal regulation or statutes that handles the management of solar PV waste (Curtis et al., 2021a). There are, however, industry and state led policies that are emerging to address the management of PV waste in the USA. The framework within these state-led policies is diverse and applies to different actors in the management activities of EoL panels. (Curtis et al., 2021a; Nain and Kumar, 2022; Weckend et al., 2016). The first state to require manufactures to collect and recycle or reuse EoL PV modules was Washington, which enacted the law in 2017. California in January 2021 have passed a regulation to manage EoL panels as universal hazardous waste allow-

Table 1
Reviewed themes on PV waste management practices.

S/N	Themes	Code	Sub-themes
1	**Solar panel technology (ST)**	**ST1**	First generation
		ST2	Second generation
		ST3	Third generation
2	**Policies and regulations (PR)**	**PR1**	Policies and regulations in place
		PR2	No policies and regulations in place
3	**Monitoring, tracking and logistics (ML)**	**ML1**	Collection, monitoring and tracking
		ML2	No monitoring and tracking
4	**Infrastructure needs (IN)**	**IN1**	Optimised recovery and recycling
		IN2	Current/available infrastructure
		IN3	No infrastructure
5	**Treatment Pathway (TP)**	**TP1**	Recycling and recovery
		TP2	Landfilling and disposal
		TP3	Exportation (Interstate and overseas)
		TP4	Reuse or reconditioning
		TP5	Incineration
		TP6	Other practices

Note: Details are available in the supplementary material (Table A1).

ing for the modules not to be chemically and thermally treated during its recycling processes. States like North Carolina (Bill 329) and New Jersey (Bill 601), in 2019 passed a senate bill and created a commission to study options associated with the management of solar PV waste (Curtis et al., 2021a).

PV waste is still not considered as e-waste in China, thus, there are no regulations governing its management even with the introduction of a policy for recycling e-waste in 2011 (Weckend et al., 2016). Research has been started on the technological development, safe disposal, and recycling of solar PV waste in China (Mahmoudi et al., 2021). Japan does not have any regulatory approach towards the management of EoL PV modules too (Nain and Kumar, 2022). PV waste is currently treated under the general waste law in India, with no regulatory or policies to manage this stream separately (Daniela-Abigail et al., 2022; Jain et al., 2022).

Currently, Australia does not have any regulations or legislations in the management of EoL PV modules. However, in 2019 it was listed as a priority in product stewardship scheme development under the National Waste Policy Action Plan (Australian Government, 2019). The regulation in the management of PV waste is expected to be developed by 2023 (Majewski et al., 2021; Oteng et al., 2021).

Recycling and recovery options for PV waste

The number of installed solar panels that will reach their end-of-life in the next 25–30 years is astounding, as they may reach around 60 million tons. Across the globe, there are a lot research going into the recycling and recovery of solar panels with researchers developing several processes and activities such as chemical and mechanical recycling approached, the economic challenges and social impacts (Heath et al., 2020; Padoan et al., 2019; Vargas and Chesney, 2021). The question of whether these processes and current approaches are sufficient to address the environmental impacts of PV waste remains to be confirmed.

The main problem associated with the recycling industry of solar PV waste and panels ending up in landfills is because of not meeting the collection and recycling targets due to the lack of appropriate regulations and policies (Dominguez and Geyer, 2017; Oteng et al., 2021; Salim et al., 2021). Also, the issue of local governments, users, and producers' clear roles when it comes to financial and non-financial responsibilities need further clarifications (Fthenakis, 2000; Mahmoudi et al., 2019; Salim et al., 2019). Again, the tailoring of collection, transport and recycling associated with the management of solar PV waste generation needs to be quantified in relation to its pollution and emission generation (Majewski et al., 2021).

According to Salim et al. (2021), there is no funding allocated to recycling when it comes to the collection of solar PV waste in Australia. There is a limited number of recyclers in regional states operating in Australia. Because of the limited market development, unsustainable funding inflow and little incentive in the recovery of solar PV waste, many of these upcoming recyclers may not survive for long. Consumers prefer landfill disposal compared to recycling and recovery alternatives due to the higher waste levy rates considering the current high collection fee within different Australian states.

Material and methods

This study adopts a modified Fuzzy Delphi method (FDM) in exploring the management practices of solar photovoltaic waste in Australia. The limited representativeness and restricted generalizability of the outcome of qualitative research paradigm is a main shortcoming associated with the field (Silverman, 2013), However, FDM is cost effective and limited informants in the research field can be employed to improve the efficiency and quality of the method (Padilla-Rivera et al., 2021). The methodological approach is shown in Fig. 1, which describes the modified FDM used to achieve the objectives of the study. The process of the methodology is described thereafter.

Survey design

This study uses semi-structured interviews as the instrument for collecting primary data for analysis. Veal (1997) posits that, semi structured interviews facilitate in-depth analysis through the generation of rich datasets from the subject being explored and the real attitudes of respondents are revealed through this technique (Ghauri et al., 2020). One set of interviews were designed for industry professionals including manufacturers, distributors, waste consultants, recovery, and recycling experts. The other set of interviews were designed for government participants including government organizations and institutions related to the management of PV waste. The structure of the interview is in two parts. The first part collected the demographic data and experience of the respondents. The second part contains information on developments in solar PV technologies in Australia, policies, and regulations on solar photovoltaics in Australia, strategies, and initiatives of PV waste treatment pathways. A pilot study was conducted to make sure the questions were familiar to the target respondents and the minutes were reasonable. The results from the interview were used to develop a survey questionnaire using a 5-point Likert scale to gather the experts consensus. This is developed through a set of algorithms based on the linguistic terms from the triangular fuzzy numbers. This was then sent for approval to the Human Research Ethics Committee (HREC) which received an ethics approval number H-2020–244.

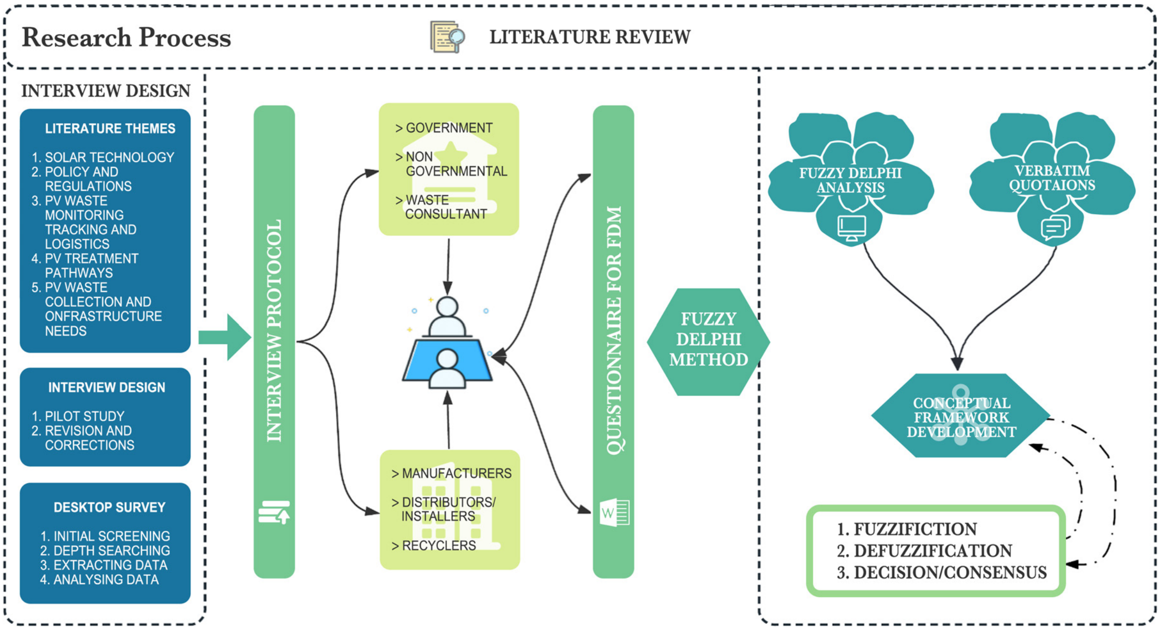

Fig. 1. Methodological approach.

Identification of field experts

In conducting the interviews, all participants were selected purposively (Etikan and Bala, 2017; Palys, 2008) within Australia who falls within the criteria set for the research. The snowball sampling (Atkinson and Flint, 2001) was also applied to ascertain respondents that are not known to the researchers. Owing to the issues of Covid-19, all participants were reached and interviewed through Zoom or Phone. In the case of participants within the State of the researchers (South Australia) who could participate face-to-face and choose to do that, all social distancing rules were observed within that State. In this case, the interview was conducted in a public space or other comfortable place that makes both participants and researchers feel safe. The criterion for selection limits the participants by their knowledge in the area as well as their experience in the field. Thus, respondents should be experts working in the solar photovoltaic industry for at least two years and should have experience on solar photovoltaics in Australia. The only exclusion criterion was a limit of less than two years in the PV industry.

The participants selected for the study were members of governmental organizations or spokesperson within the Australian Renewable Energy Agency, Clean Energy Regulator, Department of Energy and Water, Department of Agriculture, Water and the Environment /Environment Protection Authority, National Waste and Recycling Industry Council, Green Industry SA; Members of institutions such as the Australia Photovoltaic Institute and the Waste Management and Resource Recovery Association of Australia; Spokesperson of Manufacturers, Distributors/Installers, Consultants within the solar PV industry (This was retrieved from the member list of clean energy council approved retailers and crossed check using the Australian Business Register (ABN) Lookup); Experts within the recovery and recycling of solar PV industry.

A database of who does what in the field and personal information was ascertained through contact search on LinkedIn and institutional webpages for the purpose of recruitment. This information was not used for the analysis. The participants were contacted through their institutional email and/or LinkedIn addresses initially to ascertain their availability and willingness to participate in the studies. If their personal information was not available, the researcher contacted the chief operation officer or spokesperson of the institution for them to connect the researcher to the right people. The participant information sheet and consent forms were made available to all potential participants for them to decide whether they are going to participate. Once the contact is successful, a suitable time was arranged for the interview.

Interview process

After the ethics approval, the participant information sheet and consent form were made available to the identified participant on the initial contact through their institutional emails to advise them on the preliminary information of the study and as an invitation to participate in the research during recruitment. Participants were given time to voluntarily respond to the mail based on the information given them. Consent was obtained from participants using the consent forms, to explicitly acquire the use of data for the study and potential future research projects. If the participants decide to participate in the study, a comfortable date was set for the interview which was conducted virtually or through the phone because of the restrictions on Covid-19 which will help reduce any potential discomfort for the participants. The first round of interviews took place on January 2021. It took approximately 6 months to complete 80% of the interviews and another 4 months to finalize the remainders.

The number of interviews conducted for this research is 13 qualified experts within the solar PV industry. This consist of Government/Consultants organizations and Industry practitioners associated with the management of solar PV waste in Australia. The interview was concluded when the state of new information was satisfied, which meant that it had reached the “saturation effect”. The interview on average lasted for 20 to 60 min. A total of 15 respondents agreed to participate after contacting 35 respondents. In the end, 13 respondents (see Table 2) took part in the interviews. This consisted of 5 respondents from the government/consultants and 8 respondents from the solar PV industry.

To provide a fair presentation and accurate analysis of the data, NVivo software for qualitative data analysis, is used to analyze the interview data (Welsh, 2002). With consent from the participants, all the interviews were audio or video recorded. The interviews were then transcribed within Microsoft Word and coded into nodes using NVivo. Personal details such as names are replaced with unique codes when analyzing the data to protect the identity and privacy of the participants. Thus, in the case of this study the participants comments, and details are presented anonymously. Thematic analysis is applied in establish-

Table 2
Characteristics of respondents.

No	Organization	Position	Code
1	Government / Consultants /Institutions	Chief Executive	P1
		Program Lead Investment Facilitation	P2
		Industry Research Analyst	P3
		Project Officer	P4
		Technical Standards and Safety Officer	P5
2	Industry practitioners (Manufacturers, recyclers, distributers, installers)	Sales Associate	P6
		Business Developer	P7
		Project Consultant	P8
		Co-founder	P9
		Head of Recycling	P10
		Chief Executive Officer	P11
		Director	P12
		Chief Technology Officer	P13

Note: Name of organisations are removed from the demographics to respect and protect the confidentiality of participants as stated in the ethics document number H-2020–244.

Table 3
Fuzzy triangular numbers for FDM assessment.

Linguistic terms	Likert Scale	Triangular fuzzy numbers		
		n1	n2	n3
Strongly agree	5	0.6	0.8	1
Agree	4	0.4	0.6	0.8
Not sure	3	0.2	0.4	0.6
Disagree	2	0	0.2	0.4
Strongly disagree	1	0	0	0.2

ing a good understanding of the interview data (Jankowicz, 2013). The established themes under the interview design were the bases for the development of the survey instrument for the FDM. Verbatim quotations from the interviews are also used to support the discussion derived from the analysis.

Fuzzy Delphi method

This study adopts a modified FDM to develop a conceptual framework for end-of-life solar photovoltaic management in Australia. The FDM is a combination of the conventional Delphi method with fuzzy theory. This was created to avoid the ambiguousness in the Delphi method when it comes to consensus from the panel, it also reduced the time for investigation (Marlina et al., 2022). Several researchers have recommended a sample size of between 5 and 20 experts for a Delphi panel (Okoli and Pawlowski, 2004; Rowe and Wright, 2001).

There are three main stages when it comes to the FDM process. The first one is the input preparation, which includes the information gathering, questionnaire preparation and expert selection. The second stage is the data analysis which consists of changing the linguistic terms to fuzzy numbers, setting the threshold and percentage for consensus, and defuzzification. The last stage is the final decision where you make the decision based on the results from the analysis. FDM has been applied in waste management studies such as sustainable solid waste management (Bui et al., 2020). The FDM procedure is adopted in this study to assess the significance of individual criterion from experts using linguistic variables (Negash et al., 2021). To translate the qualitative information into values, the fuzzy triangular numbers (TFNs) were used to handle the linguistic preferences of the participants as shown in Table 3.

The respondent evaluation score was aggregated using the geometric mean, the fuzzy weight (F_m) of each criterion was determined.

$$F_m = \left\{ u_m = \min\left(u_{nm}\right),\ v_m = \left(\sum_{m=1}^{k} \left(v_{nm}\right) \right)^{1/k},\ w_m = max\left(w_{nm}\right) \right\} \tag{1}$$

From Eq. (1), where m is the significance evaluation score criterion m, n is the expert rated criterion m, k is the number of experts, and u, v, and w stand for the lower, middle, and upper values of the TFNs, respectively.

The aggregated fuzzy weights of each criterion are defuzzified using the equation below:

$$D_m = \frac{u_m + v_m + w_m}{3} m = 1, 2, 3, \ \ldots y \tag{2}$$

From Eq. (2), y is the number of criteria. The threshold (τ) for screening out the nonsignificant criteria was set: $D_m \le \tau$, then the $_m$th criterion is rejected; if $D_m \ge \tau$, then the criterion is accepted. Under a typical situation, $\tau = 0.5$ is used. The percentage approval from experts should be more than 75%.

Results and discussions

The results of the analysis from the Interviews and FDM are presented under the major themes highlighted in the literature review with additional support from verbatim quotations from the interview transcripts. The themes include solar technologies in Australia, policies and regulations in Australia, PV waste monitoring, tracking and logistics in Australia, treatment pathways in Australia, and PV waste collection and Infrastructure needs in Australia. The waste flow and recycling opportunities are expanded with comparative literature from the solar PV field. The work also draws on current and relevant literature to better understand the situation and recommend solutions.

Fuzzy Delphi analysis

The table below (Table 4) shows the results from the FDM, showing the themes, sub themes, fuzzy evaluation. Average of fuzzy numbers and the decisions made. The agreements of the experts are gathered using the Fuzzy Delphi technique, making sure that the percentage agreement is equal or greater than 75%.

Table 4 shows the decision from the results from the FDM analysis and serves as a validation and consensus from the experts. This is discussed in the sections below supported by some verbatim comments from the experts.

Solar technologies in Australia

The solar panel technologies theme shows a decision of one accepted and two rejected. The fuzzy evaluation (FE) for ST1, ST2 and ST3 are 9.400, 3.733 and 1.733, respectively. The Average of fuzzy numbers (AFN) show a value of 0.723 for ST1, 0.287 for ST2 and 0.133 for ST3. The decision to accept the first generation as the most installed panels in Australia received a high consensus with some experts having more to share on the topic. The verbatim comments from some of the experts are discussed. There are several solar technologies on the Australian market. Most of the participants confirmed the Mono and Poly crystalline silicon panels as the most installed in Australia:

'*… Most of the time is mono and poly, the industry is only mostly mono and poly …. Because the standards in the industry are mono and poly, that is 80% of the supplies maybe 90% …*' [P2]

'*Well, there is two, polycrystalline and monocrystalline, they are generally the most common panels…. So, we do the Poly and the monocrystalline panels here.*'[P4]

Others [P6 and P9] also explained that they only recycle the mono and poly crystalline silicon panels. According to D'Adamo et al. (2017), 85% to 90% of the global PV market is made up of the Crystalline Si module technology. Australia is not far from these statistics as explained by Mahmoudi et al. (2019) in their PV waste forecast in Australia. This also showed the current PV waste stream and what the future waste stream will look like. The researchers also wanted to highlight the knowledge on the new technologies that were flooding the market and whether new technologies will continue to be developed:

Table 4
FDM results.

Themes	Codes	Sub themes	Score		Decision
			Fuzzy Evaluation	Average of fuzzy numbers	
Solar panel technology (ST)	**ST1**	First generation	9.400	0.723	**Accepted**
	ST2	Second generation	3.733	0.287	**Rejected**
	ST3	Third generation	1.733	0.133	**Rejected**
Policies and regulations (PR)	**PR1**	Policies and regulations in place	4.467	0.344	**Rejected**
	PR2	No policies and regulations in place	7.000	0.538	**Accepted**
Monitoring, tracking and logistics (ML)	**ML1**	Collection, monitoring and tracking	2.667	0.205	**Rejected**
	ML2	No monitoring and tracking	9.000	0.692	**Accepted**
Infrastructure needs (IN)	**IN1**	Optimised recovery and recycling	2.200	0.169	**Rejected**
	IN2	Current/available infrastructure	6.600	0.508	**Accepted**
	IN3	No infrastructure	2.600	0.200	**Rejected**
Treatment Pathway (TP)	**TP1**	Recycling and recovery	9.600	0.738	**Accepted**
	TP2	Landfilling and disposal	7.800	0.600	**Accepted**
	TP3	Exportation (Interstate and overseas)	8.400	0.646	**Accepted**
	TP4	Reuse or reconditioning	8.600	0.662	**Accepted**
	TP5	Incineration	7.400	0.569	**Accepted**
	TP6	Other practices	8.400	0.646	**Accepted**

’… *I think newer technologies will be things like roof tiles like Tesla, if the products are becoming simpler and easier to install the volume will grow more and more. … I think, flexible solar panels and roof tiles are probably where the next ones are pretty much heading* …’ [P2]

According to [P2], the Tesla roof and flexible panels are some of the new technologies in the market. With the development and adoption of Building Integrated Photovoltaics (BIPVs), the makeup of the PV waste stream may change in the coming years. Moreover, cell technologies like copper indium gallium selenide, gallium arsenide, and cadmium telluride continues to compete with the c-Si technology which is the most installed currently (Heath et al., 2020). Monitoring of the technological changes is very important to the industry as iterated in the analysis, closely linked to their capacity to address how recycling is satisfied in the future. According to Heath et al. (2020), this deployment recycling cycle should be closely monitored. This is supported by *[P6]*, who also confirmed these emerging technologies and how the design and capacity is changing with these new technologies.

Policies and regulations in Australia

The results revealed that PR1 had a fuzzy evaluation score of 4.46 and the average of fuzzy number score of 0.344. PR2 received an FE score of 7.000 and an AFN score of 0.538. The values are further justified in the discussion. Looking at the policies and regulations, the respondents were asked if they knew of the existence of any regulations that guides the management of solar PV panels. The common answers are no, however, there were interesting discussions that came out. Especially, [P7] had an interesting take on this:

‘*The government can do some research and provide guidance, but I think is still an industry problem and is a civilian problem. People themselves should be a bit more aware of the choices that they make…*’ [P7]

The respondents argument was based entirely on how the industry can push and be the leader in this process of recycling and recovery. The voluntary participation without government intervention is not ideal. Moreover, the lack of collection points for PV waste and cheap disposal fee has seen the increase of PV waste in landfills (Salim et al., 2021). The respondent also made mention of how the government can educate the community on the toxic or harmful elements in the panels which can leach into the ground at the EoL stage. On this question of a working policy and regulation, [P3] posits that:

‘One of my colleagues has been involved I mean I will not call it a policy but trying to work on a product stewardship, but I mean it is still in its infancy … but, no, there is none in place and even the product stewardship is taking some time and trying to get all the states talking to each other on it as well. I am not aware of anyone (policy or regulation) in place but what I am aware of its we are still working on that product stewardship.’[P3]

Australia, as rightly confirmed by all the respondents is working on a product stewardship that will govern the management of solar PV waste. This is still in the process and believe to be ready by 2023. Others also brought the researchers attention on the landfill ban of PV waste in some states:

‘In Victoria there is a landfill ban on PV models. That was introduced in 2019, I think. … There are no other states that have that sort of legislation yet.’ [P12]

There were some few interesting takes from experts from industry and that from the government sector. One industry expert was of the view that, the PV waste is an industry and civilian problem. People should be more aware, and that the policy and education should start from them to achieve and effective regulation on PV waste management in Australia. The establishment and development of a policy and product stewardship for PV waste can contribute to the reduction of unregulated disposal of damaged and unwanted PV waste panels. An effective management scheme can serve as an indicator on renewable energy uptake, promote sustainable energy targets related to exceptionally implemented regulatory and policy frameworks clearly contributing to the countries energy resilience (Majewski et al., 2021). This will provide Australia with a guide to appropriately establish a recycling infrastructure and support for PV waste management.

PV waste monitoring, tracking and logistics in Australia

The collection, monitoring and tracking of PV waste is a big issue in Australia because of the spread of the land, The results clearly identify the problems when it comes to monitoring showing an FE an AFN of 9.000 and 0.692, respectively for ML2, and 2.667 and 0.205 for ML1. To quantify the amount of waste to manage, a proper tracking and monitoring of waste flow is significant. There are other waste like construction and demolition waste that are monitored and recycled in Australia. The first-generation panels have been installed over some decades and will be coming to their EoL stage soon. The lack of awareness on the part of some manufactures and consumers on the importance of recycling and material recovery within the PV supply chain has led to the disposal of EoL PV into landfills, rather than recycling the panels. Landfilling is believed to be the cheaper options therefore the enormous patronage (Khawaja et al., 2021). This is what the respondents had to say:

‘… *If there is hail damage for example and the panels get broken, and gets replaced … a lot of these ends up going through middlemen who ends up selling them privately or they go down to recycling stores where a lot of these companies buy or get these panels cheap and then they sell them out …*’ [P9]

‘…*I think that is the one area where we can see some real regulation, or I think there should be an onus on the property developer to demonstrate where the waste is ended up … I think if the recourse came back to the developer* *and he had to prove where it was disposed off, the illegal dumping and things like that would certainly dry out.*' [P12]

The comments of the participants demonstrate the unregulated movement of solar PV waste in and out of Australia as well as within the states. Because there are no policies in place (Majewski et al., 2021), some of them are already being dumped into landfills. Even with some states banning solar PV waste from Landfill, there is still no regulation as to what should be done with the panel at the EoL stage. This is a major problem as it promotes illegal dumping and unregulated movement of the waste stream in and out of Australia. There are some few companies like Reclaim PV, they have started the process of collecting and treatment of solar PV waste. However, data on this waste stream is very low as suggested by [P5]:

'*…So, that is where a lot of work needs to be done and I mean we are even looking to do some here in Victoria because the level of data is very low…*' [P5]

The low data makes it difficult to know the current waste flow and logistics associated with waste solar PV. Some of these are sent overseas for reuse and reconditioning without proper testing [P3, P8, P10]. Regulated waste flow will be significant to the management of PV waste, especially recovering essential and rare metals back into the supply chain. This promotes a good circular economy for the sector. Solar PV waste is a new form of waste stream which is now growing, the effective monitoring of this waste stream will aid policy makers and practitioners to better understand the situation and approach it thereof.

PV waste collection and infrastructure needs in Australia

The results from the FDM reveals that, IN1 received an FE score of 2.200 and an AFN score of 0.169. IN2 received an FE score of 6.600 and an AFN score of 0.508. The last one which is IN3 received an FE score of 2.600 and an AFN score of 0.200. This is interpreted as the availability of a facility for the treatment of PV waste, which is known to some and others not having an idea of this facility. The absence of a policy or economic drivers is preventing the motivation of the solar industry from taking sustainable management decisions on EoL PVs. However, initiatives and standards led by the industry can promote sustainable PV waste management decisions that are environmentally friendly and economical (Tura et al., 2019). Most were of the view that, the government should make incentives available, others looked at the environmental benefits and commercial viability of the whole process:

'*Government initiatives and assistance will motivate, but it will obviously come down to cost and time … If it is mandated by law then that passes the cost to the customer, if its optional then it is a soft slope, you either take it or you do not take it …*' [P4]

'*I just think is capital and labor intensive. We are going to understand what its involved and if there is an opportunity there, we will try and take advantage of it.*' [P9]

'*Obviously, the driver for the company is the cost benefit and we must make money for us to survive and to grow, but the core of what we are doing is passion about the environment.*' [P11]

The need for infrastructure is important in the management of solar PV waste. The federal state and local governments may invest in PV recycling if there is resource security, supply chain stability, job creation and new market opportunities (Curtis et al., 2021a; Dominguez and Geyer, 2019; Weckend et al., 2016). Again, the market demand for these recycled materials will improve if manufacturers are encouraged to use a percentage of recycled materials. Recyclers are not motivated because of the current domestic market and its low commodity value (D'Adamo et al., 2017; Salim et al., 2021). An efficient collection network will also reduce some economic burden (Oteng et al., 2022) and drive recyclers to recover solar PV waste. Respondents gave their views on the drivers and barriers that hinder Australia when it comes to solar PV waste infrastructure needs:

'*…because it is an Australian kind of problem where we are all so spread out … when you think of the solar farms, they are a long way probably the biggest barrier I see now and the lack of data when it comes to the feedstocks…*' [7]

Others [P9, P12] commented on the profitability of the venture and the opportunities that comes with recycling solar panels. But the most stressed problem was the geographical spread of the country and how it will make it difficult for recyclers to cope with the logistics of transporting and recovering the materials as well as returning it back to the production stream.

Treatment pathways in Australia

The results show that TP1 has an FE value of 9.600 and an AFN value of 0.738, TP2 has an FE value of 7.800 and an AFN value of 0.600, TP3 has an FE value of 8.400 and an AFN value of 0.646, TP4 has an FE value of 8.600 and an AFN value of 0.662, TP5 has an FE value of 7.400 and an AFN value of 0.569, and TP6 has an FE value of 8.400 and an AFN value of 0.646. There are several routes that solar PV waste may take at the EoL stage. Currently, some Australian states have banned the disposal of solar panels going into landfills. This has seen some individuals and companies who have started the collection and treatment of solar PV waste. Some states are also providing incentives for the recycling of solar panels. The researchers established the current treatment of solar PV waste in Australia through this theme and further received respondents comments on the best treatment pathway for solar PV waste in Australia. It was established that:

'*…if they came to one of our processing facilities, we would turn them away and send them to the landfill…*' [P2]

'*Recycling is something that we are doing … If you recycle in an efficient way and you get the right amount of materials back from the panels…*, I think it is great.' [P10]

Most of the panels were going into landfill, however, there are some companies that are collecting and treating solar panels in Australia. There is the lack of innovation and incentives when it comes to recycling of PV waste (Oteng et al., 2021) in Australia as some of the respondents affirmed. However, some industry professionals are voluntarily creating their own innovations and systems to (Oteng et al., 2022) aid in the recovery of solar PV waste (Islam et al., 2020; Mahmoudi et al., 2021). The extent of the recovering and recycling is still under investigation. The opinions of the respondents on the best treatment pathway for Australia when it comes to PV waste management was answered in different ways:

'*There should be a five-year roadmap where people should start thinking about how to incorporate recycling into the cost factors and almost give people a heads up when any panels that are being decommissioned after a certain time must follow a strict regulation…*' [P2]

'*So, just things like that I think moving towards making the recycling processes that are happening, you know more organic in terms of if there are chemicals being used it should be more organic, easier to dispose of and/or maybe reusable.*' [P8]

From the comments, respondents were happy and eager to embrace change but wanted it to be executed appropriately with a comprehensive plan. Others wanted the innovation to be safe enough so not to cause more harm with the recycling and recovery processes.

The situation in other countries compared to Australia

According to Chowdhury et al. (2020), the technological market share of solar panels is dominated by silicon based (c-Si) panels. This takes 95% share of the global market (IRENA, 2019). Because Australia does not manufacture solar panels (a local manufacturer Tindo Solar started recently), old panels are supplied through the global supply chain, therefore, the technology in the Australian market is linked to that of the global market. Making the first-generation panels the predicted future waste stream.

The European Union including countries like United Kingdom, Germany, Italy, and France has established a WEEE directive governing

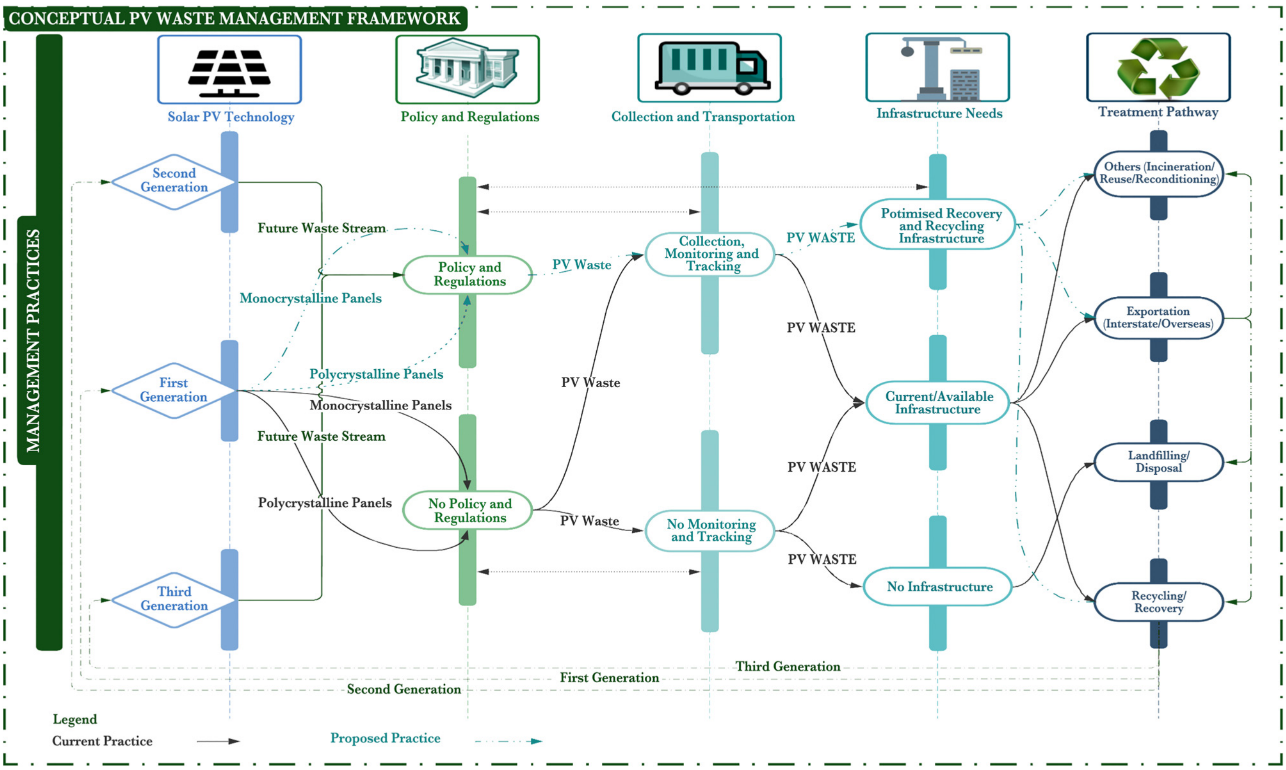

Fig. 2. Conceptual framework of solar PV waste management practices.

the management of EoL PV (Berger et al., 2010; Majewski et al., 2021; Weckend et al., 2016). Countries like the USA, India, China, and Japan, lack specific regulatory measure in the management of EoL solar PV. This study identifies Australia as one of the countries without policy or regulations in place in the management of solar PV waste.

Jain et al. (2022) posits that, there is a resource challenge because of the supply crunch and competitive consumption in the manufacturing of solar PV modules related to critical metals such as copper, aluminum, cadmium, tellurium, silver, silicon, lithium, germanium. This metals from recycling could feed into this stock by about 90% reduction in the waste owing to high recyclability. This will also ensure and prevent these precious metals from going into deficit in the future with proper innovative research, thus, also diverting them from Landfill (Curtis et al., 2021a; Farrell et al., 2020; Salim et al. 2019; Xu et al., 2018). Australia can benefit from this economically, by creating incentives for innovative recycling as established in countries like the United Kingdom, Germany, and France. Moreover, the pollution levels generated, and costs associated with the transport flows of recycling plants are very high in Australia (D'Adamo et al., 2017). The solution to this issue could come from treating different waste typologies at the same recovering center. Recently, the local government in South Australia and Victoria, have created incentives for recyclers and academics to develop ways of recovering precious metals from solar panels.

There is a market for the recovered products especially the glass and aluminum but not the entire PV panels in Australia. The unavailability of market for materials may have a serious impact on the industries supply chain (Farrell et al., 2020). Recyclers in Australia are developing consumers interest in the recycled materials.

Proposed framework of PV waste management practices

According to Farrell et al. (2020), to promote resource efficiency, a framework is needed to provide proper signals to stakeholders associated with the management of solar PV waste. The current management practices within the Australian PV waste industry have been conceptualized in Fig. 2. It demonstrates the currently installed solar panels in Australia, which may end up in landfills, exported or recycled. The monitoring and movement of the three generations of PV waste is also highlighted. Currently, there is no tracking of PV waste within and across State boarders. With no policy in Australia, the diagram establishes the current industry and consumer practice at the EoL stages. The recycling and infrastructure needs are also identified, showing the current practice in Australia. This framework serves as an elaborate picture of the current solar PV waste situation in Australia.

Among the three generations of solar PV technology, the first generation specifically the mono and polycrystalline modules are the technologies currently installed and flooding the PV waste stream in Australia. In the coming years, whiles planning for the first generations, government and stakeholders should be aware of the growth of the other technologies and appropriate measures taken to effectively manage their end of life. There is currently a ban of PV waste from going to landfills, however, no policy to regulate the movement and management of this stream. This means that, the PV waste stream is not monitored and tracked in Australia. There are companies such as Reclaim PV, PV industries and Lotus energy collecting and finding ways to treat end-of-life solar PV. Some States are also providing incentives to the recyclers and academics to develop innovative recycling technologies. Currently, most of them are still being dumped in landfills in several States. Some of them are sent to different countries for either treatment, reuse or dumped in landfills as shown in the treatment pathway in the framework. Unless a legislation or policy is confirmed or established, the first-generation panels are expected not to be regulated and monitored, thus, leaving industry to lead the recovery and recycling process, with few going to landfills. The ones that go through the currently available infrastructure may end up being exported, reused, or recycled. Proper monitoring and tracking should be available for all PV technologies to make it easier to track at the end-of-life stage. An optimized recycling and recovery infrastructure should be available in the state to cater for this waste stream as illustrated in the framework.

For the second and third generation (top-left and bottom-left of Fig. 2), the future PV waste stream generated may use existing waste management policy and regulations. Because the new technologies are now being installed and may take some years until they reach their end of life, their movement and monitoring may be established by then, since the Australian government has listed PV waste in section 108A of the Product Stewardship Act 2011. A committee has been set to develop a regulation on solar PV waste and this is expected in the year 2023. This will guide the panels as they reach the EoL stage, however, they may be updated to suit the new technologies as their composition vary and specific directions will eb needed for each.

Conclusion and policy implications

The implementation of PV waste management options is of concern to international bodies, policymakers, and communities. This is not only related to life cycle environmental impacts, but also to the preparation of a long-term plan and its successful implementation. The analysis of experts' interviews revealed that, crystalline silicon panels were the most common panels on the Australian market and the ones that were being installed frequently. New emerging panels with better capacities and innovative designs are also being developed and commercialized.

On policies, even thou the government has banned PV waste from going to landfill, currently, there is no policy or regulation to manage them. A product stewardship that will govern the management of solar PV waste is forthcoming, but this is still in the process and is expected to be ready for consideration by 2023. The long process of legislation approval and implementation will create a void in PV waste management in Australia at least for another few years and may leave a significant amount of solar PV waste behind before the forthcoming product stewardship legislation becomes operational. The absence of policies and regulations validates the unregulated movement and tracking of solar PV waste in and out of Australia as well as within the states.

A limited number of individual companies such as Reclaim PV (South Australia), PV Industries (New South Wales) and Lotus Energy (Victoria), have started the collection and treatment of solar PV waste with some state governments providing incentives to recyclers and researchers to develop innovative recycling approaches. However, the extent of the recovery and recycling is under investigation. Infrastructure and logistics predicament are among the key findings. The most stressed problem is the geographical spread of the country and its effect on the logistics of transporting and navigating the supply chain when it comes to cost and resources.

The established conceptual framework of the current treatment of solar PV waste in Australia, provides researchers and industry with the practical situation on the ground and define an appropriate system boundary for life cycle assessment and policy research. This can serve as a guide for industry to fully understand the current situation on solar PV management to appropriately establish recovery and recycling needs. Future research should be conducted on the life cycle assessment of PV waste management based on the conceptual framework. Again, because consumers are not in the scope of this study, consumers' willingness to accept regulations and associated collection fees should be investigated.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Daniel Oteng: Conceptualization, Methodology, Writing – original draft, Formal analysis. **Jian Zuo:** Conceptualization, Supervision, Writing – review & editing. **Ehsan Sharifi:** Conceptualization, Supervision, Writing – review & editing.

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Supplementary materials

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Supplementary Material

An expert-based evaluation on end-of-life solar photovoltaic management: Lessons and best practices

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A.1 Literature Review

The table details the literature on solar photovoltaic waste management research and describes the practices across the globe when it comes end-of-life PV.

Table A1: Literature on PV waste management practices

S/N	Themes	Sub-themes		Description	References
		Generation	**Technology**		
1	**Solar panel technology**	First generation	Monocrystalline Silicon Cells (Mono c-Si) Polycrstalline Silicon Cells (Poly c-Si)	There are three classifications of solar PV technology. The classifications are first, second and third generations. The one that is readily available in the market for consumers is the first and second generation. The third generation is still yet to reach the market with a lot of research being conducted for its commercialisation. The first-generation technology are crystalline silicon (c-Si) wafer-based cells. Among the second generation are the single-junction Gallium Arsenide (GaAs) Cells, amorphous Silicon (a-Si) cells, Copper indium gallium di-selenide (CIGS) cells, and the Cadmium telluride	(Farrell et al., 2020; Oteng et al., 2021; Paiano, 2015; Shubbak, 2019; Sundaram et al., 2016)
		Second generation	Amorphous Silicon Cells (a-Si) Cadmium telluride (CdTe) Copper indium gallium di-selenide (CIGS)		

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		Third generation	Single-junction Gallium Arsenide (GaAs) Dye sensitised (DSSC) Perovskite Cell Organic (OPV)	(CdTe) cells which are also known as thin film technologies. These two technologies are available in several applications because of their mass production in the solar PV market. The third generation are emerging technologies including the multijunction cells, Dye Sensitized Solar Cell (DSSC), perovskite solar cells (PSC) and organic solar cells (OPV) which are under research for commercialisation.	
		Countries	**Policies**		
2	**Policies and regulations**	Countries with policies	European Union WEEE Directive (United Kingdom, Germany, Italy, France, and others)	To minimize the landfilling and optimize recycling of end-of-life solar PV, the European Union (EU) implemented the WEEE directive which includes an integrated approach to regulate the generation of PV waste in Europe. However, there is a tremendous market growth of solar PV in countries like the USA, India, Australia, China, and Japan, however, they lack specific regulatory measure in the management of EoL solar PV.	(Berger et al., 2010; Chowdhury et al., 2020; Farrell et al., 2020; Jain et al., 2022; Mahmoudi et al., 2021; Majewski et al., 2021; Oteng et al., 2021; Sica et al., 2018; Weckend et al., 2016; Zou et al., 2017)
		Countries with no policies	China, Korea, Japan, USA, Australia, India, and other developing countries		
		Discipline	**Category**		
3	**Monitoring, tracking and logistics**	PV market and waste projection	Forecast and screening of waste flow Emerging technologies	The federal government as well as state and local governments may invest in PV recycling if there is resource security, supply chain stability, job creation and new market opportunities. An efficient collection network will also reduce some economic burden and drive recyclers to recover solar PV waste.	(Choi & Fthenakis, 2014; Goe & Gaustad, 2016; Islam et al., 2020; Mahmoudi, Huda, Alavi, et al., 2019; Mahmoudi, Huda, & Behnia, 2019; Oteng et al., 2022; Vargas & Chesney, 2021)
		Reverse logistics	Network design and supply chain logistics Collection and transport Processing and sorting		
		End-of-life pathway	**Assessments**		

4	**Treatment Pathway (Environmental, Economic, and Social Implications)**	Recycling/ Recovery	Life cycle assessment Material Separation and Metal extraction processes Experimental and mathematical modelling	Across the globe, there are a lot research going into the recycling and recovery of solar panels with researchers developing several processes and activities. The question of whether these processes and current approaches are sufficient to address the environmental impacts associated with them remains to be confirmed. The main problem associated with the recycling industry of solar PV waste and panels ending up in landfills is because of not meeting the collection and recycling targets due to the lack of appropriate regulations and policies. The issue of local governments, users, and producers' clear roles when it comes to financial and non-financial responsibilities need further clarifications.	(Ansanelli et al., 2021; Berger et al., 2010; Chowdhury et al., 2020; Faircloth et al., 2019; Farrell et al., 2020; Jain et al., 2022; Kang et al., 2012; Mahmoudi, Huda, Alavi, et al., 2019; Mahmoudi et al., 2020; Nain & Kumar, 2020; Oteng et al., 2022; Salim et al., 2019a; Shin et al., 2017)
		Landfilling/Disposal	Leaching of metals (Hazardous materials) Fees and collection rate		
		Exportation	Within state boundaries Overseas		
		Others	Incineration Reuse/reconditioning		
		Citing of Infrastructure	**Modelling and Methods**		
5	**Infrastructure needs**	Spatial Analysis	Suitability analysis Location allocation modelling System trade-offs (fees and costs) Pollutant and Greenhouse Gas Emission	The capital that goes into any business is very important. Proper care must be taken to ensure that, the project is economically feasible. The recovery of high valuable materials is not cost effective because the associated processes, infrastructure and technology are not currently optimized. Uncertain risks are directly reduced on the side of the investor if these market conditions and liabilities are known. Thus, if these risks are known, future investments could be accomplished.	(Choi & Fthenakis, 2014; Curtis et al., 2021; Goe & Gaustad, 2016; Goe et al., 2015; Islam et al., 2020; Oteng et al., 2022; Salim et al., 2019b)
		Risk Assessment	Human Health risks		
		Stakeholder cooperation	Government role Industry role Consumer role		

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Appendix C – Manuscript: Environmental emissions influencing solar photovoltaic waste management in Australia: An optimised system network of waste collection facilities

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Research article

Environmental emissions influencing solar photovoltaic waste management in Australia: An optimised system network of waste collection facilities

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ABSTRACT

The Australian urban construction electricity sector has witnessed a transformational effect in the use of small-scale solar photovoltaic (PV) systems in the past decade. Currently, Australia has one of the highest rates of rooftop solar PV users with over 20% of households connected. This will see a rapid growth in the volume of PV waste in the coming years when these PV systems come to their end-of-life or require replacement. The collection and transportation involved in solar PV waste treatment has a significant impact on the environmental sustainability of Australian cities while designing a holistic reverse logistic (RL) network may play an essential role in the reduction of the associated cost and environmental impacts. In this study, the Weibull distribution model is employed to forecast the PV waste in the next three decades in South Australia. The study further estimates the pollutant emission associated with the collection and transportation of the waste for recycling and recovery using hotspot analysis, location allocation modelling and vehicle routing problem. Generation of pollutants - Particulate Matter (PM), Carbon Monoxide (CO), Carbon dioxide (CO_2) and Nitrogen Oxides (NOx) associated with transport and energy consumption are estimated through three routing scenarios. Results indicate that, there will be 109,007 tons of PV waste generated in urban and suburban context in South Australia by 2050. Among the three routing scenarios generated, the third scenario with optimised transfer stations and an additional recycling facility showed more than 34% reduction in pollutant emission. Such additional PV waste management facilities require policy support and regulations to effectively manage solar PV waste treatment and logistics.

1. Introduction

Solar energy is renewable, non-polluting, and efficient. The prospect of using Photovoltaic (PV) technology to meet the future energy needs of the world has seen a massive increase in the past decade. It is expected that, the electricity generated by solar PV will become the primary source of global energy within the current century (Hosseini-Fashami et al., 2019; Xu et al., 2018). Therefore, the potential to produce clean energy globally, has created a large market for solar PV panels (Chowdhury et al., 2020). There is a rapid growth in the use of rooftop solar because it reduces the electricity bills for domestic and commercial users. Meanwhile in Australia, households also may generate revenue through feed-in tariffs and self-generated electricity from the solar panels. The financial stress related to energy is substantially reduced as Australian households with solar PV saves an average of A$538 on electricity bills annually compared to households without solar PV systems (Best et al., 2021). There is also government initiative such as price subsidies which has seen the cost of solar panels fall considerably. The uptake of rooftop solar reduces emissions such as carbon dioxide (CO_2) from the electricity sector (Best et al., 2019) and is encouraged by a lot of countries to aid in achieving the greenhouse gas emission (GHG) reduction goals. The Australian electricity city sector has seen a transformational effect in the use of small-scale solar PV systems. Australia is among the highest rate of rooftop solar PV users with over 20% of households using solar PV as of December 2018 and greater than 3 GW of new rooftop solar capacity added in 2020, setting a new installation record (IEA, 2016; Clean Energy Regulator, 2021). South Australia and Queensland are the states with the highest solar PV percentage for residential dwellings with an installation average of 37%, with PV systems and localities having rooftop solar densities of over 50% (Egan et al., 2020).

There are two different types of PV capacity, i.e., the distributed (residential) and utility scale PV systems. When it comes to waste collection, both types have their own unique challenges. Distributed solar panels are located on rooftops or owner-occupied lands. They are customer-sited panels (Goe and Gaustad, 2016a) and maintains the

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largest share of capacity in Australia (Australian Photovoltaic Institute, 2021). The utility scale are large installations that occupies a lot of land area with capacity greater than 100 kW. There are a number of challenges that come with handling the waste of distributed and utility scale PV. Third party contractors mostly purchase from different types of manufactures when installing distributed scale solar panels. Therefore, issues like decreased efficiency, weathering, breaking, that causes the panels to reach its end of life creates a huge problem for owners as they do not know what to do with these panels (Oteng et al., 2021; Goe and Gaustad, 2016a). Thus, to prevent negative impacts of leaching to humans and the environment, recycling is often recommended (Choi and Fthenakis, 2010).

1.1. Research background, gap, and objectives

First Solar a solar panel manufacturer collects its end-of-life (EoL) utility scale panels for recycling, however, this option is not available for distributed scale panels. This option is normally referred to as the producer take-back system. Goe and Gaustad (2016a) posits that, the incentive for the collection and recycling of end-of-life solar is very low with the panels eventually ending up in municipal waste streams if there are no legislative interventions. There is need to aim towards recycling and treating these wastes from PV modules which is becoming a global issue. The treatment involves the systematic and holistic management of these discarded PV modules which are inevitable. There is a global demand to develop recycling infrastructure and guidelines in the management of PV waste and this requires an integrated framework, nevertheless, the focus has been regionalised (Mahmoudi et al., 2021). Several countries like the UK and EU have legislations that require solar PV panels to be recycled at their end-of-life and others like Australia and Japan continues to work towards related legislations (Majewski et al., 2021). The role of policymakers on how to involve investors in the treatment of end-of-life PV heavily relies on the research and development programs, financial incentives and the enactment of suitable regulation and legislations to create an economically profitable climate for PV waste management. However, the valuable material contents, proximity of suitable recycling facilities to PV waste stream, and the geographic concentration of end-of-life panels are major considerations when it comes to the economic feasibility of treating solar PV waste (Mahmoudi et al., 2021). Currently, there have been efforts to recycle solar PV waste with some companies setting up recycling facilities in Australia. This includes creating a reverse logistic network and collection system for distributed PV panels for the recycling and recovery of end-of-life solar panels in Australia.

The reduction of risks in the investment of treatment programs for EoL solar PV is very critical as it creates an avenue for investors and policy makers. Implementation of policies and legislations heavily rely on how reliable and accurate the future prediction of the total amount, value of reclaimable material and the material composition of waste from solar PV panels. This also has a huge impact on the economic feasibility of treatment processes. The clearer the results, the higher the profitability as well as a proper assessment of the environmental burdens that comes with it, which serves as a great incentive for investors and policy makers to take a better step in the successful treatment of waste from solar PV modules (Peeters et al., 2017). The introduction of various incentives from the government and the increase of public awareness on the environment has seen a rapid increase in the installation of residential rooftop PV in Australia. However, the environmental and economic performance of solar PV waste is yet to be thoroughly examined in the Australian condition (Oteng et al., 2021; Nicholls et al., 2015) especially from the pollutant emission aspects related to transportation.

The collection and transportation involved in solar PV waste treatment has a significant impact on the environment and sustainability. Reverse logistics (RL) according to Stock (1992), is "*… the term often used for the role of logistics in re-cycling, waste disposal and management of hazardous materials; a broader perspective includes all issues relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal*". The design of a holistic reverse logistic (RL) network will effectively facilitate the collection and transportation of PV waste to reduce the costs and environmental impacts in the treatment of EoL PV waste both globally and regionally. However, there is a lack of active research and development on EoL PV waste generation and distribution in the Organisation for Economic Co-operation and Development (OECD) member countries when it comes to a holistic RL network (Mahmoudi et al., 2021). The collection and transport of waste should be critically designed to reduce pollutants and emissions into the air. The consumption of a litre of fuel produces 2.5g of CO_2, 30g of NOx, 20g of VOC, 100g of CO, and other poisonous, harmful substances like compounds of heavy particles, sulfur and lead (Ilić et al., 2014). Thus, environmental impacts of road transport from EoL PV waste should be comprehensively understood to prevent the increase of GHG emissions. Goe and Gaustad, 2016b posits that, the environmental trade-off between recovery energy use and transport distance of PV waste, as well as the impacts from its geographic dispersion has not been explicitly investigated.

In Australia, Islam and Huda (2020), estimated the optimised capacity and location of recycling facilities and collection points in New South Wales between 2001 and 2017 through a spatial distribution of generated solar PV waste. This was explored across various councils using the historical PV deployment of the state. Their study also revealed that, forecasting the waste generation using the Weibull distribution model would have been useful. In locating the recycling facilities, reference should be made to councils that generate a lot of PV waste. This study is the first of its kind in solar PV waste management research that addresses the distance and pollutant emissions associated with the collection and transportation of end-of-life solar PV. This research goes ***further*** to estimate the waste volume using the Weibull distribution-based model, in addition estimating the distance and emission of solar PV waste management at its end of life making reference to postcodes that generate a lot of PV waste. Thus, the main objectives of this study are to: a) forecast the generation of solar PV waste volume within South Australia (SA) in each postcode using the Weibull distribution-based model; b) analyse patterns under early and regular loss waste scenarios to create the spatial distribution of solar PV waste volume; c) optimise a system for the collection and transport network of solar PV waste to recycling and recovery facilities within the highest waste generated postcodes; and d) determine the influence of vehicle routes on pollutant emissions on the generated network.

2. Materials and methods

This section defines the study area and its contribution to the energy market and explains the spatial characteristics of solar PV waste generation across SA using the Weibull distribution-based model. The optimisation of the routing distances of recycling and landfill facilities across South Australia is also elucidated, how the Geographic Information System (GIS) was used in achieving the aforementioned and its associated environmental impacts are clarified. The flow of the study process is shown in Fig. 1 below.

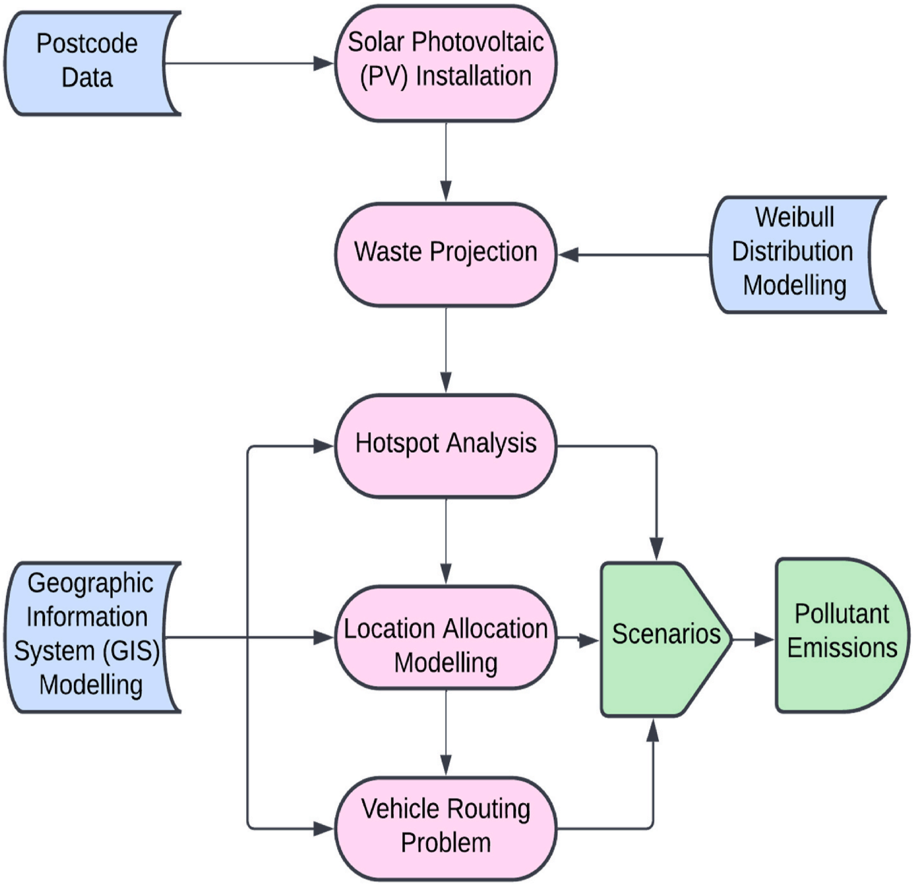

Fig. 1. Flow chart of the study process.

2.1. Study area

South Australia has a population around 1.77 million and covers a total land area of 983,482 km^2 making the fifth largest by population and fourth largest by area among the Australian states and territories. Rooftop solar panels constitutes 20% of Australian households' energy, making it the world's highest uptake of residential solar panels (Zander et al., 2019). In September 2020, there was a low demand for grid-based power across three states as records were sent tumbling because of the solar power boom in Australia. In particular, South Australia (SA) achieved a key milestone with the state becoming the first state in Australia and anywhere in the world to be powered entirely by solar power for over an hour in October 2020 (Clean Energy Regulator, 2021).

2.2. Waste projection scenarios and methods for spatial analysis

Geographic Information System provides an effective tool in analysing the spatial representation of data of different types in geographical visualised platform. It aids in the collection, output and distribution, analysis, storage and maintenance of spatial information and data (Chari et al., 2016). The dataset used for the estimation is obtained from Clean Energy Council. The data contains solar PV installations of capacity less than 100 kW from the year 2001–2021. In this study, this data was then compared and verified with data from Australian Photovoltaic Institute (APVI) data on similar installations in South Australia. The waste scenarios early and regular loss are forecasted using the acquired data.

2.2.1. Waste forecasting via Weibull distribution model

The current postcode installation data was collected from the Clean Energy Regulator (2021) resources on postcode data for small-scale installations as of June 2021. The dataset is current as of 31st April 2021 from the year 2001. The waste is calculated into early and regular loss scenarios (as shown in the supplementary information). The solar PV waste is calculated using the formulae:

$$F(t) = 1 - e^{-\left(\frac{t}{\tau}\right)^{\beta}} \tag{1}$$

where, the Weibull function is F(t), the life in years of the panels is t, the scale parameter which is the average lifetime of the panels is equal to τ. The shape factor, which is β, is responsible for the Weibull curve. All the years were calculated separately and then merged into one worksheet.

2.2.2. Hotspot mapping technique

Hotspot analysis measure the statistical significance of p-values and z-values derived from the identification of spatial clustering of low (cold spot) and high (hot spot) values (Chen et al., 2018). This spatial statistical method is used in different disciplines describing how high a value or region is relative to their surroundings. Spatial analysis provides valuable insights through the analysis of connections, locations and attributes in spatial data (Amiri et al., 2021). This research focuses on the mapping cluster method using the Getis-Ord (Gi*) hotspot analysis.

Getis and Ord (2010) was the first study to introduce the autocorrelation method which is the Getis-Ord (Gi*) spatial statistics. Their methods are able to discriminate between cold spots and hot spots as compared to other previous methods. The G* is able to tell the difference between concentrated low and high value locations within local observations as well as identify spatial clustering (Songchitruksa and Zeng, 2010). Thus, the features surrounding a high value feature should also have high values to be considered as a high spot. The general form for Getis–Ord (G_i^*) is:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i},{}_{j} x_j - \overline{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{2}$$

where x_j is the attribute value for feature j, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and:

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{3}$$

$$\mathrm{S} = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\overline{X})^2} \tag{4}$$

The G_i^* statistics is a z-score, so no further calculations are required. Low-value spatial clustering is represented by a negative z-score indicating a small p-value and a low z-score; however, high value spatial clustering is represented by a positive z-score indicating a small p-value and a high z-score (Chen et al., 2018; Prasannakumar et al., 2011).

2.3. Network analysis and route optimisation

In GIS, a network is a system with elements that are interconnected. Connections of streets to one another or to intersections, cities that are connected by roads, and points that are connected by a series of lines can all be visualised using a network. A network dataset (NDS) can be generated for analysis using the extension, Network Analyst (NA), in ArcGIS ArcMap. The networks that are created from the feature source in NA are stored in the NDS. Network attributes within the features like the one-way street locations, speed limits, street restrictions for specific vehicles, road length for fuel consumption and travel time are used to model and measure impedances (Tavares et al., 2009). Network analysis is commonly used to minimise distance (shortest route) or minimise travel time (fastest route) when ascertaining the optimal route or path of an element.

Solid waste collection can be optimised using the network analysis. The software ArcGIS can be used to design and optimise route using real-time road conditions. Some studies have employed the software in the application of minimizing distance or travel time in solid waste collection (Islam et al., 2021; Zsigraiova et al., 2013; Tavares et al., 2009). This study determines the Minimise Weighted Impedance (P-Median) within the Location-allocation modelling and Vehicle Routing Problem (VRP) using ArcMap version 10.8.1. The distance and travel time from the GIS modelling and analysis are used to calculate the associated emissions of transporting solar PV waste within and around South Australia.

The data used for the network analysis were retrieved from the Australian and SA government data directory. Data such as the shapefile for roads, waste management facilities, administrative regions, and information on speed limits and heavy-duty vehicles were obtained from the Department for Infrastructure and Transport (DTI). In SA, speed limits for unsealed roads are permitted up to 80 km/h. Roads that are not traffic routes have 50 km/h as speed limits and a default of 100 km/h speed limit as the maximum speed legally permitted to travel outside built-up areas. The network dataset sets a mean of 60 km/h as heavy vehicles are limited even on some highways in SA.

2.3.1. Location-allocation modelling

Location-allocation modelling is employed in this study to determine the shortest route generated by an origin-destination matrix through the application of Dijkstra algorithm between a waste source and specified number of facilities or nodes (Yalcinkaya, 2020). The p-median approach is used in this study as it minimises the overall weighted distance, with facilities serving their nearest demand vertex (ReVelle and Swain, 1970). Thus, the transportation distance and capacity of the facilities are determined through the allocation of the solar PV waste sources to the transfer stations. The p-median problem is formulated as follows:

$$\text{minimize}, \quad \mathrm{Z} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_i x_{ij} a_{ij} \tag{5}$$

$$\text{Subject to}:$$

$$\sum_{j=1}^{n} a_{ij} = 1, \ \forall\, i = 0, 1, 2, \ \ldots, m, \tag{6}$$

$$a_{ij} \le y_j \ \forall\, i = 0, 1, 2, \ \ldots, m \ and \ j = 0, 1, 2, \ \ldots, \ n, \tag{7}$$

$$\sum_{j=1}^{n} y_j = k, \tag{8}$$

$$a_{ij}, y_j \ \in \{0, 1\} \ \forall\, i = 0, 1, 2, \ \ldots, m \ and \ j = 0, 1, 2, \ \ldots, \ n, \tag{9}$$

$$\text{Decision variables}:$$

$$a_{ij} = \begin{cases} 1, & \textit{if waste source } i \textit{ is sent to a station located in } j \\ 0, & \textit{otherwise} \end{cases}$$

$$y_j = \begin{cases} 1, & \textit{if a station opened in } j \\ 0, & \textit{otherwise} \end{cases}$$

where, waste sources (solar PV waste) total is m; the total number of transfer stations is n; the chosen transfer stations in the model is k (k < n); index of potential transfer stations is j; index of waste sources is I; the shortest distance between potential stations and waste sources is represented by x_{ij}; the weight of the demand waste source at point i (known as the waste amount) is represented by d_i. The number of stations (k = 1, 2, 3, 4, …, n) as they increase are solved in this model. The objective function Z, as shown in equation (5) aims to minimise the overall distance between the waste sources and transfer stations. In assigning waste sources to transfer stations, equation (6) requires the assignment of one waste source to one station. If a station is not open, equation (7) does not assign any waste source. The restriction of several stations that is opened to k is achieved using equation (8).

A weight of 1–4 were allocated to the transfer stations, with 1 allocated to values that are not significant, and within the cold spot of 90%–99% confidence. 2, 3 and 4 were allocated to hot spot with confidence level of 90%, 95% and 99% respectively. This was to ensure transfer stations within the hot spot zones were given the highest priority before the ones in the cold spots. For the demand points or waste sources, the weight used was the amount of waste generated at the location. A search tolerance of 50000 m were set for the loading of the transfer stations and solar PV waste sources because of the large land mass in Australia.

2.3.2. Vehicle routing problem

Vehicle routing problem (VRP) solves the problem with parameters like type of output, network restrictions, network impedance and costs creating multiple routes to delivery facilities from one or more demand locations (Bozkaya et al., 2010). Dijkstra's (1959) work on his algorithm for shortest path has created an in-depth research phenomenon in road freight transportation through vehicle routing. Route optimisation which originates from the domain of graph theory and operations research continues to be used in the logistics domain where it has been adapted and extended with one being the VRP. A fleet of vehicles with a set of restrictions and different optimisation criterion can be optimised using the VRP (Schröder and Cabral, 2019). The VRP is determined using the extension within ArcMap 10.8.1 using the NA which has a built-in tabu search algorithm (Chari et al., 2016).

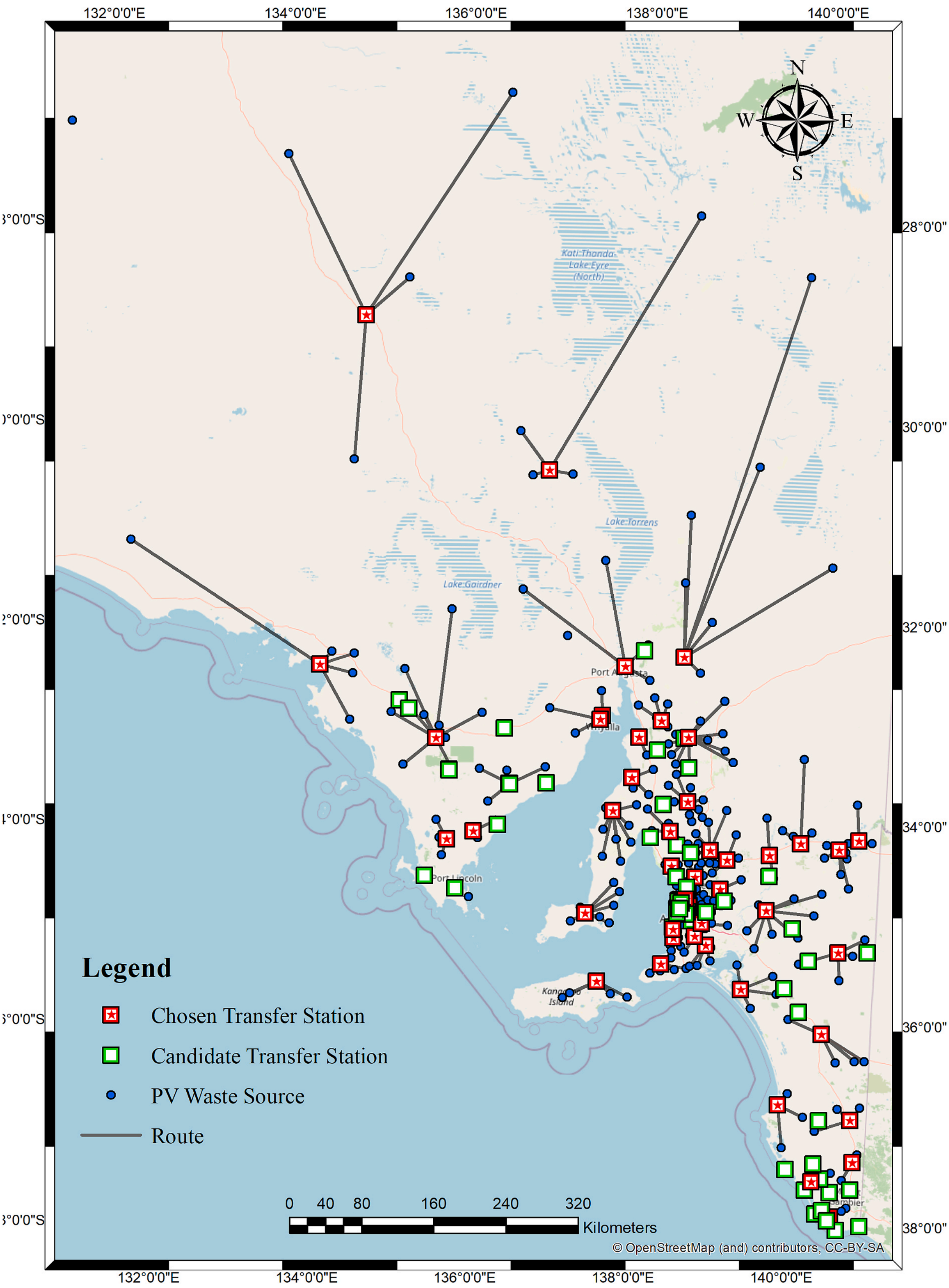

Fig. 2. Location-allocation modelling of waste sources to transfer stations.

2.4. Pollutant emissions

Waste collection and transportation influences the pollutants emitted through the operation conditions and travel distance of the vehicle in use. Pollutants such as PM, CO, CO_2 and NO_x are associated with heavy duty diesel vehicles which are commonly used for the collection and transportation of waste (Zsigraiova et al., 2013). This study uses the EURO IV diesel heavy duty vehicles for the calculation of the selected pollutants and referring to Hickman et al. (1999) methodology for calculating transport emissions and energy consumption (MEET). The corresponding emissions are calculated based on the determined optimum route in section 2.4.2. The equation used to determine the emissions are shown below:

$$E_i = \sum_{Vehicle\ route} \left(E_{i,hot} + E_{i,cold}\right) \tag{10}$$

$$E_{i,hot} = \varepsilon_{i,c} d_{tr} \tag{11}$$

$$\begin{aligned} \varepsilon_{i,c} = {} & \left(k_1 + av + bv^2 + cv^2 + \frac{d}{v} + \frac{e}{v^2} + \frac{f}{v^3}\right) \\ & \times \left[\left(k_2 + rv + sv^2 + tv^3 + \frac{u}{v} - 1\right)z + 1\right] \end{aligned} \tag{12}$$

$$E_{i,cold} = \varepsilon_{i,cold} N \tag{13}$$

The total pollutant emission i (g) is represented by E_i, $E_{i,hot}$ and $E_{i,cold}$ highlighting the total pollutant emissions, hot pollutant emissions and cold pollutant emissions respectively. The hot emission factor for pollutant i corrected for load (g/km) is represented by $\varepsilon_{i,c}$ and travel distance (km) is represented by d_{tr}. The mean velocity (km/h) is represented by v, whiles the coefficients k_1, a, b, c, d, e, f and k_2, r, s, t, u depends on the total weight of the selected vehicle. The fraction of the load transported is represented by z. The number of cold starts and cold emission factor for pollutant i (g/cold start) is represented by N and $\varepsilon_{i,cold}$ respectively. The values to the various coefficient are shown in the supplementary material, table A5.

3. Results and findings

The results of the analysed data are explained in this section. The location-allocation and vehicle routing modelling of the projected PV waste (results provided in *appendix C in the* supplementary material) is described in this section. This therefore provides a basis for the location-allocation modelling for transfer stations and route optimisation analysis of different waste scenarios. This helps to achieve a more sustainable approach in terms of pollutant emission reduction when handling the transportation and logistics of solar PV waste in Australia. This is further explained as below.

3.1. Location allocation modelling of PV waste to transfer stations

Location allocation modelling is used in multi-facility location problem to optimise and solve reverse logistic network problems in mane situations. To minimise the total waste collection and recycling distance in the state. The location allocation modelling was adopted to locate the collection centres with the aim of reducing and optimising travel distance in the transportation of future PV waste. The data on the location of transfer stations were collected from the national database retrieved from data. gov.au. The national waste management database consists of 108 transfer stations located in South Australia. This number was used as the baseline and centres for the collection of PV waste. The waste sources from the regular loss scenario are used for all analysis as it provides a standard waste loss scenario for solar PV panels. A network dataset was then built using the data provided and a projected coordinate South Australia Lambert was used for the modelling purpose. Transfer stations within Australia are facilities that temporarily holds different types of waste from collection vehicles and are them reloaded to transport vehicles to disposal or treatment sites across the state or country. The PV waste sources as shown in Fig. 2, are the collection centres or waste sources from solar PV.

The equations (5)–(9) were applied in locating these facilities. The data was analysed using ArcGIS location allocation layer with emphasis on minimizing impedance which corresponds to the p-median problem. With 108 candidate or potential facility locations identified, 54 were selected and optimised for the collection of PV waste as it proved economical and logistically efficient. The criteria for selection were based on the proximity of the transfer stations to each other and waste demand of each transfer station. Table A4 in the supplementary information provide a detail waste demand coverage and distance covered on the selected transfer stations. The selected transfer stations were then used to model the vehicle routing problem and create other scenarios to create an optimised reverse logistic network for solar PV waste collection and recycling.

3.2. Vehicle optimisation and routing scenario analysis

The routing analysis involves network dataset used for the location allocation modelling. Some assumptions were considered in the mapping of the routes. The shapefile of the road network data was retrieved from the South Australian government database provided by the department for infrastructure and transport. An average speed limit for all roads were set to 60 km/h since heavy duty trucks are limited to that speed limit on most highways and freeways. A time window was set at 8:00am to 5:00pm for all transfer stations with a service time of 30 min. A break of 1 h was also set in between the time windows. One inaccessible transfer station (Kangaroo Island resource and recovery centre) was removed from the analysis because of its location. One recycling centre was set for the analysis because of the presence of one recycler in South Australia. Lonsdale was chosen at the current site of the recycling facility for modelling.

The original distribution of 108 transfer stations was set as the base scenario with the omission one transfer station. Two other network scenarios were created to aid in achieving an optimal and efficient reverse logistic network for PV waste collection and recycling to minimise pollutant emissions associated with the collection and transport of PV waste. Two heavy duty trucks with a gross weight in the range of 7.5–16 and 16–32 tonnes were selected to be used in the collection of the waste from the transfer stations to the recycling centre.

The first scenario and baseline (Figure B1 in Supplementary Information) looked at the distribution of the waste source to all the available transfer stations in the state. The results revealed that truck 1 covered a total distance of 3074.92 km and 51.25 h within a week. The second truck covered a distance of 2727.53 km in 45.46 h within the week. Even though, truck 2 covered 54 orders compared to 53 for truck 1, the distance covered was less. This shows the long distances between transfer stations in the South Australia outbacks compared to the cities and urban areas. The total distance covered by the two trucks is 5802.45 km.

The second scenario used the optimised transfer stations from the location allocation modelling for the route analysis as shown in Figure B2 (in Supplementary Information). The distance covered by truck 1 is 2536.05 km in 42.27 h with truck 2 covering 2536.92 km within 42.28 h. Truck 1 and 2 covered 26 and 27 transfer stations respectively. A total of 5072.97 km was covered for all the 53 transfer stations within the week.

The third and last scenario shown in Fig. 3, considered introducing an additional transfer station at one of the hotspots and closer to most of the outback. An additional recycling facility was introduced at Port Augusta to cater for the transfer stations around that area. However, the optimised transfer stations were still used for the analysis. The analysis revealed that, truck 1 and 2 covered 2691.38 km and 1396.13 km with hours of 44.86 and 23.27 respectively. Truck one covered a lot of distance because of the wide distances between transfer stations, especially stations 9, 10 and 11.

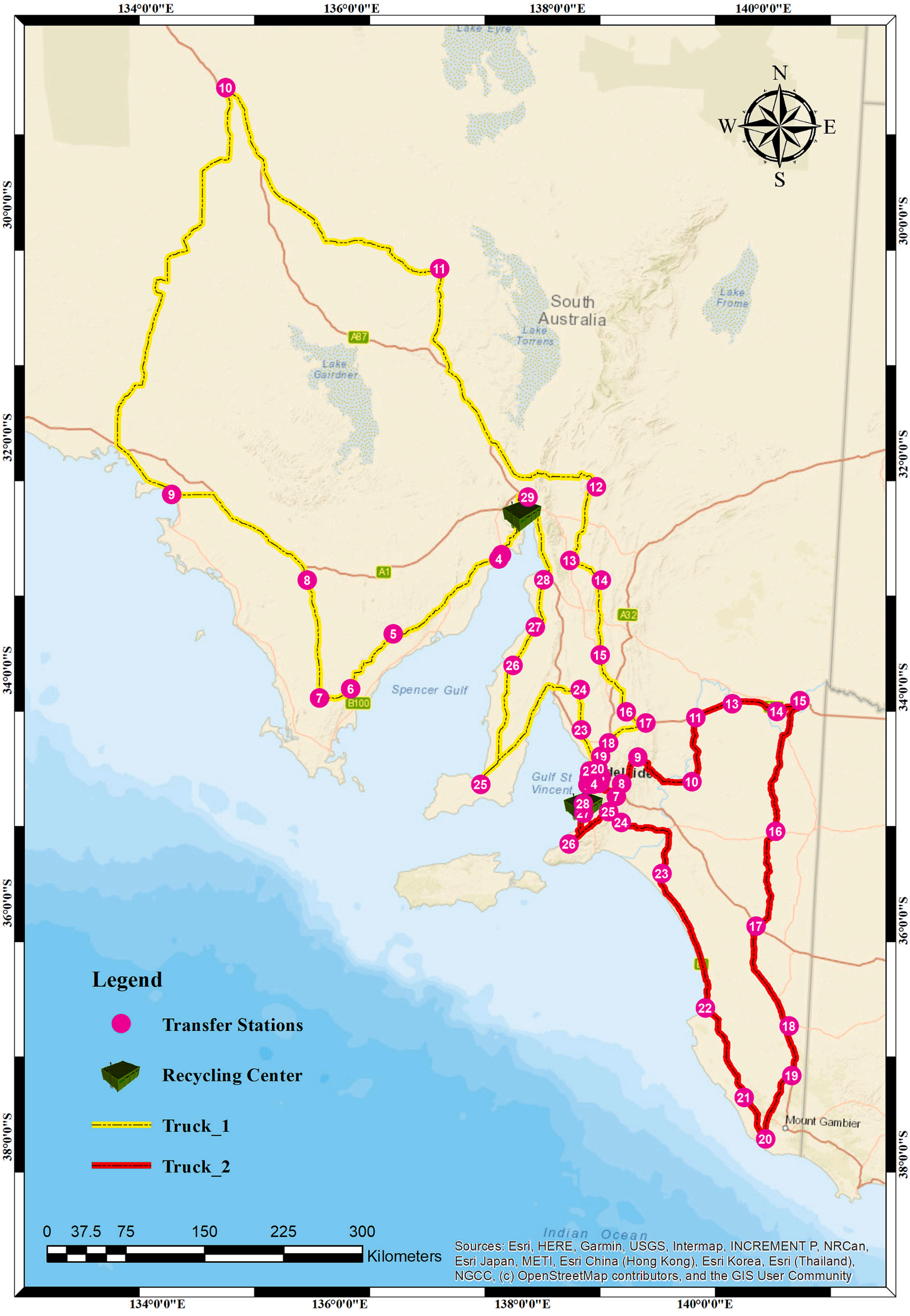

Fig. 3. Route analysis of optimised transfer stations to two recycling centres.

Table 1
Comparison of distance and percentage reduction between scenarios.

	Travel distance (Km)	Distance reduced (Km)	Percent reduction (%)	Total travel time (Hrs)	Time reduced (Hrs)	Percent reduction (%)
Scenario One (Baseline)						
Truck 1	3074.92			51.25		
Truck 2	2727.53			45.46		
Total	***5802.45***			***96.71***		
Scenario Two						
Truck 1	2536.05	538.87	17.5	42.27	8.98	17.5
Truck 2	2536.92	190.61	7.0	42.28	3.18	7.0
Total	***5072.97***	***729.48***	***12.6***	***84.55***	***12.16***	***12.6***
Scenario Three						
Truck 1	2691.38	383.54	12.5	44.86	6.39	12.5
Truck 2	1396.13	1331.40	48.8	23.27	22.19	48.8
Total	***4087.51***	***1714.94***	***29.6***	***68.13***	***28.58***	***29.6***

The comparison between the scenarios clearly highlights the differences in travel distance and coverage hours of the two trucks. It also provides a measurement of the current situation and how it can be improved. The two scenarios 2 and 3 recorded a 12.6 and 29.6 percent reduction of the total distance and time covered by the two trucks (see Table 1 above). A significant decrease in travel distance and time seen in scenario 3 places emphasis on the major effect of establishing more recycling facilities in the state.

3.3. *Pollutant emission based on route optimisation*

The effect of the travel distance on the pollution emitted was calculated using the methodology by Hickman et al. (1999). Using equation (10)–(13), the pollutant emissions for Particulate matter (PM), Nitrogen oxides (NO_x), Carbon dioxide (CO_2) and Carbon monoxide (CO) is calculated. Table A5 in the supplementary information provides the coefficient values for equations (12) and (13).

Using two heavy duty trucks of weight 7.5–16t and 16–32t, three routing scenarios were modelled and analysed using ArcGIS ArcMap 10.8.1. *Scenario 1: Baseline*. The 108 transfer stations with the exemption of the one situated on kangaroo island were modelled. With one recycling centre and 107 demand points, two trucks with loading capacities of 5.2 and 6.9 were used for the collection of the solar PV waste to the recycling centres. The trucks covered a distance of 3074.92 and 2727.53 km respectively. Both trucks with respect to emissions released 5704, 78603, 7440167 and 23851 g of PM, NO_X, CO_2 and CO respectively as recorded in Table 2. This scenario served as the baseline for this study. *Scenario 2: Optimised stations*. The second scenario used the 54 optimised stations with the exemption of the station on kangaroo island because of road transport limitations. With the same number of trucks and loading capacities, the total distance covered was reduced. However, because the recycling centre was one the travel distance didn't reduce as much. Table 2 details the pollutant emissions on this scenario. *Scenario 3: Additional recycling centre*. The last scenario used the same setup from the previous scenario (2) with the addition of an extra recycling centre to aid in reducing the load on the first recycling centre. There was a massive reduction in the emissions with this scenario. The total emissions recorded were 3801, 46543, 4792486 and 15559 g of PM, NO_X, CO_2 and CO respectively.

The three scenarios highlighted the impact of optimising the reverse logistics of end-of-life solar PV panels through the collection and transportation from transfer stations to recycling facilities. Among the scenarios, the third routing scenario showed a significant decrease in the four pollutant emissions.

4. Discussion

4.1. *Solar PV waste growth and recovery opportunities*

The government of Australia in 2016, announced in the national waste policy that, the coming years will see an increase growth of waste from solar PV which needs to be appropriately treated. Accordingly, it is necessary to perform a local analysis of the PV waste assessment. Designing a sustainable reverse logistic network necessitates the demonstration of the percentage of waste quantities in each state in Australia (Mahmoudi et al., 2019) to highlight the problems pertaining to the state. Padoan et al. (2019) posits that, the complication that comes with the recycling of end-of-life solar PV is also accompanied by the low concentration of waste PV modules for recovery. However, the recent increase in the adoption of solar PV modules worldwide and in Australia has shifted government's attention on the management of these modules when reaching their end of life. The old installed panels are coming to their end of life and most of them are being sent into the landfills as reported in the 2020 national waste report. The results of the waste projection in South Australia on both scenarios shows a significant amount of waste from PV in the year 2051.

The results of the projected waste provide data to address the assessment of environmental policy regulation and recycling strategies. Using the same equation (1), Mahmoudi et al. (2019) modelled the PV waste stream in Australia within a 30-year period with data from 2001

Table 2
Results of pollutant emissions from the three different routing scenarios.

	Scenario One[a] (Baseline)			Scenario Two[b]			Scenario Three[c]		
	Truck 1	Truck 2	Total	Truck 1	Truck 2	Total	Truck 1	Truck 2	Total
Travelled distance (Km)	3074.92	2727.53	**5802.45**	2536.05	2536.92	**5072.97**	2691.38	1396.13	**4087.51**
Total travel time (Hrs)	51.25	45.46	**96.71**	42.27	42.28	**84.55**	44.86	23.27	**68.13**
Number of Transfer stations covered	53	54	**107**	26	27	**53**	27	26	**53**
Pollutant Emission (g)									
PM	2424	3280	**5704**	1999	3051	**5050**	2122	1679	**3801**
NO_x	25,622	52,981	**78,603**	21,132	49,278	**70,410**	22,426	27,117	**49,543**
CO_2	2,707,291	4,732,876	**7,440,167**	2,232,899	4,402,160	**6,635,059**	2,369,643	2,422,843	**4,792,486**
CO	9207	14,644	**23,851**	7595	13,621	**21,216**	8060	7499	**15,559**

[a] One recycling centre serving 107 transfer stations.
[b] One recycling centre serving 53 transfer stations.
[c] Additional recycling centre making it two recyclers to 53 transfer stations.

to 2017. The data used in this study adds the data from the year 2018–2021 in the estimation of the PV waste. This study also considered installation capacity below 100k because of the huge penetration of rooftop solar panels in most of the states in Australia. However, the results also confirm the enormous amount of PV waste stream in the coming years. A strategy to recycle and recover these panels sustainably should be considered by the government as they enact policies and regulations in the coming years. Oteng et al. (2021) in their recent studies emphasised the need to recycle end of life solar panels as they may negatively impact the environment and human health. Reclaim PV, a company in South Australia has established a recycling plant in Lonsdale which was used in this study as the location of the recycling centre. The results of this study provide relevant information on the quantity and quality of PV waste flow within South Australia in the coming years which is also significant for all parties and stakeholders within the solar PV waste management system.

4.2. Influence of reverse logistics of solar PV waste recycling on pollutant emissions

The results prove the significance of logistics in the collection and transportation of solar PV waste in the coming years and how it will affect the decision of policy makers and industry in the management of PV waste in Australia. A projection of the waste from the already installed panels provides the opportunity for policy makers and industry to better prepare and institute appropriate treatment programs in the management of these wastes. However, the valuable material content, the proximity of PV waste sources to recovery centre and the concentration of the PV waste geographically is a major contribution when it comes to the economic feasibility of the treatment program (Mahmoudi et al., 2021; Fthenakis, 2000) which also affects the amount of emissions released into the atmosphere. The scenarios put emphasis on the effect collection and transportation has on the environment and how this could be reduced.

According to Tavares et al. (2009), a substantial percentage of the budget used in managing waste (including the cost of labour) is mainly associated with the collection and transportation of solid waste. The vehicles release emissions like NO_x and CO_2 in significant amounts which contributes substantially to acid rain and the greenhouse effect. A total CO_2 emission of 1118 million tons was produced by road freight transportation in 2010, accounting for 3.5% of CO2 emission produced worldwide. If there are no major changes, an increase of 30.5% is expected in the year 2050 within the entire logistics sector worldwide. The environmental impact from road freight transportation needs to be reduced to achieve the climate change related objectives through a sustainable reduction of CO2 emissions (Schröder and Cabral, 2019). Therefore, financial and environmental benefits can be achieved if the outputs of these pollutants are reduced by creating an appropriate reverse logistic network for the recycling and recovery of solar PV waste.

The geographical dispersion of PV waste sources makes the logistics in the collection and transportation of solar PV very difficult (Padoan et al., 2019). This is made much more difficult in a country like Australia where facilities like the transfer stations and recycling facilities are far apart from each other creating more coverage distance for vehicles. Therefore, a significant amount in pollutant emissions from vehicles. However, there is a substantial decrease in the pollutant emissions from PM, NO_x, CO_2 and CO when comparing the three routing scenarios from the results (Fig. 4).

4.3. The effect of policy and regulations on the logistics of PV waste management

According to Australia's net zero emission targets for 2050, transport emission would have fallen by 39 MT CO_2-e (Australian Government, 2021). With regulations and targets to reduce transport emission, it is imperative that solar PV recycling reduce transport emissions which contributes to a huge part of solar PV waste recycling and recovery (Oteng et al., 2021). The involvement of parties in the PV waste management sector mainly depends on proper laid down policies and incentives (D'Adamo et al., 2017). Policy and regulations that creates an avenue for various parties within an environmental and economic sense in the treatment of decommissioned PV panels cannot be overlooked (Mahmoudi et al., 2019). A recent study by Jain et al. (2021) emphasied the importance of policy and regulations in the effective management of solar PV waste. However, there are no current regulations established in the state of South Australia and Australia when it comes to the management of end-of-life solar panels. The "which bin" initiative in South Australia which promotes the proper disposal of various types of waste does not provide a bin for solar PV waste and recommends users to reach out to their local councils. The 2020 National Waste Report revealed that, most of the waste from solar PV were going into the landfill. With the recommendation to recycle these panels, it means the government

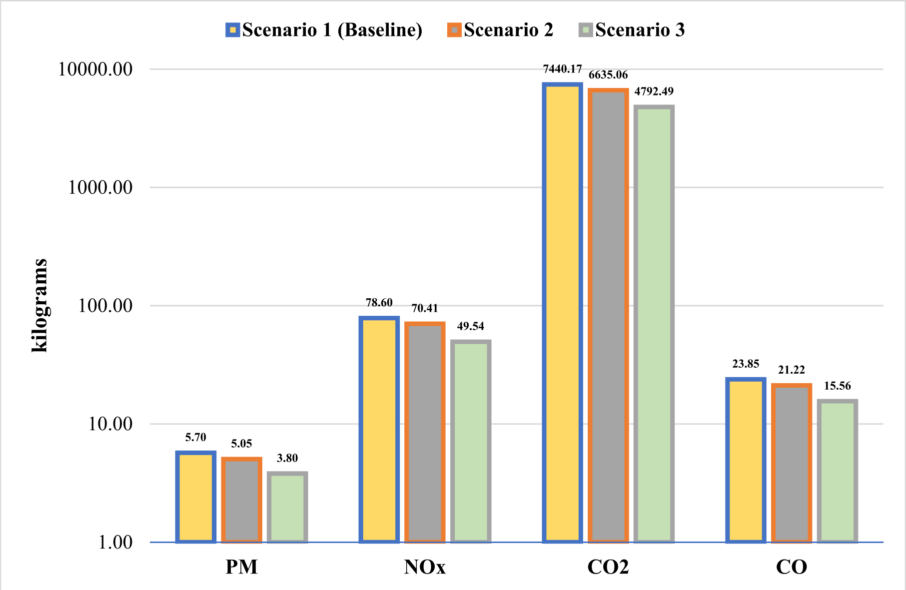

Fig. 4. Pollutant emissions of route optimisation scenarios.

has to do a lot when it comes to the management of solar PV waste by establishing policies and regulations as soon as possible. This was further established in a study by Majewski et al. (2021), calling for a robust establishment of end-of-life PV product stewardship and effective management schemes to aid in the reduction of greenhouse gas emissions. This will help to reduce emissions and contribute to the net zero emission targets set for 2050 by the Australian Government.

5. Conclusions

This study provides new projected information on pollutant emissions from the logistics in the collection and transportation of solar PV waste through establishing scenarios using multi-methodological approaches. Emissions associated with the collection, transportation and treatment of PV waste are added to the solar PV waste management system in this study. The Weibull distribution forecasted the generation of over 109,007 tons of PV waste by 2050 in South Australia. It is also estimated that, over 1000 tons of solar PV waste will be generated in 15 postcodes by 2050 based on the early and regular loss scenarios. The hotspot analysis confirmed the results with these areas of the postcodes having a hotspot of 99% confidence. Using the results from the hotspot analysis, 54 transfer stations were optimised using their travel distances. The optimisation of travel distance of the transfer stations indicates up to 34% reduction in the pollutant emissions.

Among the three routing scenarios studied, an introduction of an additional recycling centre resulted in the highest reduction of the pollutant emissions (PM, NO_x, CO_2 and CO). To facilitate more efficient management of PV waste, adequate policy may be introduced to fast-track the introduction of regulations and product stewardship to govern end-of-life solar PV waste in Australia. Effective product stewardship will help regulate the waste from landfills and motivate industry partners to seize the opportunity to collect and recycle end of life solar panels. Again, industry in collaboration with the government can set up recycling facilities in suitable areas with an effective reverse logistic network design that reduce the pollutant emission of vehicles. Similarly, the use of electric vehicle/trucks, types of solar PV technology and new recycling/treatment processes through further life cycle assessment and sensitivity analysis can also produce significant results in the reduction of emissions related to transportation.

Future research should aim at investigating a sustainable policy for the treatment of end-of-life PV modules. The pollutant emission and travel distances can serve as data for life cycle assessment of recycling and recovery of various PV technologies. The results of the hotspot analysis may be used to establish new recycling facilities for the state and to generate new recycling areas using suitability analysis.

Credit author statement

Daniel Oteng: Conceptualization, Methodology, Original draft preparation: **Jian Zuo:** Conceptualization, Supervision, Reviewing and Editing: **Ehsan Sharifi:** Conceptualization, Visualization, Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115007.

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Supplementary Information

Environmental emissions influencing solar photovoltaic waste management in Australia: An optimised system network of waste collection facilities

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(Appendix A)

Waste forecasting via Weibull distribution modelling

Weibull distribution model has been employed in previous studies to estimate, forecast, or model the waste quantity of products like e-waste (Kiran et al., 2021; Mairizal et al., 2021) and solar PV waste (Gautam et al., 2021; Mahmoudi et al., 2019; Weckend et al., 2016). The implementation of the Weibull function is more justified because of its distribution-based lifespan modelling instead of using the fixed average lifespan (Islam and Huda, 2020). In estimating the waste quantities of computers, Petridis et al. (2016) revealed that, the Weibull distribution compared with other distributions fits data better. This research therefore employs the Weibull distribution model in predicting the future volumes of PV waste.

Postcode-level data was used in forecasting the waste generation of solar panels. This study looks at solar installations with a capacity less than 100kW. The current postcode installation data was collected from the Clean Energy Regulator (2021) resources on postcode data for small-scale installations as of June 2021. The dataset is current as of 31st April, 2021 from the year 2001. This was also double checked with the PV postcode data from the Australian Photovoltaic Institute. Installation capacity greater than 100kW registered under the Large-scale Renewable Energy Target (LRET) was not included in the study. Thus, commercial PV installations are counted as systems equal or greater than 100kW. Using the Weibull distribution model, the waste generation of the PV waste was estimated to 2051 as shown in table A1. The waste is calculated into early and regular loss scenarios. The solar PV waste is calculated using the formulae;

$$F(t) = 1 - \mathrm{e}^{-\left(\frac{t}{\tau}\right)^{\beta}} \tag{1}$$

Where, the Weibull function is F(t), the life in years of the panels is t, the scale parameter which is the average lifetime of the panels is equal to τ. The shape factor, which is β, is responsible for the Weibull curve. In this research, the Weibull shape factor (β) for early-loss and regular loss scenarios are 2.4928 and 5.3759 respectively. This assumption is based on the works of expert researchers (IEA-PVPS, 2014; Weekend et al., 2016) on modelling the probability of PV panel loss through expert judgement and systematic analysis of literature. The average lifespan of the panels is assumed in both scenarios as 30 years and a probability of 99.99% of loss after 40 years (Mahmoudi et al., 2019). Using Microsoft Excel, the Weibull function was translated into a worksheet, the various scenarios were then estimated within a 30-year period with the data collected from 2001 to 2021. All the years were calculated separately and then merged into one worksheet.

Table A1: Projected solar PV waste

The table details the solar PV waste projected from the year 2001 to 2051 using the Weibull distribution function at each postcode.

S/N	***Postcodes***	***Early Loss***	***Regular Loss***	***S/N***	***Postcodes***	***Early Loss***	***Regular Loss***
1	*0872*	0.0000	0.0000	**173**	*5266*	44.59607	49.72584774
2	*5000*	601.5683	674.9664	**174**	*5267*	139.1361	156.4645358
3	*5006*	229.7543	258.6019	**175**	*5268*	247.0264	279.0714523
4	*5007*	389.6686	435.1218	**176**	*5269*	15.33334	17.46024884
5	*5008*	616.4665	688.0637422	**177**	*5270*	47.75103	53.80003144
6	*5009*	341.6981	382.4022622	**178**	*5271*	470.9927	530.8086997
7	*5010*	399.9982	448.0615076	**179**	*5272*	46.90575	52.52711712
8	*5011*	610.4979	682.3248728	**180**	*5273*	3.516404	4.035063638
9	*5012*	488.4012	546.196536	**181**	*5275*	175.1095	197.4294846
10	*5013*	824.6014	923.1406242	**182**	*5276*	123.2904	138.2944267
11	*5014*	600.8626	672.7691297	**183**	*5277*	171.1452	192.0774152
12	*5015*	327.4605	367.3443052	**184**	*5278*	26.86179	30.13421268
13	*5016*	441.2872	493.7448176	**185**	*5279*	26.89351	30.10883466
14	*5017*	205.2134	230.8153159	**186**	*5280*	447.9418	506.3292201

15	*5018*	309.5496	348.478801	**187**	*5290*	853.4119	957.5141313
16	*5019*	398.1612	446.4465182	**188**	*5291*	579.2047	649.8941453
17	*5020*	168.9775	190.3827762	**189**	*5301*	41.53831	47.01993134
18	*5021*	360.8108	404.1202817	**190**	*5302*	60.17827	68.41749758
19	*5022*	775.8092	867.9877858	**191**	*5303*	14.13808	15.51587318
20	*5023*	658.1499	735.8136519	**192**	*5304*	35.08111	40.27037883
21	*5024*	673.7568	754.7951797	**193**	*5306*	4.312701	4.90051643
22	*5025*	416.8995	466.2077818	**194**	*5307*	42.94163	48.39490657
23	*5031*	522.9514	585.7522416	**195**	*5308*	7.460291	8.4836862
24	*5032*	584.2187	654.4093005	**196**	*5309*	7.731241	8.647625565
25	*5033*	414.0562	464.5606062	**197**	*5310*	2.414284	2.744154988
26	*5034*	468.5439	526.4296943	**198**	*5311*	17.45055	19.91001172
27	*5035*	268.3658	300.1766756	**199**	*5320*	114.8271	128.4329721
28	*5037*	477.0031	535.9160592	**200**	*5321*	39.69834	44.60284044
29	*5038*	618.9563	691.8175552	**201**	*5322*	83.87874	94.53808602
30	*5039*	528.2471	590.3239105	**202**	*5330*	340.2796	382.7947492
31	*5040*	136.0403	152.4465381	**203**	*5331*	39.25698	43.66320758
32	*5041*	575.7400	644.0444588	**204**	*5332*	36.37965	41.08154582
33	*5042*	553.7587	621.0449969	**205**	*5333*	556.5448	627.9917249
34	*5043*	759.7149	848.2779224	**206**	*5340*	130.531	147.4919756
35	*5044*	571.2987	639.7215482	**207**	*5341*	713.8656	802.1976071
36	*5045*	638.0542	712.9770569	**208**	*5342*	116.5639	131.7091188
37	*5046*	368.7354	412.0088979	**209**	*5343*	468.306	530.7617994
38	*5047*	360.7098	404.1938284	**210**	*5344*	81.51815	92.92238194
39	*5048*	719.1845	804.6726393	**211**	*5345*	299.6514	340.4629121
40	*5049*	526.002	589.4057292	**212**	*5346*	28.45346	32.29159005
41	*5050*	292.4225	327.5197778	**213**	*5350*	63.25586	71.13145732
42	*5051*	795.6509	890.2123407	**214**	*5351*	442.2267	497.2459786
43	*5052*	329.0123	367.3916338	**215**	*5352*	480.3833	541.7252597
44	*5061*	563.6188	631.1548608	**216**	*5353*	306.8038	344.2737236
45	*5062*	842.7548	943.7446423	**217**	*5354*	57.18878	63.57803948
46	*5063*	540.5836	605.607048	**218**	*5355*	670.9803	753.7668364
47	*5064*	596.758	666.3502189	**219**	*5356*	54.81592	61.95123378
48	*5065*	515.5202	575.8713174	**220**	*5357*	77.18049	86.60541011
49	*5066*	703.9106	786.5196722	**221**	*5360*	83.9779	94.52671028
50	*5067*	512.2470	571.8357313	**222**	*5371*	127.2451	143.5093627
51	*5068*	588.7639	658.3177959	**223**	*5372*	172.254	192.0087761
52	*5069*	487.6347	544.4472166	**224**	*5373*	234.3799	263.2818696
53	*5070*	673.9259	751.3114661	**225**	*5374*	123.8429	137.2161978
54	*5072*	719.4862	805.0621446	**226**	*5381*	27.60244	30.79235873
55	*5073*	726.8995	812.3655311	**227**	*5400*	72.06653	80.24937911
56	*5074*	641.1682	716.8443909	**228**	*5401*	51.24515	57.23353834
57	*5075*	496.4612	555.4260355	**229**	*5410*	20.53094	23.31178293
58	*5076*	457.2011	510.553752	**230**	*5411*	18.90421	21.39646582
59	*5081*	550.6432	613.6463699	**231**	*5412*	94.62179	106.2494701
60	*5082*	724.4445	809.4756641	**232**	*5413*	60.3927	68.06403503

61	*5083*	319.8562	357.1477061	**233**	*5414*	6.043267	6.862829664
62	*5084*	403.5039	450.7300982	**234**	*5415*	16.94175	18.83095405
63	*5085*	1020.115	1138.429045	**235**	*5416*	14.63677	16.60928994
64	*5086*	818.4347	916.1671313	**236**	*5417*	108.8046	122.8084594
65	*5087*	525.8764	586.8810054	**237**	*5418*	7.770765	8.669544719
66	*5088*	223.3071	250.2765351	**238**	*5419*	14.61879	16.40398974
67	*5089*	335.3479	375.6928895	**239**	*5420*	5.848287	6.557492376
68	*5090*	368.5246	413.1405796	**240**	*5421*	6.276541	7.198336179
69	*5091*	364.1050	407.743424	**241**	*5422*	106.8605	120.98938
70	*5092*	789.7065	884.8163323	**242**	*5431*	88.11462	99.31325764
71	*5093*	394.5312	442.1062681	**243**	*5432*	12.81396	14.56208132
72	*5094*	301.1610	336.0684128	**244**	*5433*	106.9841	121.6433078
73	*5095*	1077.307	1206.924477	**245**	*5434*	22.64889	25.72711274
74	*5096*	721.0255	809.7000674	**246**	*5440*	17.91312	20.54165549
75	*5097*	631.4592	706.0213559	**247**	*5451*	59.46332	67.41858327
76	*5098*	592.5745	665.4267055	**248**	*5452*	47.1264	53.97154267
77	*5106*	97.04292	109.448406	**249**	*5453*	409.8412	462.675437
78	*5107*	912.8447	1025.480284	**250**	*5454*	26.35793	29.74856356
79	*5108*	1834.933	2054.245231	**251**	*5455*	2.480081	2.826799347
80	*5109*	1009.423	1132.581727	**252**	*5460*	66.241	74.99407289
81	*5110*	655.7571	733.9804458	**253**	*5461*	189.7003	213.3277564
82	*5111*	67.53442	74.78923865	**254**	*5462*	35.82708	40.60168076
83	*5112*	801.0403	894.5713132	**255**	*5464*	34.6927	38.90367603
84	*5113*	662.9219	741.357669	**256**	*5470*	7.658271	8.547295986
85	*5114*	1750.182	1954.642362	**257**	*5471*	5.019397	5.619120305
86	*5115*	505.0453	560.4745378	**258**	*5472*	14.89035	16.74009154
87	*5116*	522.9906	585.3271728	**259**	*5473*	53.12735	59.83533459
88	*5117*	349.4114	389.5650708	**260**	*5480*	83.79516	95.27174512
89	*5118*	1245.718	1395.968382	**261**	*5481*	52.01276	58.58735911
90	*5120*	435.4264	486.3510551	**262**	*5482*	44.96971	51.24705091
91	*5121*	239.6720	265.424518	**263**	*5483*	23.6387	26.70946544
92	*5125*	1015.7730	1138.601399	**264**	*5485*	45.54019	51.28988325
93	*5126*	330.9480	370.2418414	**265**	*5490*	13.43216	15.42062939
94	*5127*	364.8212	409.4350917	**266**	*5491*	174.5797	196.5142369
95	*5131*	79.81178	90.02816903	**267**	*5493*	5.705592	6.497105907
96	*5132*	57.20703	64.73655372	**268**	*5495*	61.85629	69.95186262
97	*5133*	36.46125	41.07728845	**269**	*5501*	770.7204	860.2460657
98	*5134*	36.56594	41.25288061	**270**	*5502*	134.5063	150.6566047
99	*5136*	34.62102	38.57040319	**271**	*5510*	7.640488	8.713363602
100	*5137*	66.07959	74.08126669	**272**	*5520*	37.5513	42.41569321
101	*5138*	35.18656	39.45084136	**273**	*5521*	11.39635	12.9027022
102	*5139*	52.11066	57.91269645	**274**	*5522*	163.3718	185.2755773
103	*5140*	25.88697	28.82206622	**275**	*5523*	120.5644	136.0148634
104	*5141*	58.6182	65.70825994	**276**	*5540*	963.237	1088.613915
105	*5142*	56.7750	64.09096968	**277**	*5550*	141.8623	157.5633068
106	*5144*	36.87923	41.57939186	**278**	*5552*	24.46054	27.80662047

107	*5150*	8.398979	9.391499321	**279**	*5554*	381.9642	431.2580926
108	*5151*	27.94413	31.5728786	**280**	*5555*	41.34133	46.77443016
109	*5152*	324.4804	363.0616359	**281**	*5556*	360.4599	404.3134616
110	*5153*	593.8984	667.3409552	**282**	*5558*	472.1835	530.5083638
111	*5154*	172.6552	193.2527527	**283**	*5560*	42.36438	47.96713144
112	*5155*	195.1017	217.4414593	**284**	*5570*	55.70238	62.48462354
113	*5156*	41.43584	46.6426154	**285**	*5571*	157.6084	177.58313
114	*5157*	254.4023	285.841569	**286**	*5572*	12.07281	13.74328221
115	*5158*	1291.127	1450.977526	**287**	*5573*	198.6279	223.9501645
116	*5159*	1660.918	1865.209675	**288**	*5575*	256.298	288.9836709
117	*5160*	298.3997	335.504416	**289**	*5576*	82.16349	92.91031884
118	*5161*	496.8037	558.6253797	**290**	*5577*	45.54041	50.92144247
119	*5162*	1661.957	1865.812214	**291**	*5580*	30.26704	34.10396882
120	*5163*	744.6956	834.163668	**292**	*5581*	73.84093	83.17727328
121	*5164*	192.7888	215.5645645	**293**	*5582*	70.71434	79.14021672
122	*5165*	218.9898	246.0432178	**294**	*5583*	101.1921	113.4609813
123	*5166*	83.51817	93.4616605	**295**	*5600*	527.8394	597.4325874
124	*5167*	292.8361	326.4257143	**296**	*5601*	21.81532	25.02289187
125	*5168*	328.8749	368.699448	**297**	*5602*	117.27	132.6752657
126	*5169*	1021.734	1139.364663	**298**	*5603*	40.00827	44.71575014
127	*5170*	73.36135	82.05581165	**299**	*5604*	17.75634	19.63801188
128	*5171*	614.2017	693.5315845	**300**	*5605*	140.5071	158.7947715
129	*5172*	359.8142	404.1870593	**301**	*5606*	835.892	940.7253078
130	*5173*	744.7273	834.2338257	**302**	*5607*	357.9674	402.8894587
131	*5174*	201.4551	225.814457	**303**	*5608*	622.3409	703.2269162
132	*5201*	186.3446	208.5186482	**304**	*5609*	102.5264	115.9313367
133	*5202*	90.72012	101.7822236	**305**	*5611*	5.060787	5.547257569
134	*5203*	112.5351	126.4092467	**306**	*5630*	6.629787	7.467053581
135	*5204*	363.5944	406.3849479	**307**	*5631*	102.6465	116.0548938
136	*5210*	157.0541	176.3078038	**308**	*5632*	13.92606	15.72838554
137	*5211*	1271.838	1429.914032	**309**	*5633*	24.81144	27.41995826
138	*5212*	189.0268	212.2839173	**310**	*5640*	97.40971	110.1742797
139	*5213*	124.7925	140.2706462	**311**	*5641*	89.95317	99.71273658
140	*5214*	813.0125	910.3674086	**312**	*5642*	17.59242	19.75024134
141	*5220*	9.293245	10.50202051	**313**	*5650*	6.943853	7.944355543
142	*5221*	36.32003	41.03641633	**314**	*5651*	9.847282	11.27309901
143	*5222*	64.44935	72.70808148	**315**	*5652*	61.7639	69.97569774
144	*5223*	230.3312	259.8275341	**316**	*5653*	4.002167	4.520944958
145	*5231*	94.89366	106.7821047	**317**	*5654*	16.05597	18.36524551
146	*5232*	38.47676	43.1896602	**318**	*5655*	4.877582	5.597967985
147	*5233*	135.4041	151.7906428	**319**	*5660*	2.004822	2.254275524
148	*5234*	106.3294	119.573054	**320**	*5661*	11.2898	12.92918504
149	*5235*	195.354	219.3294628	**321**	*5670*	47.76468	53.89522997
150	*5236*	20.24438	22.76210648	**322**	*5671*	13.15917	15.04832164
151	*5237*	21.80229	24.62531158	**323**	*5680*	229.7858	260.3149248
152	*5238*	426.2864	478.5873987	**324**	*5690*	247.718	280.3929531

153	*5240*	87.23397	96.91714848	**325**	*5700*	728.9062	822.6147578
154	*5241*	209.748	234.1538913	**326**	*5701*	8.454944	9.532507564
155	*5242*	143.5655	160.8718618	**327**	*5710*	201.5345	227.0451491
156	*5243*	85.83466	96.20860853	**328**	*5713*	2.310027	2.638143795
157	*5244*	359.5835	403.2331993	**329**	*5715*	0.0000	0.0000
158	*5245*	245.3775	275.0529162	**330**	*5717*	8.738024	9.850432229
159	*5250*	263.854	297.783448	**331**	*5719*	5.79785	6.368148421
160	*5251*	1253.285	1396.927912	**332**	*5720*	6.277084	7.135330016
161	*5252*	380.6723	428.1166631	**333**	*5722*	11.53768	13.12866967
162	*5253*	1232.962	1390.855166	**334**	*5723*	48.34446	53.50612898
163	*5254*	284.3637	319.3712032	**335**	*5724*	1.625438	1.75425855
164	*5255*	773.7239	865.2391755	**336**	*5725*	124.7526	143.0337066
165	*5256*	123.4499	138.1168414	**337**	*5730*	7.219407	8.079773142
166	*5259*	135.5527	153.9246928	**338**	*5731*	51.90021	57.42137691
167	*5260*	118.888	134.3090545	**339**	*5732*	20.2768	23.4766687
168	*5261*	18.20668	20.82941904	**340**	*5733*	11.38513	13.00182057
169	*5262*	29.42669	33.05229104	**341**	*5734*	2.170576	2.4286321
170	*5263*	38.8203	43.96262136	**342**	*5950*	6.655638	7.53115375
171	*5264*	111.8795	126.7067312	**343**	*5960*	0.0000	0.0000
172	*5265*	25.76865	29.06635055				

Table A2: Hot spot values of early loss scenario

The table shows the details of the ten highest scores from the hotspot analysis for early loss scenario.

Postcode	*Gi Bin*	*Z score*	*P value*	*City/Town/Suburb*
5275	3	7.165	0.00	Wyomi; West Range; Wangolina; Tilley Swamp; Taratap; Sandy Grove; Rosetown; Reedy Creek; Pinks Beach; Mount Benson; Kingston SE; Keilira; Cape Jaffa; Boatswain Point; Blackford.
5267	3	6.983	0.00	Field; Coonalpyn.
5223	3	6.918	0.00	Wisanger; Western River; Vivonne Bay; Stun'sail Boom; Stokes Bay; Seddon; Seal Bay; North Cape; Newland; Nepean Bay; Middle River; Menzies; Macgillivray; Kohinoor; Kingscote; Karatta; Harriet River; Gosse; Haines; Flinders Chase; Emu Bay; Duncan; D'estrees Bay; De Mole River; Cygnet River; Cassini; Cape Borda; Brownlow Ki; Birchmore; Bay of Shoals.
5220	3	6.681	0.00	Parndana
5270	3	6.678	0.00	Swede Flat; Mundulla West; Mundulla; Kongal; Carew; Buckingham.
5302	3	6.403	0.00	Ngarkat; Lameroo.
5304	3	6.354	0.00	Pinnaroo; Peebinga; Kringin.
5606	3	6.320	0.00	Port Lincoln; Kirton Point.
5266	3	6.260	0.00	Tintinara; Deepwater; Colebatch; Bunbury.
5303	3	6.216	0.00	Parilla

Table A3: Hotspot values of regular loss scenario

The table shows the details of the ten highest scores from the hotspot analysis for regular loss scenario.

Postcode	*Gi Bin*	*Z score*	*P value*	*City/Town/Suburb*
5275	3	7.148	0.00	Wyomi; West Range; Wangolina; Tilley Swamp; Taratap; Sandy Grove; Rosetown; Reedy Creek; Pinks Beach; Mount Benson; Kingston SE; Keilira; Cape Jaffa; Boatswain Point; Blackford.
5267	3	6.966	0.00	Field; Coonalpyn.
5223	3	6.898	0.00	Wisanger; Western River; Vivonne Bay; Stun'sail Boom; Stokes Bay; Seddon; Seal Bay; North Cape; Newland; Nepean Bay; Middle River; Menzies; Macgillivray; Kohinoor; Kingscote; Karatta; Harriet River; Gosse; Haines; Flinders Chase; Emu Bay; Duncan; D'estrees Bay; De Mole River; Cygnet River; Cassini; Cape Borda; Brownlow Ki; Birchmore; Bay of Shoals.
5270	3	6.666	0.00	Swede Flat; Mundulla West; Mundulla; Kongal; Carew; Buckingham.
5220	3	6.661	0.00	Parndana
5302	3	6.385	0.00	Ngarkat; Lameroo.
5304	3	6.336	0.00	Pinnaroo; Peebinga; Kringin.
5606	3	6.300	0.00	Port Lincoln; Kirton Point.
5266	3	6.243	0.00	Tintinara; Deepwater; Colebatch; Bunbury.
5303	3	6.199	0.00	Parilla

Table A4: Optimised waste transfer stations

The table shows the 54 optimised waste collection or transfer stations using location allocation modelling.

S/N	**Name**	**Postcode**	**Waste Demand Coverage (tons)**	**Total Distance (Km)**
1	Kangaroo Island Resouce Recovery Centre	*5223*	340.39	165.60
2	Warooka Dump Site	*5577*	660.02	226.35
3	Warramboo Transfer Station	*5650*	274.76	629.83
4	Keith Transfer Station	*5267*	493.84	216.41
5	Springton Transfer Station	*5351*	966.19	79.42
6	Port Pirie Landfill Refuse Tip	*5540*	1083.80	25.24
7	Strathalbyn Waste and Recycling Depot	*5255*	1834.98	98.93
8	Cleve Refuse Depot	*5640*	272.28	155.73
9	Mallala Resource Recovery Centre	*5501*	905.23	19.69
10	Cummins Waste Transfer Station	*5631*	481.17	64.50
11	Port Broughton Waste Transfer and Recycling Centre	*5522*	253.66	79.51
12	Ausiron Development Pty Ltd Facility	*5600*	750.72	37.52
13	Adelaide Waste & Recycling Centre	*5031*	6270.17	70.48
14	E Cycle Recovery	*5094*	2867.92	19.29
15	NAWMA Material Recovery Facility	*5113*	7396.82	111.54
16	Onkaparinga Transfer Station	*5244*	1094.97	117.27
17	Riverland Litter Service	*5345*	1527.56	182.90
18	City of Burnside Depot	*5066*	3497.62	88.60
19	Campbelltown Council Depot	*5074*	7291.03	139.93
20	Toogood Avenue Waste Management Centre	*5009*	6047.01	51.18

21	Clare Recycling Depot	*5453*	634.71	226.32
22	Meningie Waste Transfer Station	*5264*	291.41	152.48
23	Kadina Landfill and Recycling Centre	*5554*	1705.44	299.72
24	Coober Pedy Waste Depot	*5723*	57.94	795.24
25	Gawler Waste and Recycling Transfer Station	*5118*	2203.53	73.29
26	Nene Valley Refuse Depot	*5291*	1432.62	46.53
27	Kingston District Council Green Waste Depot	*5275*	301.92	126.43
28	Waikerie Rubbish Dump	*5311*	572.66	223.98
29	Blanchetown Transfer Station	*5357*	249.20	88.56
30	Bowhill Transfer Station	*5238*	1843.00	376.78
31	Truro Transfer Station	*5356*	1330.02	86.40
32	Meadows Waste Depot	*5201*	1191.70	47.39
33	Windmill Hill Transfer Station	*5250*	2938.87	96.76
34	Wirrabara Transfer Station	*5481*	266.27	117.70
35	Naracoorte	*5271*	547.33	88.65
36	Boxers Recycling Centre	*5491*	434.49	442.56
37	Southern Region Waste Resource Authority	*5169*	3344.17	68.56
38	Carrieton Waste Depot	*5432*	220.89	1454.27
39	Wingfield Waste and Recycling Centre	*5094*	3295.84	51.41
40	Port Augusta Resource Recovery Centre	*5710*	364.82	417.01
41	Renmark Refuse Depot	*5341*	960.96	78.58
42	Roxby Woomera Recycling Depot	*5725*	153.95	580.62
43	Salisbury Waste Transfer and Recycling centre	*5095*	8381.37	97.96
44	Lameroo Waste Depot	*5302*	150.94	145.36
45	Haslam Waste Depot	*5680*	503.96	484.84
46	The Ungarra Refuse Transfer Station	*5607*	158.27	44.47
47	City of Unley Waste Depot	*5061*	6590.02	73.42
48	Balaklava Transfer Station	*5461*	456.69	121.88
49	Kapunda Materials Recovery Facility Site	*5373*	540.41	176.61
50	Yankalilla Waste Transfer Station	*5203*	2027.72	113.21
51	Whyalla Recycling	*5600*	1257.77	121.42
52	Lonsdale Waste and Recycling Depot	*5160*	6942.03	58.00
53	Penola Resource recovery Centre	*5277*	236.83	46.60
54	Millicent resource Recovery Centre	*5280*	474.84	32.99

Table A5: Truck coefficient values for the calculation of pollutant emissions

The table shows Truck 7.5 – 16 and 16 – 32t coefficient values for the calculation using equation (12) and (13) (Hickman et al., 1999).

Pollutant	*Gross weight of Truck (t)*	*Parameter $\varepsilon_{i,\,cold}$ (g/cold start)*	*Coefficients*
PM	7.5 – 16	0.6	$k_1 = 0.0541;\ a = 1.51 \times 10^{-3};\ b = 0;\ c = 0;\ d = 17.1;\ e = 0;\ f = 0$ $k_2 = 1.02;\ r = 2.34 \times 10^{-3};\ s = 0;\ t = 0;\ u = 0$
	16 – 32	0.6	$k_1 = 0.184;\ a = 0;\ b = 0;\ c = 1.72 \times 10^{-7};\ d = 15.2;\ e = 0;\ f = 0$ $k_2 = 1.24;\ r = 0;\ s = 0;\ t = 0;\ u = -1.06$
NO$_x$	7.5 – 16	-2	$k_1 = 2.59;\ a = 0;\ b = -6.65 \times 10^{-4};\ c = 8.56 \times 10^{-6};\ d = 140;\ e = 0;\ f = 0$ $k_2 = 1.19;\ r = 0;\ s = 0;\ t = 0;\ u = -0.977$
	16 – 32	-5	$k_1 = 9.45;\ a = -0.107;\ b = 0;\ c = 7.55 \times 10^{-6};\ d = 132;\ e = 0;\ f = 0$ $k_2 = 1.28;\ r = 0;\ s = 0;\ t = 0;\ u = -0.874$
CO$_2$	7.5 – 16	300	$k_1 = 871;\ a = -16;\ b = 0.143;\ c = 0;\ d = 0;\ e = 32031;\ f = 0$ $k_2 = 1.26;\ r = 0;\ s = 0;\ t = -2.03 \times 10^{-7};\ u = -1.14$
	16 – 32	500	$k_1 = 765;\ a = -7.04;\ b = 0;\ c = 6.32 \times 10^{-4};\ d = 8334;\ e = 0;\ f = 0$ $k_2 = 1.27;\ r = 0;\ s = 0;\ t = 0;\ u = -0.483$
CO	7.5 – 16	6	$k_1 = 3.08;\ a = -0.0135;\ b = 0;\ c = 0;\ d = -37.7;\ e = 1560;\ f = -5736$ $k_2 = 1.03;\ r = 9.77 \times 10^{-4};\ s = 0;\ t = 0;\ u = 0$
	16 – 32	6	$k_1 = 1.53;\ a = 0;\ b = 0;\ c = 0;\ d = 60.6;\ e = 117;\ f = 0$ $k_2 = 1.17;\ r = 0;\ s = 0;\ t = 0;\ u = -0.755$

(Appendix B)

Figure B1: Route analysis of all transfer stations to recycling facility

The figure shows the route analysis of all 107 transfer stations to the recycling facility.

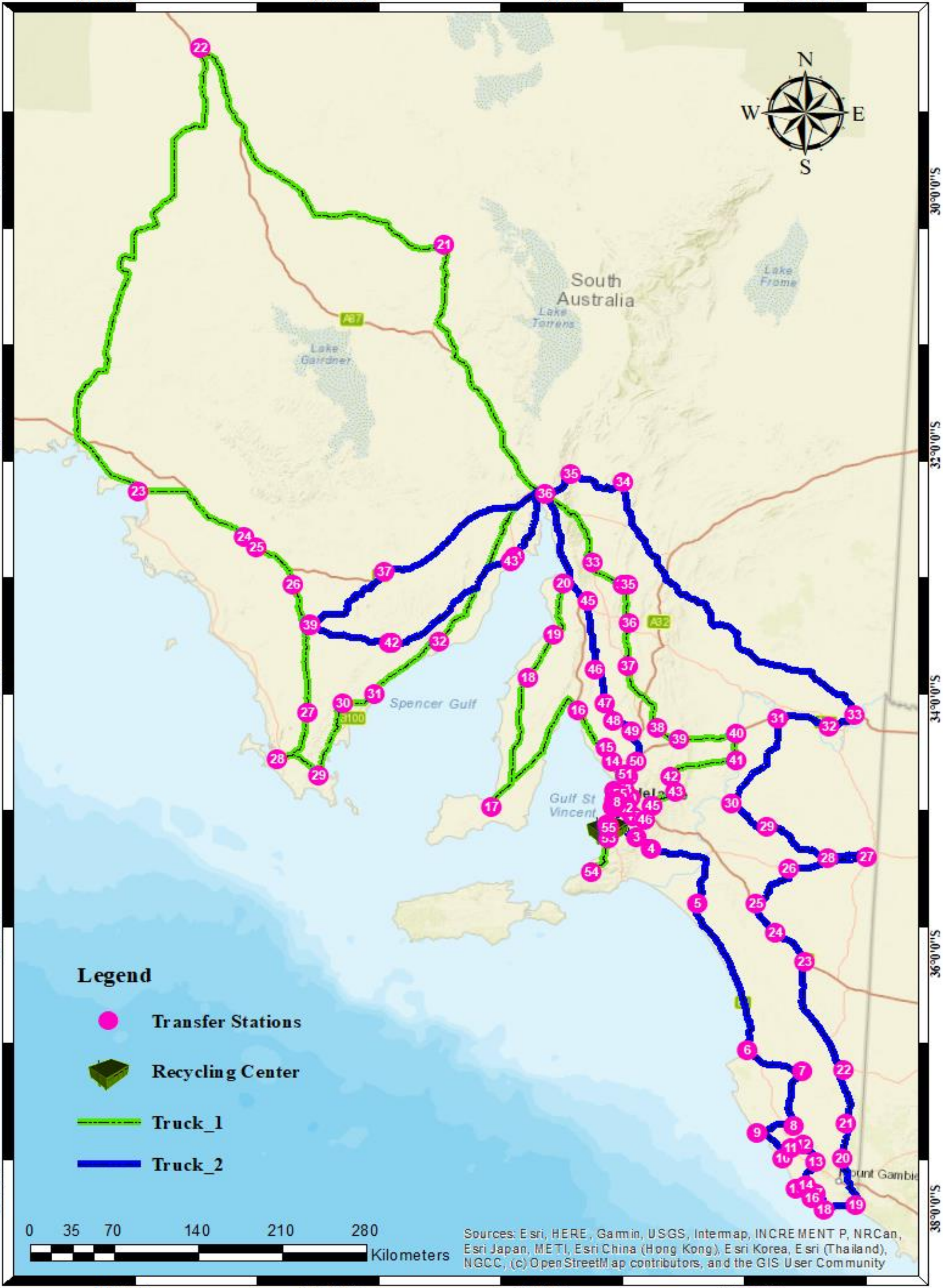
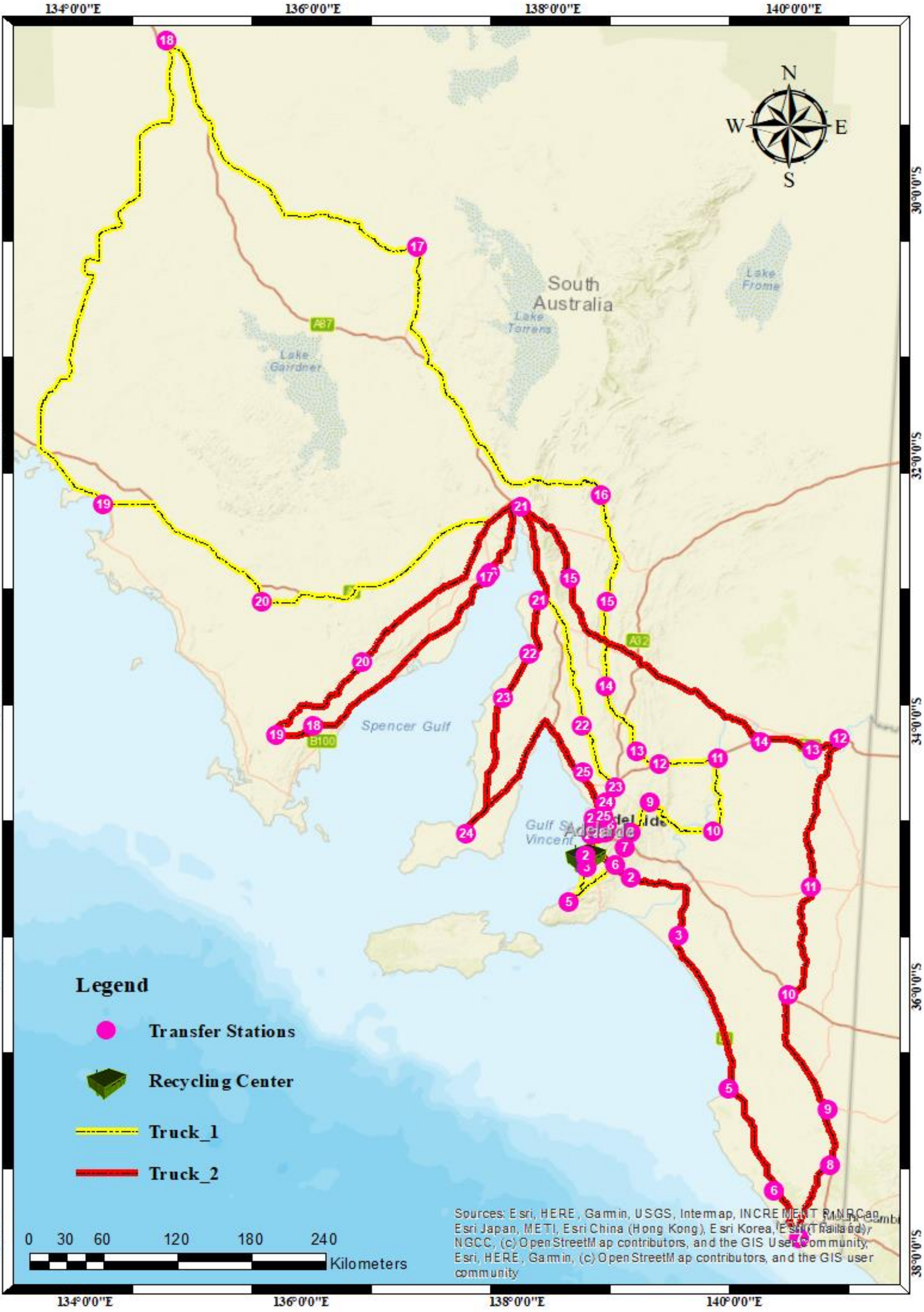


Fig. B1: Route analysis of all transfer stations to recycling facility

Figure B2: Route analysis of optimised transfer stations to recycling centre

The figure shows the route analysis of optimised transfer stations to recycling centre.



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community, Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Fig. B2: Route analysis of optimised transfer stations to recycling centre

(Appendix C)

Solar PV Waste Projection and hotspot analysis

The distribution of the projected waste and hot spot analysis is elucidated in this section. The results of the projected PV waste are calculated using the Weibull distribution function and shown in table A1. The result from the calculation is used to highlight the hot and cold spots of the solar PV waste within South Australia.

Solar PV waste projection of early and regular loss scenarios

The raw data collected from Clean Energy Regulator was entered into an excel worksheet and the waste volume calculated using equation (1) which was converted into excel in this analysis. The data of solar panel installation was collected from the year 2001 to 2021. Using the IRENA weight-to-power ratio graph, PV systems installed between the year 2001 to 2010 are assumed to have a weight of 100t/MW and installations from the year 2011 assumed as having a weight of 80t/MW. the weight growth using the available statics above was then calculated until 2051 using the average lifespan of a PV system in this study as 30 years. Reference can be made to Mahmoudi et al. (2019) on the PV waste as per technology. This is not considered as this has already been estimated, thus, the focus was the amount being transported from the source to the transfer stations. The early and regular loss calculated using the Excel workbook were extracted with its accompanying postcodes. The Excel statistics of the amount of PV waste generated in each postcode were mapped to a polygon shapefile of South Australia obtained from the government dataset.

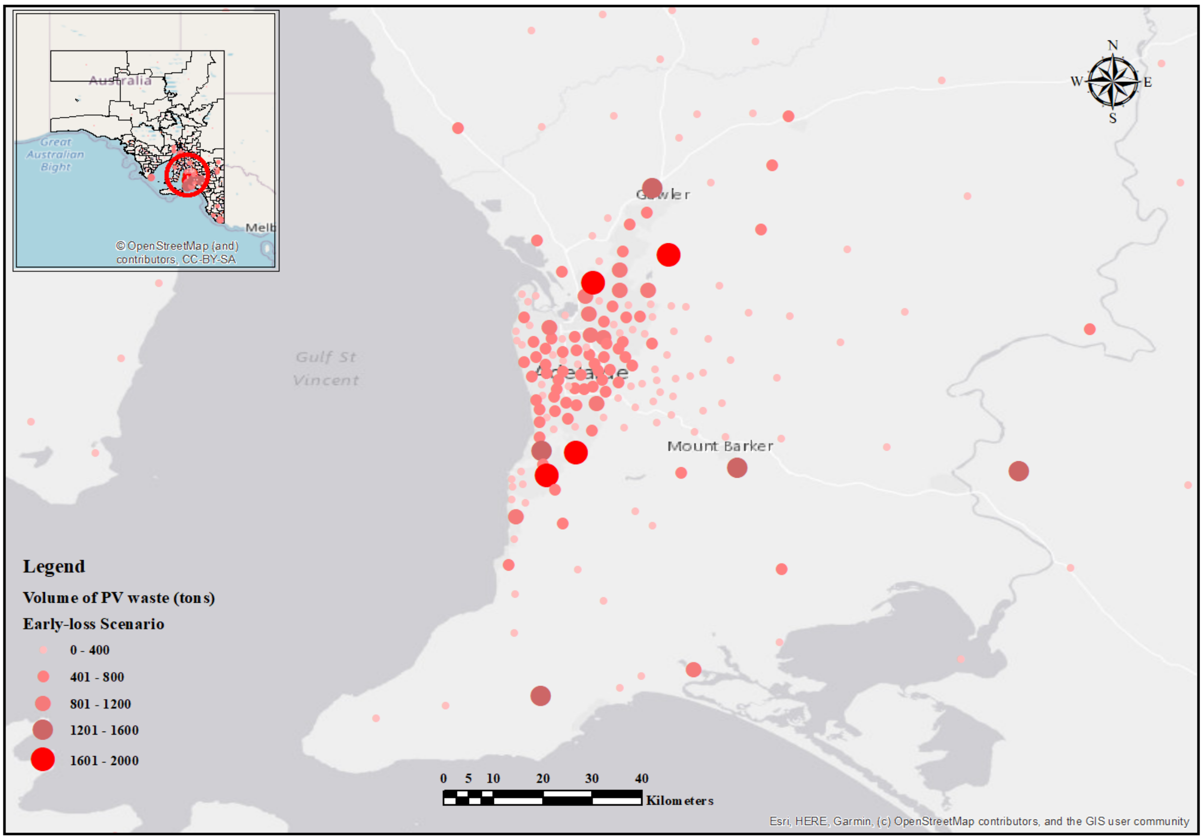


Fig. C1. Early-loss scenario of projected solar PV waste in South Australia

The Figure C1 above shows the visualisation of the projected waste. The results show that, the concentration of the waste will be clustered around Adelaide. This shows the uptake of solar panels in the City and neighbouring councils. There were some postcodes which had a lot of projected waste above 1000t. Among them are 5108, 5114, 5162, 5159, 5158, 5211, 5251, 5118, 5253, 5095, 5169, 5085, 5125 and 5109. The postcodes show some of the areas that will be generating a lot of waste according to early loss scenario; Salisbury, Smithfield, Morphet Vale, Andrews Farm, Hallett Cove, Happy Valley among other suburbs and towns. The generation of PV waste in each postcode highlights the installation capacity of those particular postcodes. This detail aids in the better planning and logistics of solar PV waste management in the future and proper planning by government and policy makers in the establishment and allocation of waste facilities for end-of-life solar panels. This is further elaborated in the discussion.

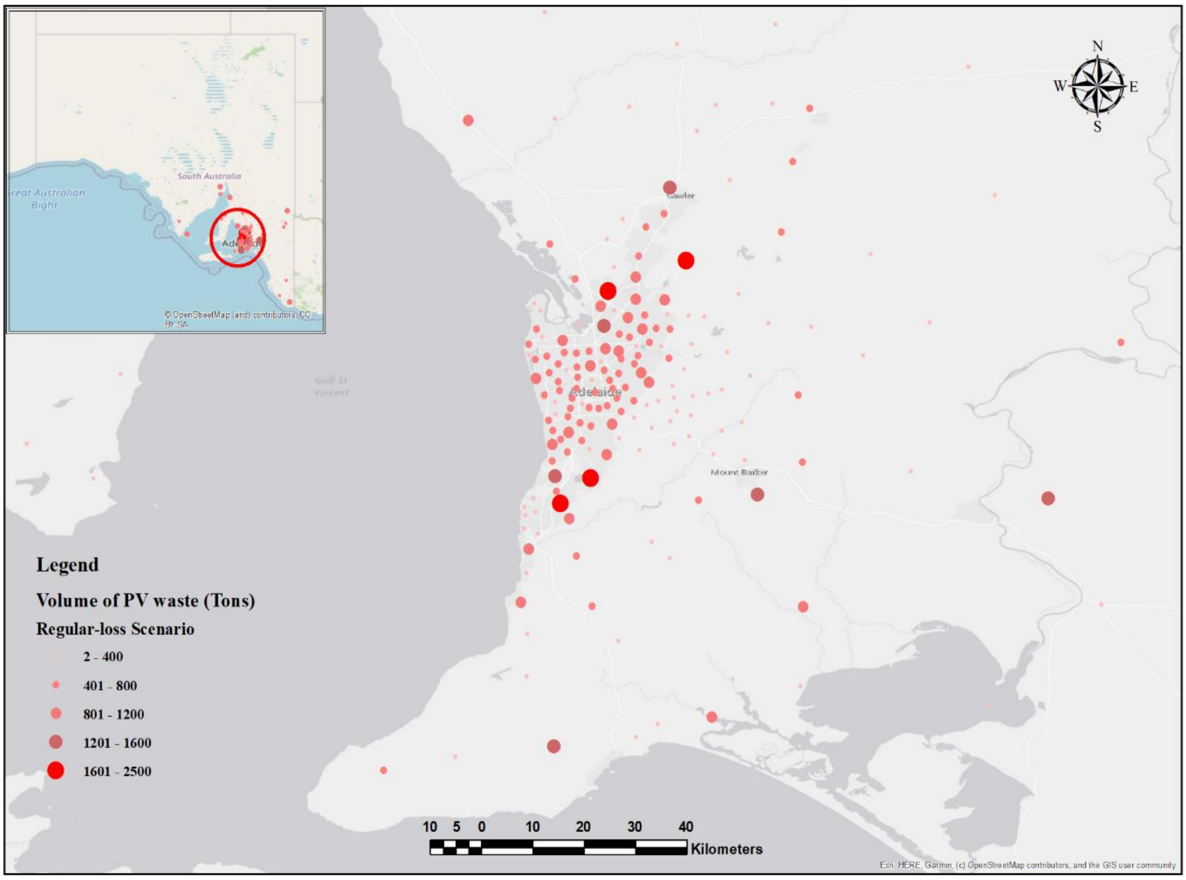


Fig. C2. Regular-loss scenario of projected solar PV waste in South Australia

The regular loss scenario also showed a similar visualisation and pattern with a lot of the concentration around the city, major towns and suburbs. The postcodes with the highest generation are 5108, 5114, 5162, 5159, 5158, 5211, 5251, 5118, 5253, 5095, 5169, 5125, 5085, 5109, 5540 and 5107. Areas like Salisbury, Paralowie, Yattalunga, Uleybury, Smithfield, Craigmore, Blakeview, Andrews Farm, Northgate, Northfield, Enfield and Clearview falls within some of these postcodes. This results further feeds into generating the hotspots for the vehicle routing analysis. Thus, the criteria for selecting transfer stations are based on these results. This is further clarified in the discussion.

Geospatial distribution of Solar PV waste early and regular loss scenarios

The distribution of solar waste based on the Getis-Ord G* was computed to determine the spatial clustering of the waste within the postcodes. Getis-Ord Gi* hotspot analysis in a given study area defines the clustering of high and low features using the z score and p values. Cold and hot spots events can be determined by the analytical tool through the calculation of each features z score and p value. The p value shows the probability that the spatial pattern observed is created by a random process whiles the z score describes the statistical importance of the clustering within stated distance (Said et al., 2017). With the z score, the low values which are spatially clustered within -1.96 to -2.58 and below indicates a low negative z score; and high values which are spatially clustered within 1.96 to 2.58 and above indicates a high z score. In a standard normal distribution, it is observed that, 99% and 95% are thresholds mostly adopted because they lie between -2.58 and 2.58 and between -1.96 and 1.96 respectively. However, a result is referred to have no spatial clustering if it has a z score of 0 (Gibertoni et al., 2021). Therefore, highly significant value shows a hotspot that has a high confidence level and other features around it also has high values (Chen et al., 2018).

Figure C3 and C4 shows the representation of the hot spot analysis of the projected solar PV waste in South Australia. The blue dots in the figures indicates the cold spots and whiles the red dots indicate the hot spots. According to the analysis on the early loss scenario shown in fig C3, the red spots are located mainly in the cities and major towns and suburbs. The cold spots are mostly around the South Australia outback and small towns.

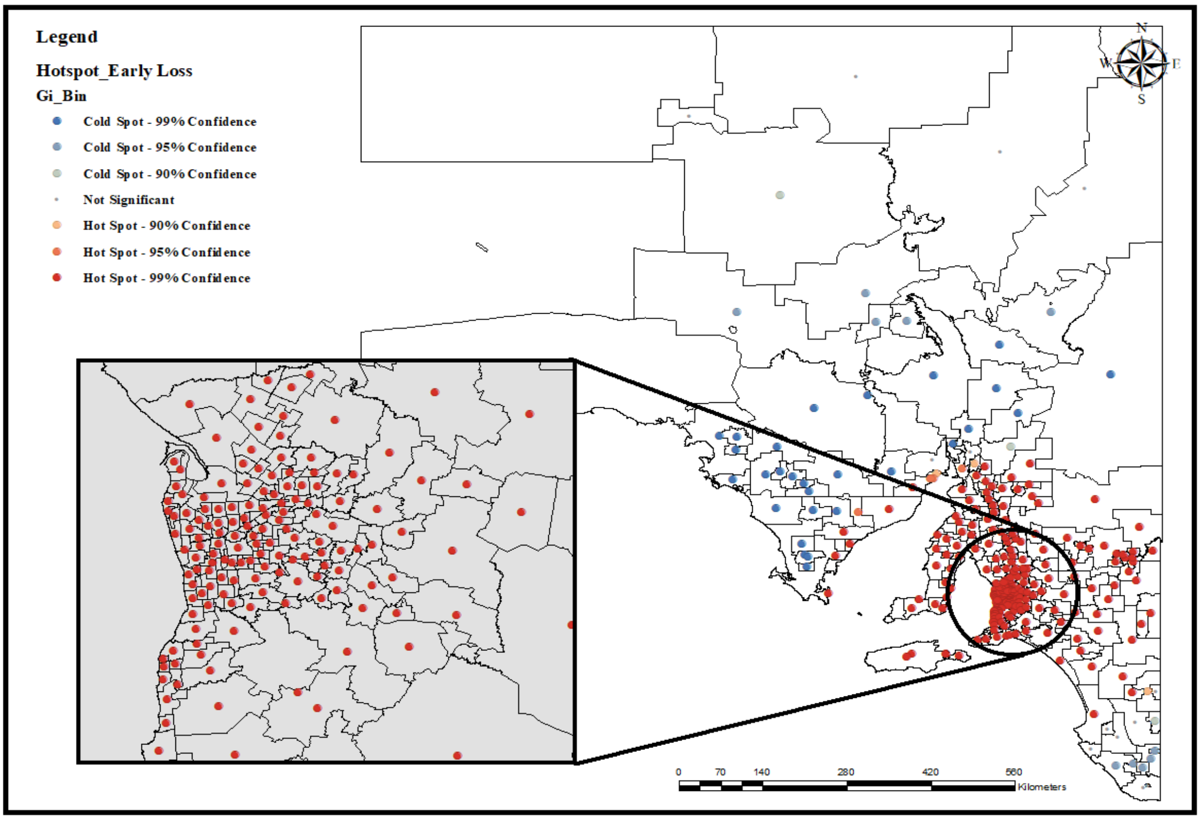


Fig. C3. Hotspot analysis of early loss scenario

The regular loss scenario shown in figure 5 exhibits the same concentration of hotspots around the city and major towns and suburbs. The results are very positive as it will provide the opportunity for locating and selecting transfer stations or solar panel waste depots easier because of the proximity and how the PV waste is dispersed across South Australia. However, it also raises the question of how the waste generated at the cold spots will also be collected to reduce travel distance and pollutant emission from the collection and transport of these generated waste.

The reason for establishing the hotspot for early and regular loss scenarios was to determine the proximity of current transfer stations in the state to recycling centres and whether it was important to use these current depots or establish new ones. Currently, there is no regulations or product stewardship guiding the disposal and management of end-of-life solar PV waste in Australia, but there are regulations and a product stewardship in place for waste electrical and electronic equipment (WEEE) like televisions and batteries in Australia. Even thou, solar PV waste are classified under WEEE, currently most of the end-of-life solar panels coming to their service life are going into municipal solid waste (MSW) and therefore unto landfills as confirmed by the national waste report 2020. In South Australia, there is no kerbside collection for solar panel waste. The "*whichbin*" initiative by Green Industries SA which informs how to dispose of various waste types refer residents to the red bin which is landfill when it comes to disposing of their solar panel waste.

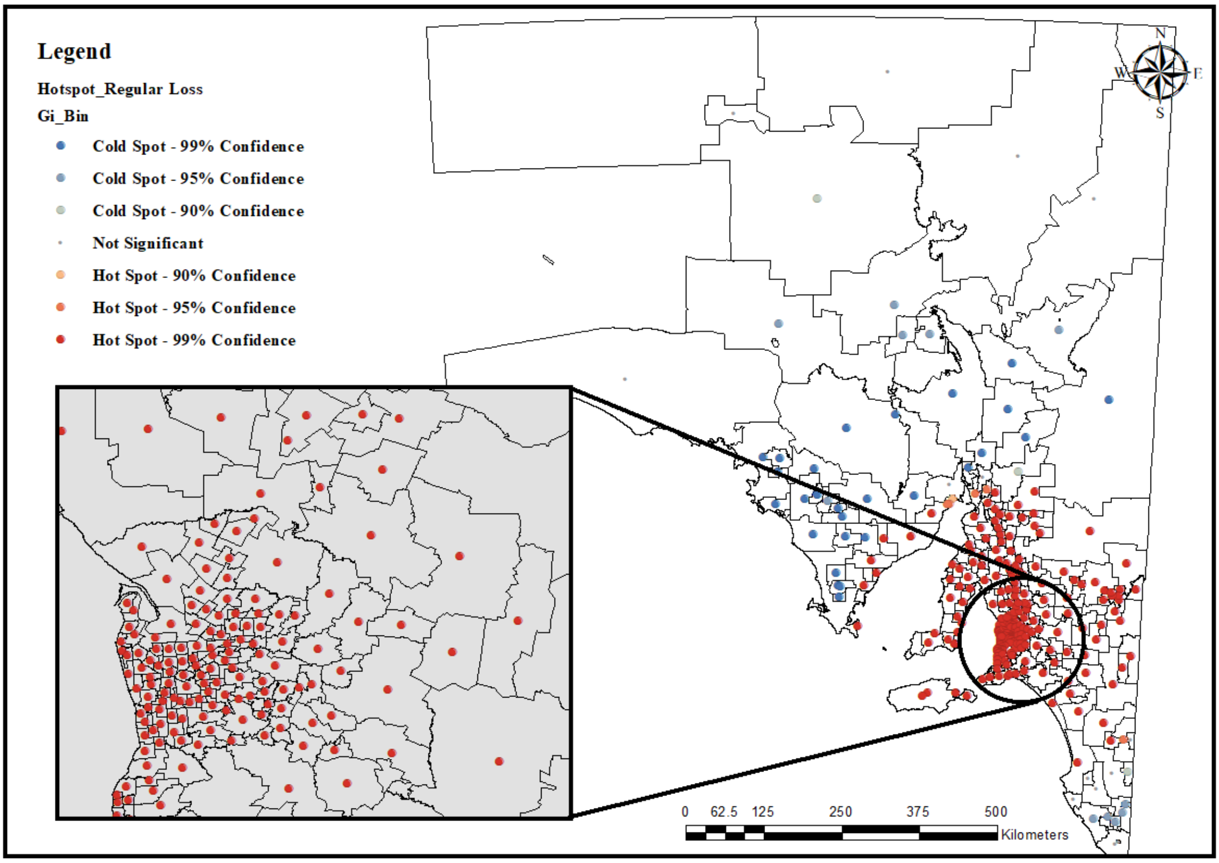


Fig. C4. Hotspot analysis of regular loss scenario

Thus, it is imperative to establish the current logistics of solar panel waste and how the current practice might influence future plans. Using the information on the hot spots there was the need to establish where the current transfer stations in the state were located and also assumed these wastes were going to the transfer stations instead of going straight to the landfill. The next section explains into detail the logistics and transportation of PV waste within the state and how they can be optimised to reduce pollutant emissions.

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Appendix D – Manuscript: An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: An environmental lifecycle assessment

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An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: An environmental lifecycle assessment

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Abstract:	The growth of solar photovoltaic (PV) waste in the coming years requires implementation of effective management options. Australia, with one of the highest rates of rooftop solar PV, is still developing policy options to manage these panels when they reach their end-of-life. This study evaluates the environmental impacts of three policy options for mono and multi crystalline silicon (c-Si) solar panel waste modules. The impact of transport distance from transfer stations to the recycling centre is also assessed. The life cycle assessment revealed that, -1E+06 kgCO2eq and -2E+06 kgCO2eq are associated with the mandatory product stewardship scenarios under global warming potential for mono and multi c-Si solar modules respectively. However, the non-existence of a product stewardship will produce a global warming impact of 1E+05 kgCO2eq for both modules. The global warming effects revealed that, collecting and recycling most of the multi c-Si panels were not effective (-365 kg CO2-eq, -698.4 kg CO2-eq, -1032 kg CO2-eq) compared to keeping them away from the landfills and fully recycling (-2E+06 kg CO2-eq) them. It was also highlighted that, the highest environmental impact regarding the transport distances was the scenario of one recyling centre serving over 107 transfer stations with a global warming potential of 1E+06 kgCO2eq. Other impact indicators were also high, compared to the optimised scenarios. This research model serves as the first conceptual and methodological framework for life cycle assessment (LCA) in transport related analysis. Since transport is very significant in PV recycling processes, it is recommended that, to further reduce these impact,other forms of low-impact modes of transportation may be explored.
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Abstract

The growth of solar photovoltaic (PV) waste in the coming years requires implementation of effective management options. Australia, with one of the highest rates of rooftop solar PV, is still developing policy options to manage these panels when they reach their end-of-life. This study evaluates the environmental impacts of three options for mono and multi crystalline silicon (c-Si) solar panel waste modules. The impact of transport distance from transfer stations to the recycling centre is also assessed. The life cycle assessment revealed that, -1E+06 kgCO_2eq and -2E+06 kgCO_2eq are associated with the mandatory product stewardship scenarios under global warming potential for mono and multi c-Si solar modules, respectively. However, the non-existence of a product stewardship will produce a global warming impact of 1E+05 kgCO_2eq for both modules. The global warming effects revealed that, collecting and recycling most of the multi c-Si panels were not effective (-365.00 kg CO_2-eq, -698.40 kg CO_2-eq, -1032.00 kg CO_2-eq) compared to keeping them away from the landfills and fully recycling (-2E+06 kg CO_2-eq) them. It was also highlighted that, the highest environmental impact regarding the transport distances was the scenario of one recycling centre serving over 107 transfer stations with a global warming potential of 1E+06 kgCO_2eq. This research model serves as the first conceptual and methodological framework for life cycle assessment (LCA) in policy and transport related analysis. Since transport is incredibly significant in PV recycling processes, it is recommended that, to further reduce these impacts, other forms of low-impact modes of transportation may be explored.

Keywords: Solar photovoltaics, impact assessment, environmental assessment, waste management, LCA, end-of-life

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1 Introduction

The last decade has seen a massive production of photovoltaic systems. This is because of the depletion of fossil sites which has been highlighted as an ongoing risk associated with the increasing use of conversional energy resources (IEA-PVPS, 2021; Savvilotidou et al., 2017). Moreover, with the increasing energy demand and cost of materials for manufacturing declining, there is a tremendous growth within the renewable energy sector especially in the solar photovoltaic (PV) industry (Mahmoudi et al., 2019; Nain & Kumar, 2020b). Crystalline silicon (c-Si) and thin films are the common commercially available photovoltaic panels. The latter is cost effective and more flexible; whereas the former has the advantage of high efficiency and higher market share (Daljit Singh et al., 2021; Nain & Kumar, 2020c).

The designed lifetime of solar PV modules ranges from 25 to 30 years. Most of the crystalline silicon modules are reaching or have already reached their lifetime and may lead to a tremendous amount of waste generated in the next years (Nain & Kumar, 2020c; Sica et al., 2018). There are precious and carcinogenic metals including tellurium, selenium, copper, silver, lead, chromium, silicon, and cadmium in solar photovoltaic systems, which at the end of their operational life requires recovery and recycling to prevent environmental pollution and also to extract the valuable metals (Tao & Yu, 2015).

The growing interest in renewable energy sources has seen the rise in the installation of solar PV technology in recent years. The first-generation technology based on the crystalline silicon (c-Si) has remained the dominant technology. However, in 2012 the second-generation (cadmium telluride) was the second largest technology in the market with a production output of 1.8 GWp (Kranz et al., 2013; Ramos-Ruiz et al., 2017). The c-Si technology covers the market share with 90% among which 45% is mono, 55% is multi and ribbon Si represents 2%. The remaining 10% is represented by the thin-film technology, having cadmium telluride

(CdTe) with the biggest share of 5%, amorphous-Si (a-Si) with 3% and copper indium gallium di-selenide (CIGS) representing 2% (Daljit Singh et al., 2021; Sica et al., 2018).

As much research is focused on producing new recyclable high-tech panels and improving the efficiency and performance of these panels, managing old panels has become an expensive and complex problem (Fthenakis, 2000). There are studies that are recently looking into the consequences of these disposals, with some developing methods and techniques in both policy and industrial vision to help alleviate the environmental problems (Giacchetta et al., 2013; Nain & Kumar, 2021; Oteng et al., 2022a).

According to Motta et al. (2016), there is little attention given to the evaluation of inappropriate solar PV disposal and its associated environmental risks. Especially, the toxicity of the hazardous chemicals to the environment through their release of toxic elements into water sources (Nain & Kumar, 2021). The potential risks to human health and the environment, and the impact of metal release into landfills needs to be investigated to ascertain their fate in realistic environmental setting (Nain & Kumar, 2020c).

1.1. Research background and gap

Many countries do not yet have regulations that guides the management of end-of-life (EoL) solar panels; therefore, a lot of these panels end up in landfills. Again, recycling processes are not economically feasible yet in many countries because of the number of EoL solar panels available (Lunardi et al., 2018). The lifetime of solar panels can range from 25 to 30 years, with such relatively long lifetime, the amount of solar panels in the current waste stream are considered to be low. This has had a big influence on the late or non-inclusion of EoL solar PV waste in the legislations and regulations of several countries (Granata et al., 2014). Due to the Waste Electrical and Electronic Equipment (WEEE) directive, many countries in the European Union have boasted of legislations covering the management of EoL PV modules. Yet, there are several other countries around the world like Australia, China, and Japan who are still in the process of developing a comprehensive product stewardship for solar PV waste modules.

Recycling the PV panels at their EoL is environmentally favourable against landfilling, as most of the rare and valuable metals can be recovered and upcycled. This prevents hazardous and toxic substances being dumped at landfills potentially leaching into the soil and groundwater, projecting adverse effects on the ecosystems and humans via negative physiological and biochemical effects (Deng et al., 2019; Lunardi et al., 2018; Oteng et al., 2022a). The use of a solar PV module throughout its 25 to 30 years operation could result in zero-emissions, making it a preferred choice of green power generation. However, the environmental impact of the entire lifecycle of the PV module must be stressed, because of the production emissions and EoL management challenges (Deng et al., 2019). Recently, researchers are developing cost-effective alternatives to the management of solar PV waste as the volume is increasing sharply. With landfill not an option for discarding waste PV modules because of its unsustainable practice, recycling is the preferred alternative (Corcelli et al., 2018; Deng et al., 2019; Fthenakis, 2000).

Crystalline silicon PV modules currently make up the majority of installed solar systems, both commercially and residentially (Mahmoudi, Huda, & Behnia, 2019) and needs to be effectively assessed to ascertain its environmental impacts. With a lot of pilot studies on the recycling of EoL solar PV modules (especially the c-Si modules), there has been numerous improvements to get industry and policy makers on board. However, there is still the lack of knowledge and information on the environmental impacts on the treatments of crystalline silicon PV waste panels (Lunardi et al., 2018) regionally, to serve as data for life cycle assessment to help make informed policy decisions. This study adopts a pilot recycling process tailored to a regional case study for the environmental impact assessment.

Several studies on the environmental impact on c-Si PV modules mostly assume full landfilling or recycling scenarios for EoL PV modules (Dias et al., 2021; Lunardi et al., 2018; Mahmoudi et al., 2020) without necessarily comparing them to practical product stewardship arrangements to ascertain the effects that could have on the choice of treatment option. Moreover, the transport distances in several studies assumes distances (Ansanelli et al., 2021; Ardente et al., 2019; Latunussa et al., 2016) for the environmental impact assessment which is a huge gap in LCA research which this study addresses.

In Europe, solar PV waste is included in the category of Waste Electrical and Electronic Equipment (WEEE) and requires appropriate treatment of the waste stream. However, in Australia there is no effective policy guidelines, and if appropriate preventive and corrective measures are not implemented could become a huge problem, becoming the most significant stream of e-waste (Farrell et al., 2020; Majewski et al., 2021) in the country. As a result, this study investigates the environmental impacts associated with the mono and multi crystalline silicon (c-Si) modules because of their market share in the Australian PV industry. The paper addresses the following questions: i) what are the environmental impacts of mono and multi c-Si EoL solar PV within three policy options; ii) what are the impacts of transport for recycling PV waste within three established transport scenarios.

2 Material and Methods

This section explains the various approaches in developing a system for the environmental assessment of the EoL PV modules. The case context of South Australia is described in this section. The life cycle assessment processes are also detailed. “Life Cycle Assessment (LCA) is a methodology used to evaluate the potential environmental impacts of products or services along all their entire life cycle, with a “cradle to grave” approach. LCA allows to (i) assess the environmental burdens associated with a product, process, or activity, by identifying and quantifying energy and material hotspots and (ii) identify and evaluate opportunities for environmental improvements” (Consoli, 1993)

2.1 Case of South Australia

The research is conducted in South Australia using process data from a recycling plant situated at Lonsdale. The recycling plant started operations in August 2014. However, in the initial stages the idea was to collect the EoL panels until there was a substantial amount for recycling. Since 2021, they have managed to pilot a recycling process at the early stages. Because the recycling process of the plant is still ongoing and at its early stages, data from literature and the ecoinvent database (Ecoinvent, 2022) are used to complement the data collected from the plant. Ethics approval has been granted for this research. The operating director of the plant was interviewed, and several observations were made on different days to the plant for the collection of data for this research. This is important to ensure reliability of the results, data should be collected from recyclers even though available estimates from experts and databases are often used (Ziemińska-Stolarska et al., 2021).

2.1.1 Treatment processes at the plant

The first step of the process is the collection of the EoL PV modules from transfer stations to the recycling plant. The distance of the PV waste from users to the transfer stations are estimated to be 100km for the treatment of 1 ton of PV module using a 7.5t truck (Latunussa et al., 2016; Mahmoudi et al., 2020). However, the rest of the distances calculated are used in the scenario analysis for an estimated 3000-ton treatment of PV waste annually at the recycling plant.

The second step is the treatment or recycling of the PV modules at the plant. As discussed above, the plant is situated at Lonsdale, operated by Reclaim PV in South Australia. The transfer of the EoL PV modules from the transfer stations to the recycling centres are normally assumed in several research (Ardente et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2020). This study uses an estimated distance developed previously by the authors (Oteng et al., 2022a) from the transfer stations using different scenarios, which is a first and essential contribution when it comes to transport distances in the LCA of solar PV modules.

The PV modules are then unloaded by a forklift and transported to conveyor belts for dismantling. The full process is associated with recycling 1000kg of PV waste within an hour as shown in table A1 (see supplementary material). The disassembly is automated at the plant where the aluminium frame, cables and junction box are removed using a Cartesian robot and mechanical arm. The aluminium is then sold for treatment into aluminium ingots or used as a secondary material whiles the cables are collected for treatment in another plant. The plastic parts of the cables are then treated in an incineration plant with energy recovery.

The process is to treat the remaining materials after the mechanical detachment. A glass separation process is introduced to treat the waste panels without the cables and aluminium frames. The process separates the glass layer from the rest of the cells and layers of polymer (also called ‘PV sandwich’). To retrieve the PV sandwich and glass, an infra-red heat treatment process is introduced. Then a high-frequency knife button, regulated by speed and amplitude is used to mechanically detach the glass. Subsequently, a refinement process separates the sizes of the glass through sieving. The glass with impurities of mass around 2% after an optical-based separation system are sent to landfill. The PV sandwich is incinerated at the recycling plant after reducing their sizes by a cutting process, without the need to transport the PV sandwich to another incinerating plant. The process produces fly ash which is sent to a hazardous waste landfill assumed to be located 50km from the plant. The rest of the product (bottom ash) are crushed and sieved to retrieve the rest of the aluminium, whiles the rest is transferred to an acid leaching process.

The leaching process separates the silicon from other metals. During this process, water, and nitric acid (HNO_3) is mixed with the ash, this leaves the silicon as a residue in the dissolved solution of the various metallic oxides produced. Subsequently, the mixture containing the solution goes through vacuum filtration process for the recovery of the silicon. This helps recover the silicon at metallurgical grade. An electrolysis process is then introduced to recover the copper and silver from the solution at an efficiency of around 95%. This process emits an estimated 2kg per ton of treated PV waste in NO_x gases. Calcium hydroxide is added to the acid solution after electrolysis to successfully neutralise it. A filter press is then used to filter the final output, separating it into a sludge (unrecovered metals with some residual calcium hydroxide and water) and liquid waste (calcium nitrate and water). The waste is sent for disposal, transportation assumed to be 100km away. The input and output process are discussed in the life cycle inventory section.

2.2 Environmental Life Cycle Assessment

2.2.1 Goal and scope definition

The goal of this LCA is to access the potential environmental impacts of recycling mono and multi crystalline silicon photovoltaic modules using a pilot recycling process and plant situated in South Australia. This process has been developed by adapting the Full Recovery End of Life Photovoltaic (FRELP) process piloted by the Italian company “SASIL S.p.A”. for treating EoL solar crystalline silicon PV panels.

2.2.2 Functional Unit

The functional unit (FU) of this process is the recycling of 1000kg of EoL crystalline silicon modules separated into mono and multi crystalline silicon modules as illustrated in table A1 in the supplementary material. The FU does not include other module components such as the external cables and inverters but includes the internal cables.

The inputs and output are estimated based on the market share of both technologies. Mono-Si panels are estimated to have a market share of 55% with multi-Si panels having 45% market share. The latter is constructed from isolated crystals with the former based on one large crystal (Daljit Singh et al., 2021). The quantity of waste panels for the Mono and Multi c-Si are 1,350 and 1,650 tons, respectively.

2.2.3 System Boundary

The system boundary of this LCA considers the photovoltaic technologies mono and multi-crystalline modules. This process follows a cradle to grave approach, which considers only the EoL scenario without the production and use stages. Figure 1 illustrates the system boundary from the EoL solar panels to their treatment options through the three established policy options.

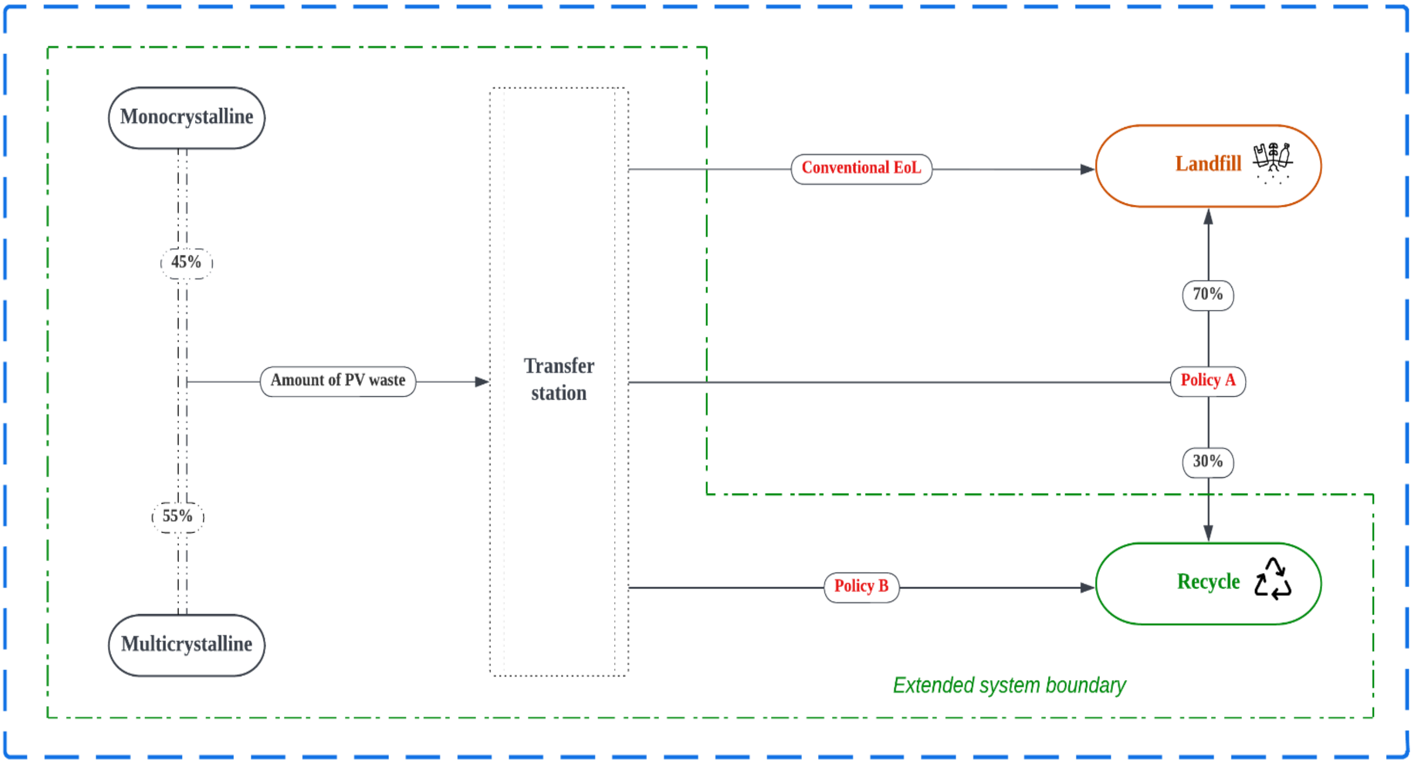

Fig 1: System boundary

The EoL scenario is based on three options:

- The first scenario considers the non-existence of policies and regulations creating a situation where all the PV waste are transported to landfills which is the baseline scenario (Conventional EoL) as shown in figure one.
- The second policy option is the introduction of a voluntary product stewardship (VPS) by the government, this may see a 30% increase in recycling but 70% of the panels may end up in landfills.
- The last option is an introduction of robust mandatory product stewardship (MPS) or extended producer responsibility (EPR) which may see 100% of the panels being recycled. The detail of the options as associated with the other technologies are illustrated in table A3 in the supplementary material.

2.2.4 Life Cycle Inventory data

The input/output sources were obtained through background and foreground data. Information from bibliographical and literature sources as well as personal interviews were acquired for the analysis. The foreground information on site specific processes was obtained through tailored interview questionnaire from a PV plant as the main primary data for the assessment. Foreground data was collected in a form of interviews on the operation of the plant and modelled against the FRELP process to fill in the missing data. The transportation distance of end-of-life solar panels to the recycling plant was estimated. Table 1 shows the detail information of the inventory data for the assessment.

Table 1: Details of inventory data for the recycling of 3000 tonnes of crystalline solar PV.

Input/output	**Quantity**		**Unit**	**Note**
	Mono c-Si	**Multi c-Si**		
Input				
PV waste panels	1350	1650	ton	Estimated annual PV waste flow to the year 2050 in South Australia

Electricity	153.29	187.36	KWh	Required power for different treatment processes as explained in the processes in section 2
Diesel fuel	1.54	1.88	Litre	Used for forklift operations
Water	418.11	511.02	ton	Water consumption for acid leaching, electrolysis, and neutralisation process
HNO_3	9.56	11.68	ton	Acid leaching process
$Ca(OH)_2$	49.28	60.23	ton	Neutralisation of acid solution
Output, recovered materials				
Aluminium scrap	246.58	301.37	ton	
Glass scrap	926.10	1131.90	ton	
Copper scrap	5.91	7.23	ton	
Silicon metal (Metallurgical grade)	46.82	57.22	ton	
Silver	0.68	0.83	ton	
Lead	0.36	0.44	ton	
Tin	0.36	0.44	ton	
Output, energy recovered				
Electricity	335.93	410.59	KWh	Produced through the incineration of back-sheet layer, encapsulation, and polymers from cables
Thermal Energy	678.83	829.69	Mj	Produced through the incineration of back-sheet layer, encapsulation, and polymers from cables
Output, waste to Landfill				
Contaminated glass	18.90	23.10	ton	Disposal in landfill
Fly ash (hazardous waste)	2.7	3.30	ton	Disposal in hazardous waste landfill
Liquid waste	413.28	505.12	ton	Disposal in landfill
Sludge (hazardous waste)	67.84	82.91	ton	Contains metallic residue, disposal in special landfill
Output, emission to air				
NO_x	2.7	3.30	ton	Emission from electrolysis

Background information on related data such as emissions from the treatment of waste, auxiliary materials, use of energy and the generation of energy, dataset of unit processes and allocation at point of substitution were acquired from secondary data from AusLCI and Ecoinvent database (Ecoinvent, 2022; Lifecycles, 2022) and scientific literature (Ansanelli et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2020). Table A2 in the supplementary material shows the details of the background lifecycle inventory dataset.

2.2.5 Life Cycle Impact Assessment

The LCA was modelled using the SimaPro software version 9.1.0.11. The Best Practice Guide for Mid-Point Life Cycle Impact Assessment in Australia (ALCAS Best Practice LCIA carbon neutral) was chosen for the assessment with thirteen impact categories comprising Climate change (Global warming): Global Warming Potentials (GWP) for a 100 year time horizon, as per IPCC Forth Assessment Report (IPCC, 2007) in kgCO_2-eq; Resource (abiotic) depletion – minerals (ADE): abiotic depletion of minerals based on concentration of currently economic reserves and rate of de-accumulation in Sb-eq; Resource (abiotic) depletion – fossil fuels (ADF): abiotic depletion of fossil fuels based on energy content (lower heating value) in MJ; Water scarcity (WS) - Method of Ridoutt and Pfister (2010), with water stress indices of Pfister et al. (2009) in m^3H_2O-eq; Eutrophication (EP): eutrophication potentials which assumes both N- and P-species contribute in kgPO_4-eq; Acidification (AP): if assessed, use the change in critical load exceedance, currently based on European characterisation factors in kg SO_2-eq; Toxicity: human (cancer, HTC and non-cancer, HTN) and freshwater eco-toxicity (FET) based on USEtox- with regionalised characterisation factors of Australia, derived based on regionalisation approach in CTU; Photochemical ozone formation (oxidation): Photochemical Ozone Creation Potentials (POCP) in C_2H_4-eq; Particulate matter formation (PMF): Fate and exposure based on Wolff, using the CALPUFF model in kg$PM_{2.5\text{-eq}}$. ALCAS is selected for this study because of the geographical location of the studies, to help in achieving accurate results from the selected impact categories.

In a Life Cycle Assessment, energy recovery and material recycling benefits associated with the environment can be approached in several ways. The approach that is mostly used is to allocate credits for any recycling benefits (example is substituting the respective materials to be produced) (Held & Ilg, 2011). This was introduced in the assessment of the waste PV panels for this study.

3 Results

This section details the results of the assessment of the various options analysed in the LCA. The assessment is divided into three options starting from full disposal which is the base scenario (Conventional EoL: full disposal into landfill); Policy A: 30% of the panels being recycled; and Policy B: 100% of the panels being recycled that is mandating manufacturers to recycle all solar panels. The results from the analysis can be a basis for the development of a sustainable product stewardship by the government as well as inform stakeholders on the environmental impacts associated with end of life management of solar PV modules (Finkbeiner et al., 2006). The results also provide relevant information and suggestions for improvement.

3.1 Interpretation of Environmental analysis

The results are divided into three sections. First, the waste from monocrystalline silicon is assessed under the three policy options which covers the treatment of 1350 tonnes/year of the panels. The second results are from the Multicrystalline silicon modules also under the three policy options covering the treatment of 1650 tonnes/year of the panels. The last results discuss the comparative assessment of the three options as against each PV technology.

3.1.1 Monocrystalline Silicon

The figure 2 below shows the individual contributions of the three options analysed under the mono c-Si waste panels.

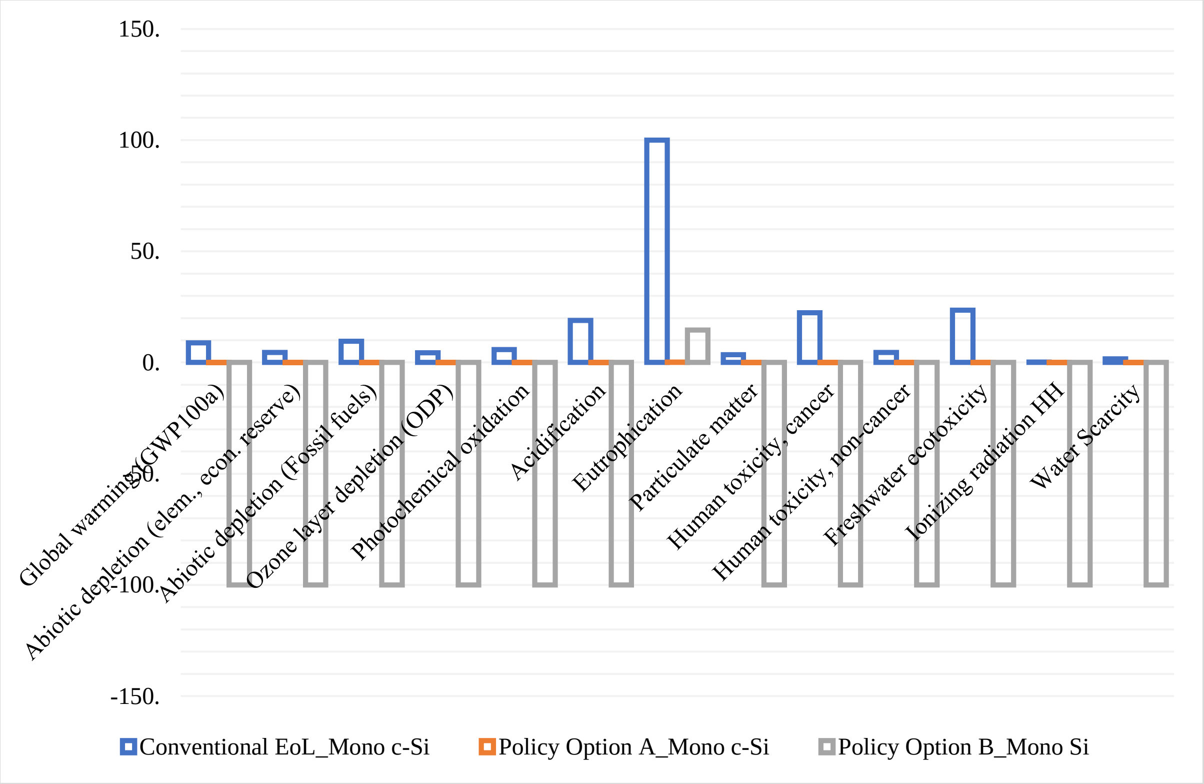

Fig 2: life cycle assessment of three options on end-of-life monocrystalline solar panels

It is noticed among the three options that, Conventional EoL, has the highest impact and burdens when you consider the fact that the panels will be landfilled at the end of their life. Again, the option A provide a buffer between the two. It shows less burden but not as much as the option B, which is the full treatment of the solar panels.

Table 2: life cycle assessment of three options on end-of-life monocrystalline solar panels

Impact category	**Unit**	**Conventional EoL_Mono c-Si**	**Policy Option A_Mono c-Si**	**Policy Option B_Mono c-Si**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	1E+05	-298.64	-1E+06
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	4.39	-0.03	-95.94
Abiotic depletion (Fossil fuels)	MJ NCV	1E+06	-3310.50	-1E+07
Ozone layer depletion (ODP)	kg CFC-$11_{\text{-eq}}$	0.01	-3E-05	-0.10
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	26.72	-0.12	-463.2
Acidification	kg $SO_{2\text{-eq}}$	1713.00	-1.51	-90
Eutrophication	kg $PO_{4\text{-eq}}$	401.00	0.30	58.81
Particulate matter	kg $PM_{2.5}$	38.86	-0.31	-1123.00
Human toxicity, cancer	CTUh	3E-04	-2E-07	-0.00
Human toxicity, non-cancer	CTUh	0.00	-9E-06	-0.04

Freshwater ecotoxicity	CTUe	3E+08	-179483.00	-1E+09
Ionizing radiation HH	kBq $U235_{-eq}$	11.70	-13.30	-44354.00
Water Scarcity	$m^3H_2O_{-eq}$	99.07	-1.71	-5943.00

From the table 2, the global warming potential for the Conventional EoL is much higher at around 1E+05 kg CO_2 eq, with A having around -298.60 kg CO_2 eq, and the last option B having -1E+06 kg CO_2 eq. This shows the major difference in the implementation of these regulations. The negative figures show the credits from the avoided products such as aluminium, solar glass, copper, silicon, silver, lead and tin. These products are assumed to be upcycled or used as alternative materials after recycling. There is a lot of credit in full recovery than a percentage of the panels as shown in the table. To get a good understanding of the processes, the recycling option was broken down to detail the burdens and credits of the processes. Figure 2 shows the burdens and credits of each process associated with the recycling of the panels.

From the supplementary materials figure B1, it is apparent that transport contributes massively to the burdens of the recycling which is shared by various assessment (Latunussa et al., 2016; Mahmoudi et al., 2020). The impact of the incineration and disposal of fly ash also has a significant impact on Eutrophication, human toxicity (cancer) and freshwater ecotoxicity. Thou, the incineration has a significant impact, it is also expected to recover thermal energy an amount of 500MJ and electricity of 250MJ through the combustion of the polymers.

3.1.2 Multicrystalline Silicon

The figure 3 shows the individual contributions of the three options analysed under the multi c-Si waste panels. The results are remarkably similar because the same recycling process is used in both cases.

Fig 3: Life cycle assessment of three options on end-of-life Multicrystalline solar panels

From the figure, a similar result can be observed among the indicators as compared to the mono c-Si panels. The highest impact and burdens are associated with the landfill option which explains that 100% of the panels will go to landfill if no regulations or policies are in place.

Table 3: life cycle assessment of three options on end-of-life Multicrystalline solar panels

Impact category	**Unit**	**Conventional EoL_Multi c-Si**	**Policy Option B_Multi c-Si**	**Policy Option C_Multi c-Si**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	1E+05	-365.00	-2E+06
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	5.37	-0.03	-117.30
Abiotic depletion (Fossil fuels)	MJ NCV	2E+06	-4046.00	-2E+07
Ozone layer depletion (ODP)	kg CFC-$11_{\text{-eq}}$	0.01	-3E-05	-0.13
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	32.66	-0.15	-566.10
Acidification	kg $SO_{2\text{-eq}}$	2094.00	-1.85	-11043.00
Eutrophication	kg $PO_{4\text{-eq}}$	490.10	0.37	71.88
Particulate matter	kg $PM_{2.5}$	47.50	-0.38	-1373.00
Human toxicity, cancer	CTUh	3E-04	-2E-07	-0.00
Human toxicity, non-cancer	CTUh	0.00	-1E-05	-0.04
Freshwater ecotoxicity	CTUe	4E+08	-2E+05	-2E+09
Ionizing radiation HH	kBq $U235_{\text{-eq}}$	14.30	-16.25	-54211.00

Water Scarcity	$m^3H_2O_{-eq}$	121.10	-2.10	-7264.00

Table 3 details the values of the various indicators contributed by the three options. Considering ozone layer depletion, recycling of all the panels which is policy option B measuring -0.13 kg CFC_{-11} eq contributes less impact than the options A measuring -3E-05 kg CFC_{-11} eq and Conventional EoL measuring 0.01 kg CFC_{-11} eq. This is the same for all the other indicators. With full recycling or policy option B having the least environmental impacts, a further assessment is performed to identify the associated burdens and credits of the recycling process and the various process contributions.

From figure B2 in the supplementary material, particulate matter, ozone layer depletion, acidification and eutrophication are highly impacted by the recovery of the metals from the bottom ash. Eutrophication is the most impacted when considering the process of acid neutralisation, electrolysis, acid leaching and sieving in the recovery of the metals. The other phases such as cutting of the PV sandwich, thermal separation, disassembly and unloading of the PV waste modules contributes little to the overall impacts.

3.1.3 Comparative assessment of different policy options

The figure 4 shows the comparative assessment of the individual contributions of the three options analysed under the mono and multi c-Si waste panels.

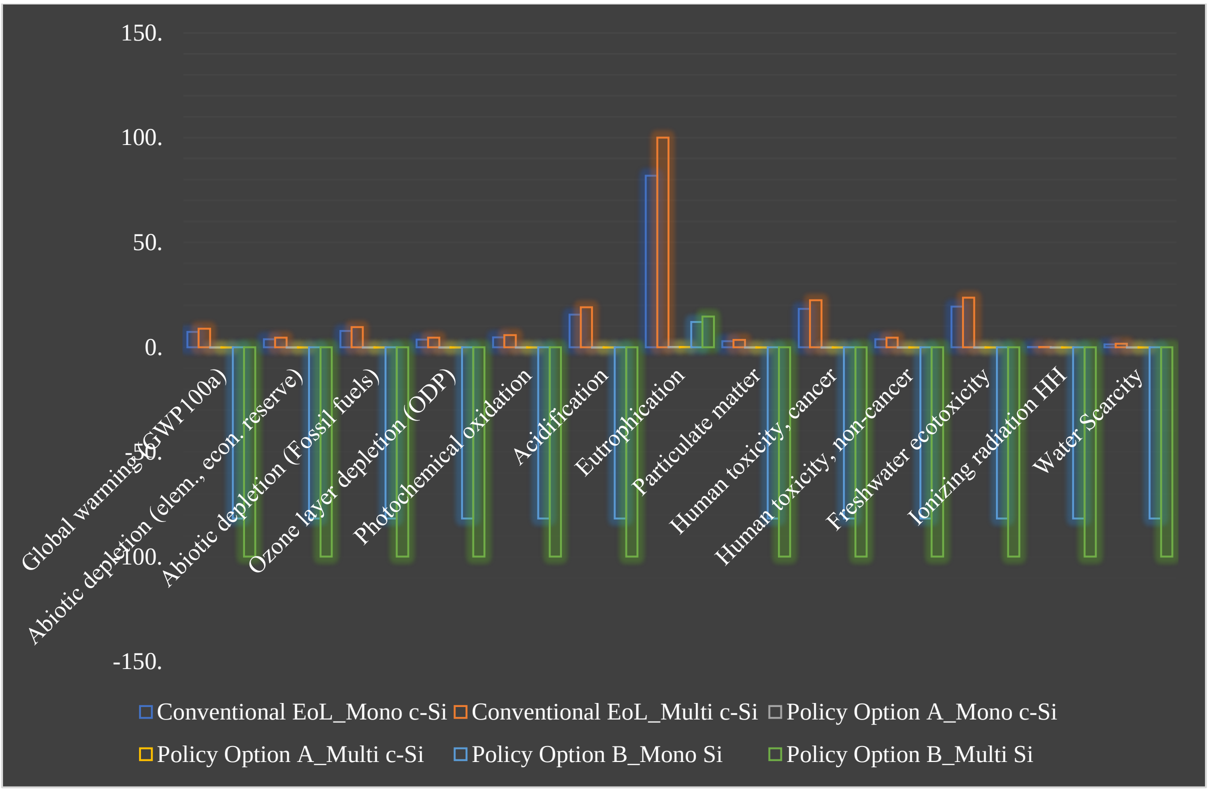

Fig 4: Comparative assessment of all policy options under the two technologies

It was imperative to compare the various policies against different technologies. Observing the Conventional EoL between the two technologies, reveals that, multi c-Si contributes more when it comes to burdens on the environment than the mono c-Si. This may stem from the percentage market share of multi c-Si as against the mono c-Si (Daljit Singh et al., 2021; Oteng et al., 2021). Thus, the amount of waste going to landfill will be more. This is the same for the other two options A and B.

Table 4: Comparative assessment of all policy options under the two technologies

Impact category	**Unit**	**Conventional EoL_Mono c-Si**	**Conventional EoL_Multi c-Si**	**Policy Option A_Mono c-Si**	**Policy Option A_Multi c-Si**	**Policy Option B_Mono c-Si**	**Policy Option B_Multi c-Si**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	1E+05	1E+05	-298.60	-365.00	-1E+06	-2E+06
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	4.39	5.37	-0.03	-0.03	-95.94	-117.30
Abiotic depletion (Fossil fuels)	MJ NCV	1E+06	2E+06	-3310.00	-4046.00	-1E+07	-2E+07
Ozone layer depletion (ODP)	kg CFC-$11_{\text{-eq}}$	0.01	0.01	-3E-05	-3E-05	-0.10	-0.13

Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	26.72	32.66	-0.12	-0.15	-463.20	-566.10
Acidification	kg $SO_{2\text{-eq}}$	1713.00	2094.00	-1.51	-1.85	-9035.00	-11043.00
Eutrophication	kg $PO_{4\text{-eq}}$	401.00	490.10	0.30	0.36	58.81	71.88
Particulate matter	kg $PM_{2.5}$	38.86	47.50	-0.31	-0.38	-1123.00	-1373.00
Human toxicity, cancer	CTUh	3E-04	3E-04	-2E-07	-2E-07	-0.00	-0.00
Human toxicity, non-cancer	CTUh	0.00	0.00	-9E-06	-1E-05	-0.04	-0.04
Freshwater ecotoxicity	CTUe	3E+08	4E+08	-2E+05	-2E+05	-1E+09	-2E+09
Ionizing radiation HH	kBq $U235_{\text{-eq}}$	11.70	14.30	-13.30	-16.25	-44354.00	-54211.00
Water Scarcity	$m^3H_2O_{\text{-eq}}$	99.07	121.10	-1.71	-2.10	-5943.00	-7264.00

From table 4, the particulate matter of Conventional EoL mono is 38.86 $PM_{2.5}$ whiles multi is 47.50 $PM_{2.5}$, for option A mono is -0.31 $PM_{2.5}$ whiles multi is -0.38 $PM_{2.5}$, for option B mono is -1123.00 $PM_{2.5}$ whiles multi is -1373.00 $PM_{2.5.}$ The example from particulate matter clearly highlights the differences in the various options thou they are not very significant. This is because the market share between the technologies is not that significant. However, the multi c-Si panels contributes more to the environmental impacts as against the mono c-Si. In the same vain, the policy B for each contributes the least to the environmental impacts as against the Conventional and option A.

3.2 Sensitivity analysis

A sensitivity analysis of the various ways the PV waste should be recycled and how much is going to landfill was assessed. Since full recycling and landfilling are inevitable and are always discussed in the literature, the sensitivity analysis provides a way of measuring the impacts of PV waste from different recycling and landfilling perspectives. The monocrystalline modules were first analysed. The percentage of recycling the panels were 30, 50 and 70 percent. This was to arrive at a relative decision on how the change in the collection of PV waste could affect the environment. The transition to a full recycling of PV waste may be slow, however, it will soon transition through a lower collection percentage to a higher percentage. Therefore, the need to analyse the impacts these may raise as many countries transition to a mandatory product stewardship, especially Australia.

Table 5: Sensitivity analysis on monocrystalline silicon modules

Impact category	**Unit**	**Mono c-Si_30%**	**Mono c-Si_50%**	**Mono c-Si_70%**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	-298.60	-571.40	-844.20
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	-0.03	-0.05	-0.07
Abiotic depletion (Fossil fuels)	MJ NCV	-3310.00	-6418.00	-9525.00
Ozone layer depletion (ODP)	kg CFC-$11_{\text{-eq}}$	-3E-05	-5E-05	-7E-05
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	-0.12	-0.22	-0.32
Acidification	kg $SO_{2\text{-eq}}$	-1.511	-3.66	-5.81
Eutrophication	kg $PO_{4\text{-eq}}$	0.30	0.23	0.16
Particulate matter	kg $PM_{2.5}$	-0.31	-0.54	-0.77
Human toxicity, cancer	CTUh	-2E-07	-5E-07	-8E-07
Human toxicity, non-cancer	CTUh	-9E-06	-2E-05	-2E-05
Freshwater ecotoxicity	CTUe	-2E+05	-5E+05	-8E+05
Ionizing radiation HH	kBq $U235_{\text{-eq}}$	-13.30	-22.17	-31.04
Water Scarcity	$m^3H_2O_{\text{-eq}}$	-1.71	-2.92	-4.13

Table 5 highlights the impacts of three different approaches in the collection of PV waste in Australia under the voluntary product stewardship arrangement. Comparing the three recycling percentages, there was a significant change on the impacts of a 70% recycling rate to a 50% and 30% recycling rate as graphically represented in figure B3 (see supplementary material). A GWP of -844.20 as against -571.40 and -298.60, reveals the climate change impact of recycling more to landfilling based on the current scenario. This is replicated in the ADE, ADF, ADP, POCP, AP, PMF, HTC, HTN, FET, IOR and WS. There is, however, a serious impact to EP because of the percentage going to landfill whether recycling or disposing of PV waste. The value of 0.30, 0.23 and 0.16 derived from the 30, 50 and 70 percent EP are single indicators based on the ‘stoiciometric nutrification potentials’ based on the Australian best practices owing to the absence of regionalised factors derived from fate-exposure models. The credits of the recycling may go back to the manufacturing stage but the process and landfilling of a number of the PV modules may have adverse effects on the ecosystems especially aquatic as compared to terrestrial due to Australia having low population densities and nutrient limited soils.

Table 6 shows the comparison of the three different scenarios of recycling and landfilling the Multicrystalline PV modules. Pertaining to the earlier evaluated voluntary product stewardship of 30%, a varying 50% and 70% were analysed to ascertain the impact changes to the environmental categories as graphically expressed in figure B4 (see supplementary material).

Table 6: Sensitivity analysis on Multicrystalline silicon modules

Impact category	**Unit**	**Multi c-Si_30%**	**Multi c-Si_50%**	**Multi c-Si_70%**
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	-365.00	-698.40	-1032.00
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	-0.03	-0.06	-0.08
Abiotic depletion (Fossil fuels)	MJ NCV	-4046.00	-7844.00	-11642.00
Ozone layer depletion (ODP)	kg CFC-11$_{\text{-eq}}$	-3E-05	-6E-05	-9E-05
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	-0.15	-0.28	-0.39
Acidification	kg $SO_{2\text{-eq}}$	-1.85	-4.48	-7.10
Eutrophication	kg $PO_{4\text{-eq}}$	0.36	0.28	0.20
Particulate matter	kg $PM_{2.5}$	-0.38	-0.66	-0.95
Human toxicity, cancer	CTUh	-2E-07	-6E-07	-1E-06
Human toxicity, non-cancer	CTUh	-1E-05	-2E-05	-3E-05
Freshwater ecotoxicity	CTUe	-2E+05	-6E+05	-1E+06
Ionizing radiation HH	kBq U235$_{\text{-eq}}$	-16.25	-27.10	-37.94
Water Scarcity	$m^3H_2O_{\text{-eq}}$	-2.10	-3.57	-5.05

The GWP of -1032.00 kg $CO_{2\text{-eq}}$ shows the positive impact associated with collecting and recycling more PV waste to sending them to the landfill. This is influenced by the high collection rate of PV waste which will then be recycled. There is also a significant difference between the GWP for collecting and recycling some of the PV waste to fully recycling all the PV waste. Making reference to table 4, the GWP for fully recycling PV waste is significantly higher than all the scenarios of recycling a percentage of the multi c-Si waste panels. This is very important because of the effects of climate change such heat stress, infectious diseases, flooding, malnutrition and wildfires.

3.3 Optimised transport LCA analysis

One of the major limitations to LCA are the omissions and assumptions made on transport distances (Dias et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016), especially from the collection centres or transfer stations to the recycling plant, thou, it has significant impact on the recycling process.

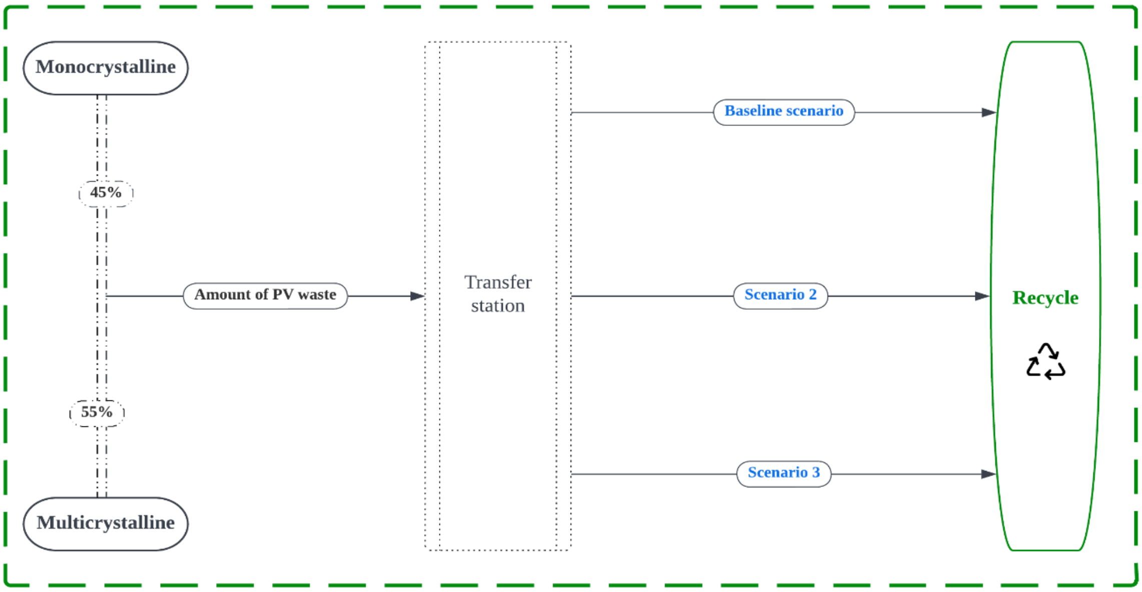

Fig 6: Extended system boundary

This study bridges that gap by using estimated travel distances as previously estimated by the authors (Oteng et al., 2022a) for the scenario analysis as shown in figure 6.

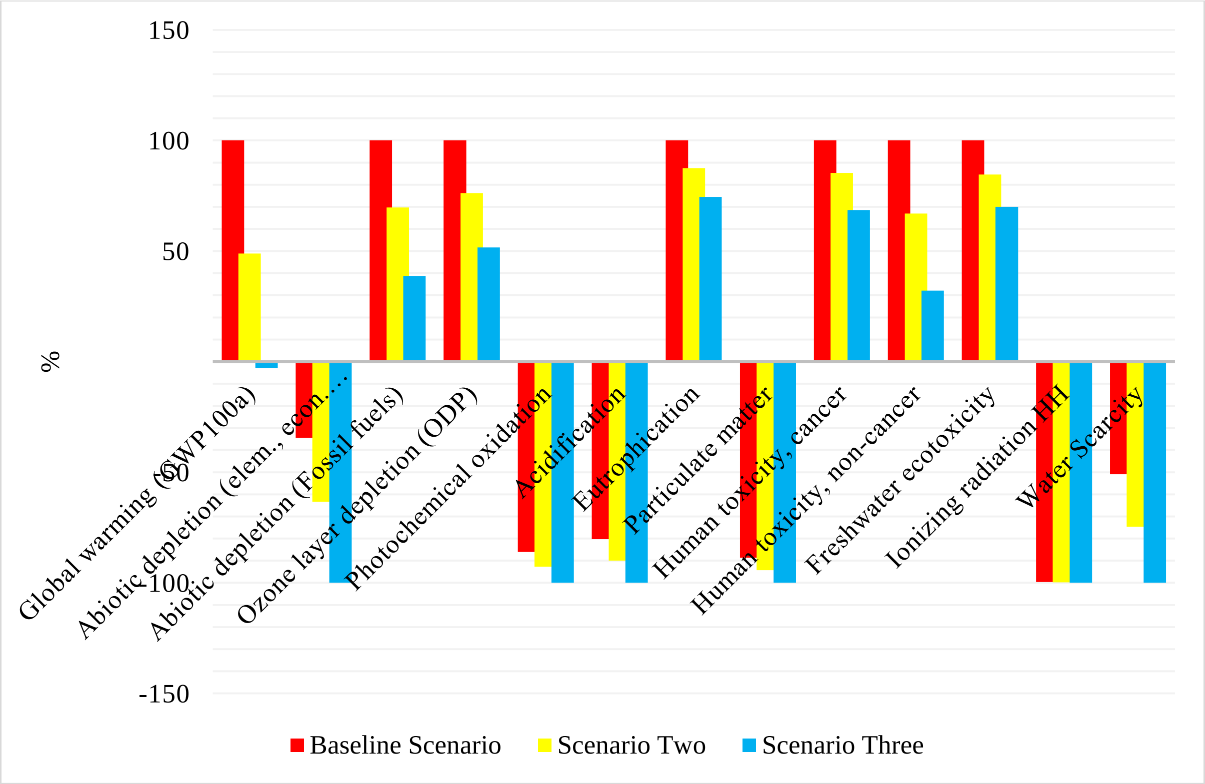

Fig 7: Different scenarios of transport distance of PV waste to recycling centres

The figure 7 highlights the contribution of three different transport distances as estimated by Oteng et al. (2022a) in their environmental emission assessment. The results, reveals that, scenario three which has the shortest distance among the others contributes less to the environmental impacts as compared to that of the baseline scenario and scenario two.

Table 7: Different scenarios of transport distance of PV waste to recycling centres

Impact category	Unit	Baseline Scenario	Scenario Two	Scenario Three
Global warming (GWP100a)	kg $CO_{2\text{-eq}}$	1E+06	5E+05	-28722.00
Abiotic depletion (elem., econ. reserve)	kg $SB_{\text{-eq}}$	-28.18	-51.78	-81.73
Abiotic depletion (Fossil fuels)	MJ NCV	2E+07	2E+07	1E+07
Ozone layer depletion (ODP)	kg CFC-$11_{\text{-eq}}$	0.29	0.22	0.15
Photochemical oxidation	kg $C_2H_{4\text{-eq}}$	-645.20	-695.90	-750.16
Acidification	kg $SO_{2\text{-eq}}$	-10522.00	-11793.00	-13106.00
Eutrophication	kg $PO_{4\text{-eq}}$	2231.00	1952.00	1662.30
Particulate matter	kg $PM_{2.5}$	-1691.00	-1799.00	-1906.70
Human toxicity, cancer	CTUh	0.02	0.02	0.01
Human toxicity, non-cancer	CTUh	0.05	0.04	0.02
Freshwater ecotoxicity	CTUe	2E+10	2E+10	1E+10

Ionizing radiation HH	kBq U235$_{\text{-eq}}$	-97499.00	-97639.00	-97796.00
Water Scarcity	$m^3H_2O_{\text{-eq}}$	-2917.00	-4277.00	-5731.00

Table 7 reports on the individual impacts categories associated with the three scenarios. The contribution of the scenario three shows a significant reduction in all the impact categories for example global warming potential has a value of -28722.00 kg CO_2 eq for scenario three, 5E+05 kg CO_2 eq for scenario two and 1E+06 kg CO_2 eq for the baseline scenario. The results affirm the need to introduce another recycling plant because of the long distances covered by transport trucks when transporting PV waste for recycling.

The limitations of this LCA are associated with the input and output data used for the flows and emissions of this study is developed from the FRELP pilot project. Again, the plant used in Lonsdale is at the initial stage of recycling. Therefore, the data used should be verified once the plant becomes fully operational in the coming years.

4 Discussion

The discussion details the comparative analysis of the results with previous and current literature to make inform decision and suggestions.

4.1 Recycling and recovery scenarios of EoL solar PV panels

There are several studies on the recycling of decommissioned solar PV panels using life cycle impact assessment (Ardente et al., 2019; Dias et al., 2021; Faircloth et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2020). Among these, Müller et al. (2006) posits that, there can be a total reduction of 37% from acidification, 24% from global warming potential, 26% from human toxicity potential and, 74% from terrestrial ecotoxicity through the recycling process of EoL PV modules from “cradle to grave”. Again, by comparing the production of primary Si wafer to recycled Si wafer, the energy used could be reduced by 70% if recycled materials are used (Deng et al., 2019; Vellini et al., 2017).

As assessed in this study, comparing different end-of-life scenarios produces lower environmental impacts or footprint for upcycling and downcycling when compared to direct landfill although the recycling process involves the use of chemicals and energy (Huang et al., 2017; Stolz, 2017). Furthermore, Lunardi et al. (2018) in their studies revealed that upcycling achieved a lower environmental footprint in all the categories (resources, ecosystem and human health) when they assessed and compared LCIA scenarios of chemical recycling, mechanical recycling, thermal recycling, reuse, incineration and landfilling. Thus, high value recycling processes developed and assessed in this study is very necessary towards achieving a sustainable management of EoL PV modules.

Again, the recycling of end-of-life PV modules are associated with high categorical impacts pertaining to transport (Dias et al., 2021). Transport is therefore very essential to collecting and recycling of PV waste. This issue is mostly ignored in several studies, assumptions are mostly used to assess the distances covered throughout the process. This study addresses the issue by developing an optimised system and assessing the LCA of the process. The optimised process showed a net environmental benefit for GWP as compared to the other two scenarios. This is particularly important because of the significant contributions transport have on climate change when it comes to recycling solar PV panels.

4.2 Policy, control measures and practices of PV waste management

To prevent environmental pollution, the government must take the necessary steps to prevent EoL solar panels from being disposed of in landfills. The European Union (EU) enacted the WEEE Directive, which governs EoL solar panels through extended producer responsibility. This ensures that hazardous or valuable materials in the panels are recovered or recycled, reducing landfill waste (Ramos-Ruiz et al., 2017). Other countries outside the EU market are still working on developing appropriate regulations for managing solar PV waste. Although the United States lacks a federal policy, states such as California, Washington, New Jersey, and North Carolina have passed bills to recycle EoL solar PV, with states such as Hawaii and Rhode Island still pending (Curtis, Buchanan, Heath, et al., 2021; Curtis, Buchanan, Smith, et al., 2021). The United States, Japan, China, India, and Australia are among the countries that lack specific policies (Oteng et al., 2022b; Xu et al., 2018). The majority of these countries are currently developing policies to regulate PV waste. The Australian government is developing a national product stewardship programme to govern the management of PV waste which is expected to be operational from 2023.

These policies should lead the process of creating an avenue for manufacturers to recycle through these regulations to prevent hazardous materials from going into landfills. The extended producer responsibility is yet to be adopted and mandated (mandatory product stewardship) to aid in the collection, tracking and recycling of panels by manufactures (Mahmoudi et al., 2019; Oteng et al., 2022a; Sharma et al., 2021). The government should provide incentives for industry led initiatives to also come up with innovative recycling technologies. Without proper control measures, the broken panels in the landfills may percolate and leach into the ground water (Nain & Kumar, 2020a, 2020b) which will cause several environmental and health issues.

5 Conclusions

Significant amount of solar PV waste, reaching their 25-30 years lifetime, is expected to overwhelm the industry in the coming years. These panels may end up in landfills due to lack of effective polices for regulating waste PV modules. This study therefore discusses the environmental impacts of three different policy options, sensitivity analysis and the impact of transport on recycling of EoL PV models.

The global warming potential for the non-existence of a product stewardship or policy was 1E+05 $kgCO_{2}$-eq for both PV modules which is a significant shift from the mandatory product stewardship or extended producer responsibility considering the -1E+06 $kgCO_{2}$-eq and -2E+06

$kgCO_{2}$-eq for mono and multi c-Si modules, respectively. The credits attributed to the avoided products under the EPR such as aluminium, solar glass, copper, silicon, silver, lead, and tin goes back to the production stream creating significantly lower environmental footprint. This also reveals the significant environmental impact of the multi-Si panels when disposed in landfills but comparatively better than the mono-Si panels when recycled. Consequently, the comparison of different recycling and landfilling scenarios were assessed. The results revealed that, collecting and recycling most of the mono and multi c-Si panels were not effective (-365.00 kg $CO_{2\text{-eq}}$, -698.40 kg $CO_{2\text{-eq}}$, -1032.00 kg $CO_{2\text{-eq}}$) compared to keeping them away from the landfills and fully recycling (-2E+06 kg $CO_{2\text{-eq}}$) them especially when it comes to climate change.

The transportation impact of the recycling process was also assessed. Scenario three (-28722.19 $kgCO_{2}eq$) which was the shortest distance from the transfer stations to the recycling centres had the least environmental impact (global warming potential) on the recycling process. The highest impact (1E+06 $kgCO_{2}eq$) regarding global warming was the scenario of one recycling centre serving around 107 transfer stations. The optimised collection centre which is the second scenario had an environmental impact (5E+05 $kgCO_{2}eq$) between the baseline scenario and the third scenario. The methodology serves a s a first LCA assessment using a developed transport distance for the recycling process which can be replicated in other states and other countries. To further reduce the significant impact of transport distance on the PV recycling process, low-impact modes of transportation using renewable energies may be used in the transportation of the PV waste volume. It suggested that, using this model assessment, the social and economic aspects of the policy options may be assessed.

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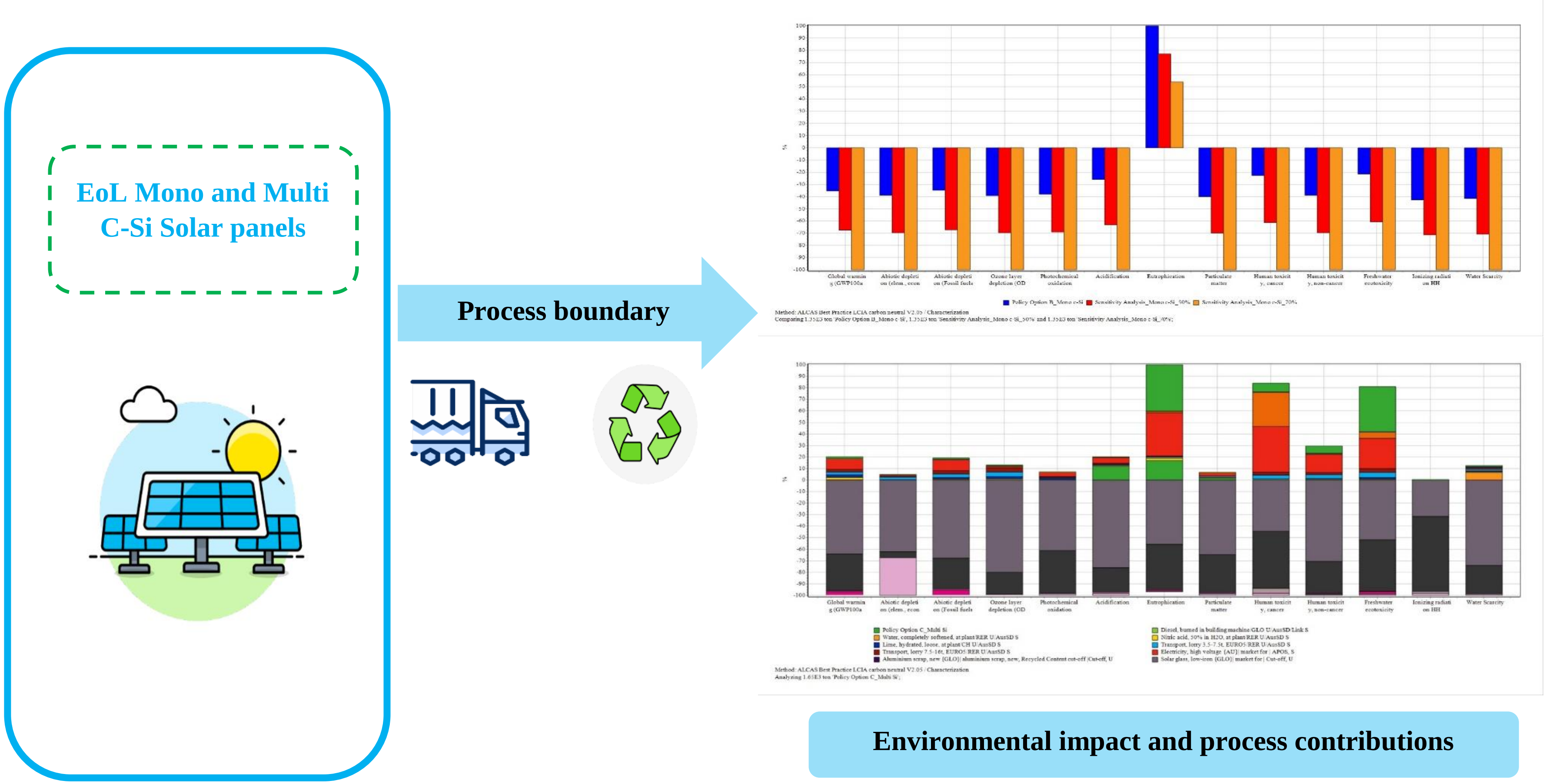
Graphical Abstract



EoL Mono and Multi C-Si Solar panels

Process boundary

Environmental impact and process contributions

Highlights

- Environmental impact of policy options of EoL PV are evaluated.
- There is a significant change when considering MPS and EPR environmental impact.
- LCA assessment reveals first results on product stewardship associated with EoL solar photovoltaics.
- Further transportation assessment offers more insight on the recycling process.

Supplementary File

CRediT author statement

Daniel Oteng: Conceptualization, Methodology, Writing - original draft; Formal analysis: **Jian Zuo:** Conceptualization, Supervision, Writing - review & editing: **Ehsan Sharifi:** Conceptualization, Supervision, Writing - review & editing.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Supplementary Material

An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: An environmental lifecycle assessment

Daniel Oteng[*], Jian Zuo, Ehsan Sharifi

School of Architecture and Civil Engineering, The University of Adelaide, Adelaide, South Australia, Australia.

A.1 Data for LCA

As shown in Table A1, the data for LCA for one ton of PV waste is provided.

Table A1: Data for LCA (Mass composition of 1000kg (1 ton) of PV waste as input to the process). (Latunussa et al., 2016)

Component	**Quantity**	**Unit**	**Percentage**
Glass, containing antimony (0.01-1%/kg of glass)	700	kg	70.00
PV frame, made of aluminium	180	kg	18.00
Polymer-based adhesive (EVA) encapsulation layer	51	kg	5.10
Solar cell, containing silicon metal	36.5	kg	3.65
Back-sheet layer (based on Polyvinyl Fluoride)	15	kg	1.50
Cables (containing copper and polymers)	10	kg	1.00
Internal conductor, aluminium	5.3	kg	0.53
Internal conductor, copper	1.14	kg	0.11
Silver	0.53	kg	0.053
Other metals (tin, lead)	0.53	kg	0.053
Total	**1000**	**kg**	**100**

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A.2 Inventory data for LCA

The details of the background inventory for recycling the c-Si solar PV panels are shown in table A2

Table A2: Details of the lifecycle inventory dataset used in this study

Item	**Used for the process phase**	**Dataset used**
Transport	Transport of PV waste to the recycling plant	Transport lorry 16-32 t EURO5/RER U/ AusSD S
	Transport of: PV waste to local collection point; cables to cable treatment plant and cable polymer to the incineration plant; glass residue to landfill; PV sandwich to incinerator; ash to the treatment plant; fly ash to special landfill.	Transport lorry 3.5-7.5 t EURO5/RER U/ AusSD S
	Transport of sludge from the recycling plant to landfill	Transport lorry 7.5-16 t EURO5/RER U/AusSD S
Diesel fuel	Unloading	Diesel burned in building machine/GLO U/AusSD S
Electricity	Disassembly, cable treatment, glass separation, glass refinement, cutting of PV sandwich, sieving, acid leaching, filtration, electrolysis, neutralisation, and filter press	Electricity, high voltage (AU) | market for |APOS, S
Disposal of fly ash in landfill	Incineration	Disposal average incineration residue 0%, water to residual material landfill/CH
Incineration of plastics from cables	Cable treatment	Disposal, wire plastic, 3.55% water, to municipal incineration/CH U/AusSD S
Incineration of PVF	PV sandwich incineration	Disposal, polyvinyl fluoride, 0.2% water, to municipal incineration/CH U/AusSD S
Incineration of EVA	PV sandwich incineration	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U/AusSD S
Landfilling of the contaminated glass	Glass treatment	Disposal, glass, 0% water, to inert material landfill/CH
Treatment for the recycling of cables	Cable treatment	Disposal, treatment of cables/CH
Production of heat (avoided impacts from energy recovery during the incineration)	Incineration of cable polymer and PV sandwich, energy recovery	Heat natural gas at industrial furnace > 100 kW/RER
Production of electricity (avoided impacts from energy recovery during the incineration)	Incineration of cable polymer and PV sandwich, energy recovery	Electricity, high voltage (AU) | market for |APOS, S
Landfilling of sludge with metal residuals	Filter press	Disposal, sludge, pig iron production, 8.6% water, to residual material landfill/CH S/ AusSD S
Landfilling of inert sludge	Filter press	Disposal, limestone residue, 5% water, to inert material landfill/CH U/AusSD S
Ca $(OH)_2$	Neutralisation	Lime hydrated loose at plant/CH U/ AusSD S
Nitric acid (HNO_3)	Acid leaching	Nitric acid 50% in H_2O at plant/RER U/ AusSD S
water	Acid leaching, electrolysis, neutralisation	Water, completely softened, at plant/RER U/AusSD S/ AusSD S
	Production process of photovoltaic panel	Photovoltaic panel, mono-Si wafer (GLO) | market for | APOS, S

	Production process of photovoltaic panel	Photovoltaic panel, multi-Si wafer (GLO) | market for | APOS, S
	Landfilling of the photovoltaic panels	122 Waste treatment, Landfill of waste, Metals nec, EU27 123 Waste treatment, Landfill of waste, Glass/inert, EU27 121 Waste treatment, Landfill of waste, Copper, EU27 120 Waste treatment, Landfill of waste, Aluminium, EU27 118 Waste treatment, Landfill of waste, Plastic, EU27
	Production process of photovoltaic panel	Transport, lorry 3.5-7.5 t EURO5/RER U/AusSD S

A.3 Policy options for treating PV waste

The table details the policy options on solar photovoltaic waste treatment and describes the percentages for recycling and landfilling.

Table A3: Policy options in the treatment of solar photovoltaic waste annually

Photovoltaic Technology	**Percentage Market Share** *(Daljit Singh et al., 2021)*	**Residential PV waste generated annually till 2050** *(Oteng et al., 2022)*	**Conventional EoL**			**Policy Option A Voluntary Action**			**Policy Option B All PV Recycled**		
	(%)	(In tonnes) g	Collection rate (%) c	Recycled $R = g \times c$	Landfilled $L = g - R$	Collection rate (%) c	Recycled $R = g \times c$	Landfilled $L = g - R$	Collection rate (%) c	Recycled $R = g \times c$	Landfilled $L = g - R$
Mono-crystalline Silicon (Mono c-Si)	45%	1350	0%	0	1350	30%	405	945	100%	1350	0
Multi-crystalline Silicon (Multi c-Si)	55%	1650	0%	0	1650	30%	495	1155	100%	1650	0
Total	**100%**	**3000**	**0%**	**0**	**3000**	**30%**	**900**	**2100**	**100%**	**3000**	**0**

B.1 *Process contribution for mono c-Si panels*

The table details process contribution of the life cycle assessment of monocrystalline solar panels

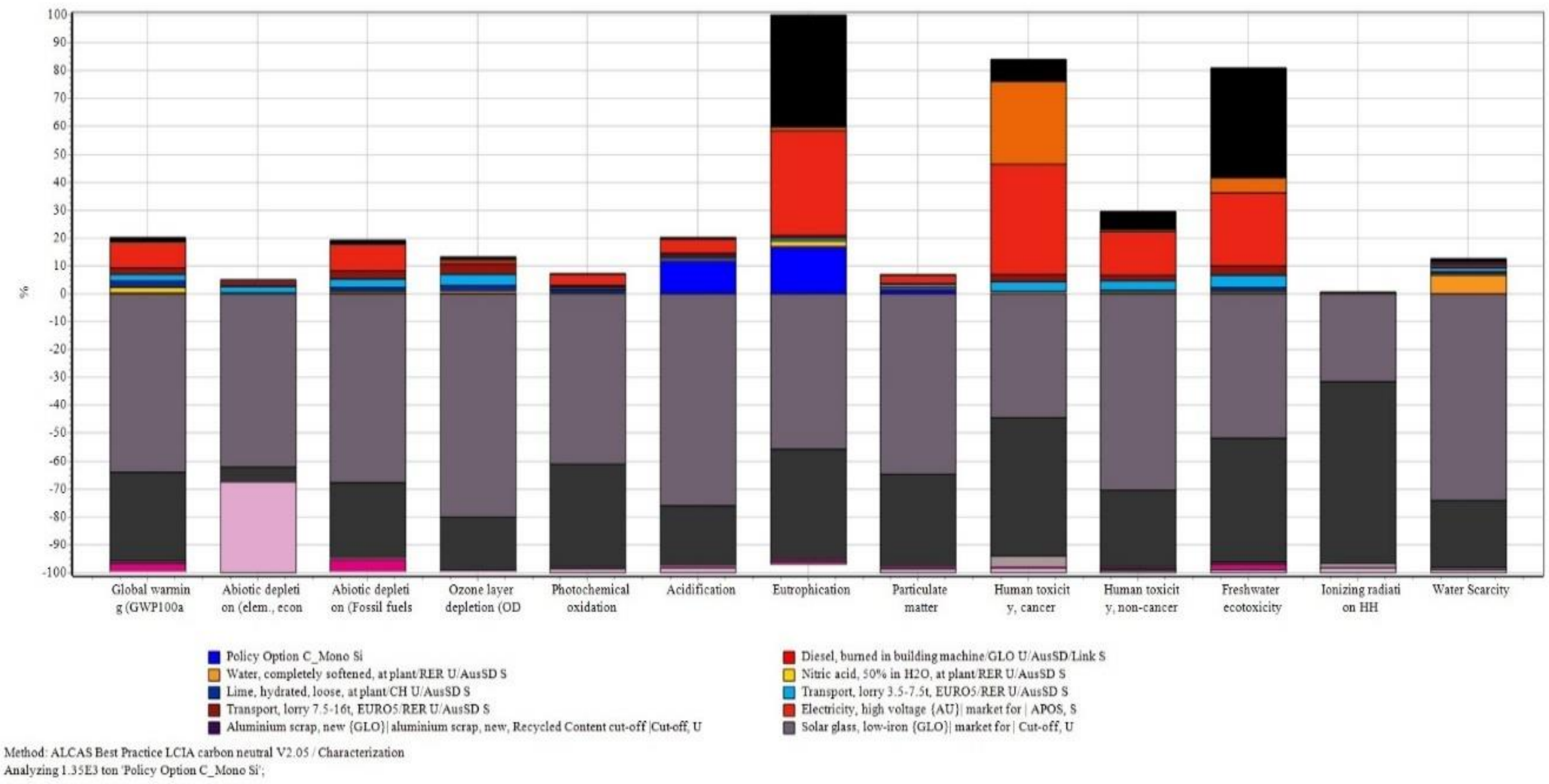


Fig B1: process contribution of the life cycle assessment of monocrystalline solar panels

B.2 Process contribution for multi c-Si panels

The figure details process contribution of the life cycle assessment of monocrystalline solar panels

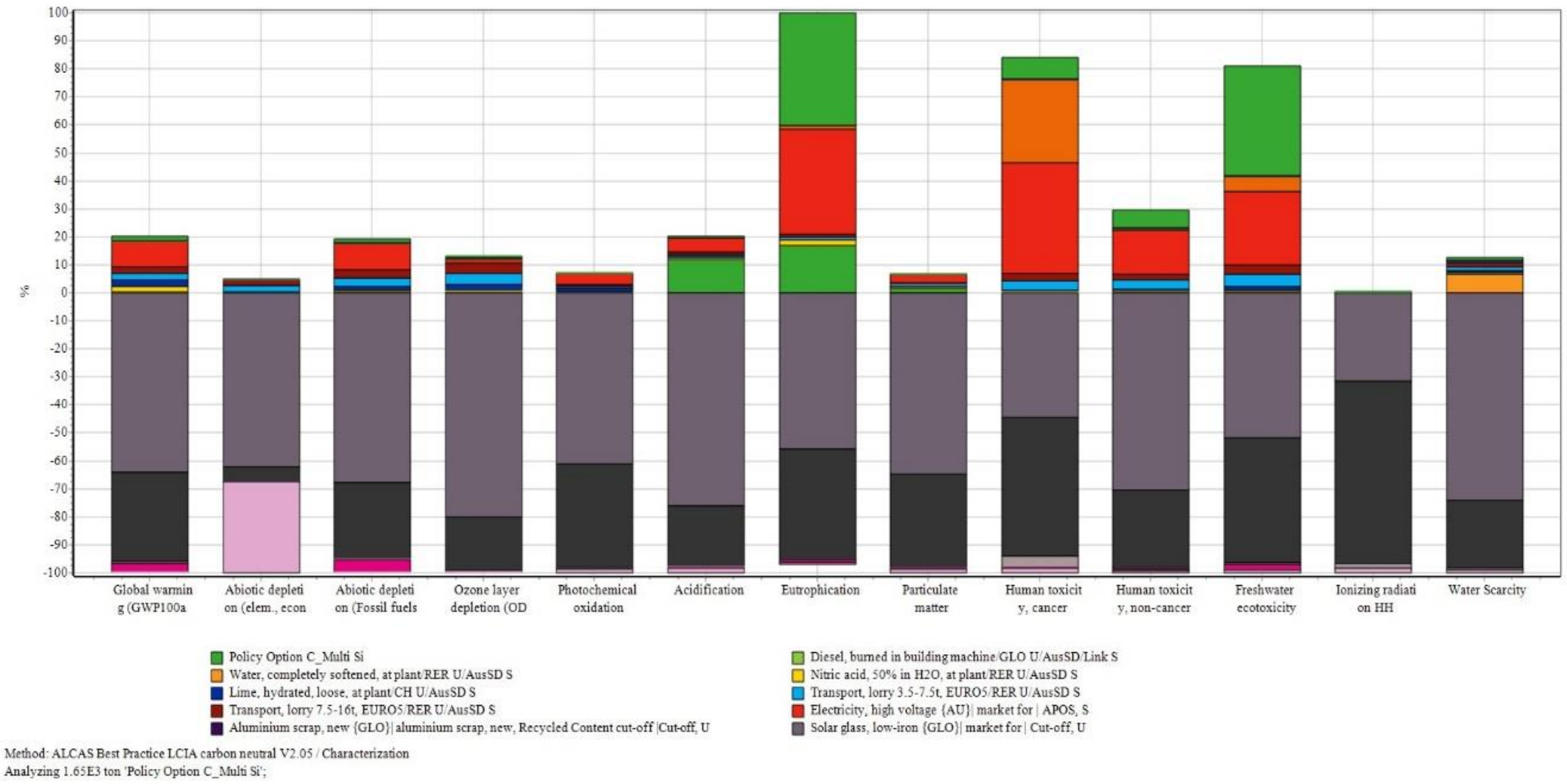
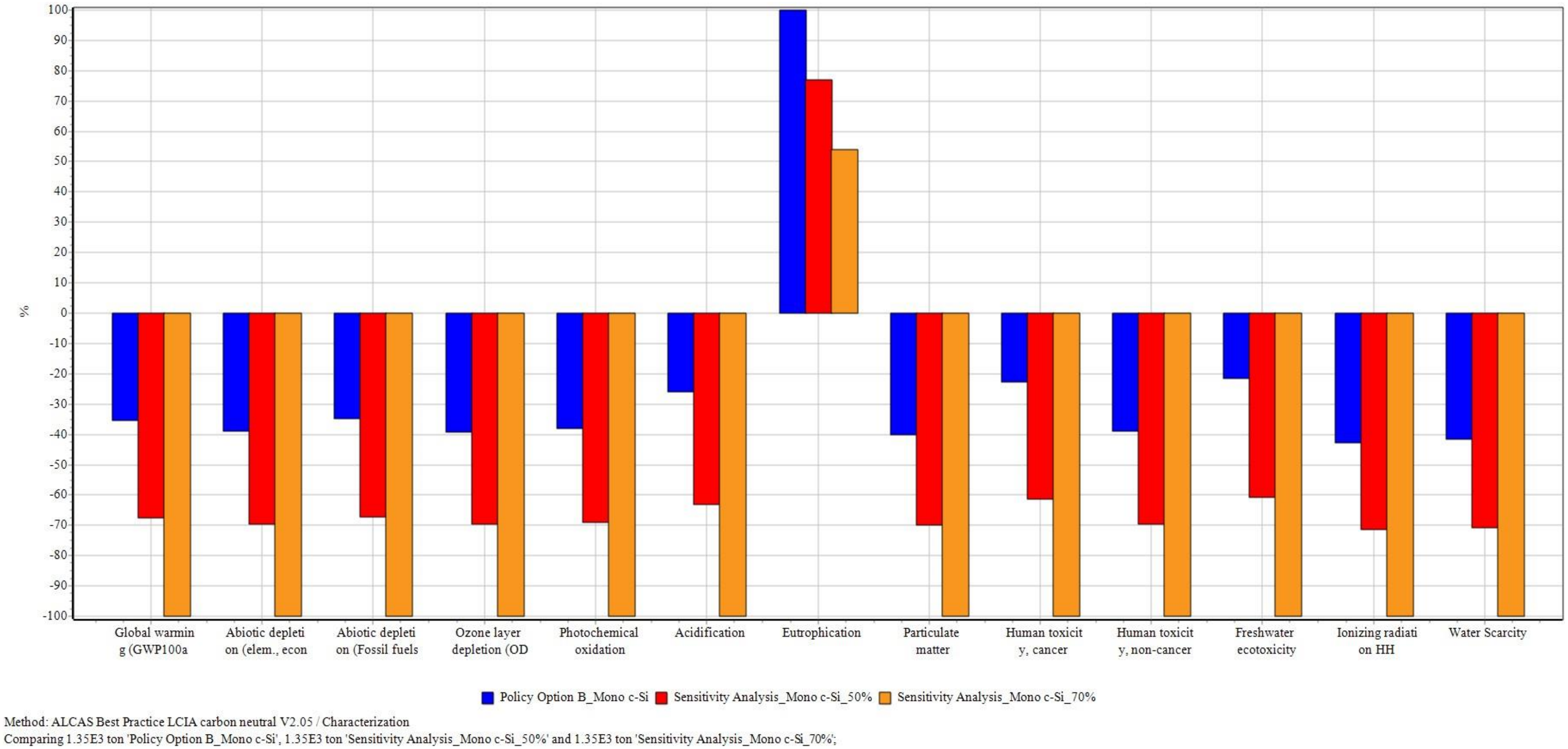


Fig B2: Process contribution of the life cycle assessment of multicrystalline solar panels

B.3 Sensitivity analysis on mono c-Si panels

The figure details the sensitivity analysis of the life cycle assessment of monocrystalline solar panels

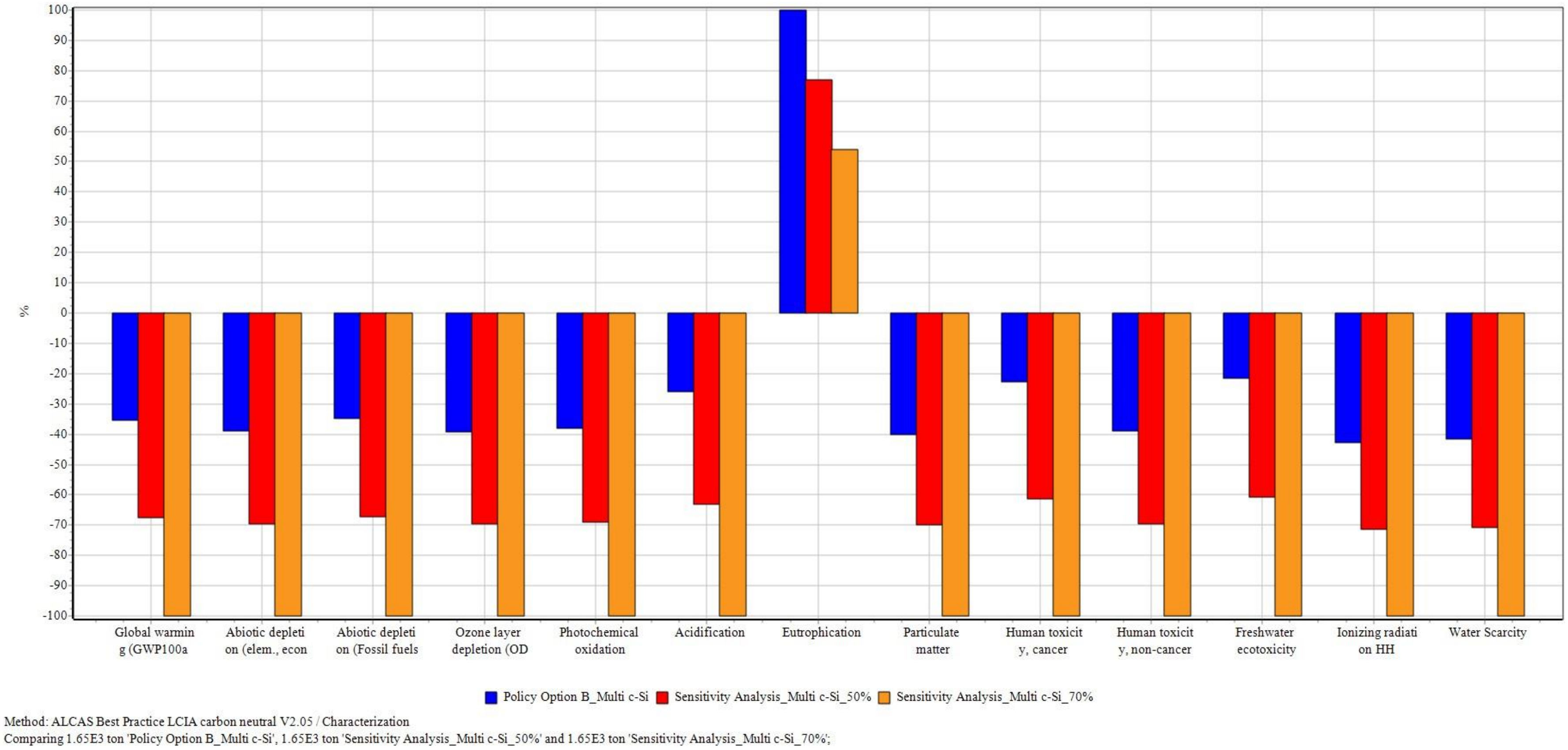


Method: ALCAS Best Practice LCIA carbon neutral V2.05 / Characterization
Comparing 1.35E3 ton 'Policy Option B_Mono c-Si', 1.35E3 ton 'Sensitivity Analysis_Mono c-Si_50%' and 1.35E3 ton 'Sensitivity Analysis_Mono c-Si_70%';

Fig B3: Sensitivity analysis of the life cycle assessment of monocrystalline solar panels

B.4 Sensitivity analysis on multi c-Si panels

The figure details the sensitivity analysis of the life cycle assessment of multicrystalline solar panels



Method: ALCAS Best Practice LCIA carbon neutral V2.05 / Characterization
Comparing 1.65E3 ton 'Policy Option B_Multi c-Si', 1.65E3 ton 'Sensitivity Analysis_Multi c-Si_50%' and 1.65E3 ton 'Sensitivity Analysis_Multi c-Si_70%';

Fig B4: Sensitivity analysis of the life cycle assessment of multicrystalline solar panels

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Appendix E – Ethics approval

RESEARCH SERVICES
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CRICOS Provider Number 00123M

Our reference 34830

17 November 2020

Professor Jian Zuo
School of Architecture & Built Environment

Dear Professor Zuo

ETHICS APPROVAL No: H-2020-244
PROJECT TITLE: Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia

The ethics application for the above project has been reviewed by the Executive, Human Research Ethics Committee and is deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research 2007 (Updated 2018)* involving no more than low risk for research participants.

You are authorised to commence your research on: 17/11/2020
The ethics expiry date for this project is: 30/11/2023

NAMED INVESTIGATORS:

Chief Investigator:	Professor Jian Zuo
Student - Postgraduate Doctorate by Research (PhD):	Mr Daniel Oteng
Associate Investigator:	Dr Ehsan Sharifi

CONDITIONS OF APPROVAL: “ Thank you for addressing the feedback. The revised ethics application provided on the 16th of November 2020 has been approved.

Ethics approval is granted for three years and is subject to satisfactory annual reporting. The form titled Annual Report on Project Status is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/research-services/oreci/human/reporting/. Prior to expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the information sheet and the signed consent form to retain. It is also a condition of approval that you immediately report anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,

- previously unforeseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol or project investigators; and
- the project is discontinued before the expected date of completion.

Yours sincerely,

Professor Paul Delfabbro
Convenor

The University of Adelaide

Appendix F – Participant consent form: Government participants

Human Research Ethics Committee (HREC)

CONSENT FORM FOR GOVERNMENT/CONSULTANTS

1. I have read the attached Information Sheet and agree to take part in the following research project:

Title:	**Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia**
Ethics Approval Number:	**H-2020-244**

2. I have had the project, so far as it affects me, and the potential risks and burdens fully explained to my satisfaction by the research worker. I have had the opportunity to ask any questions I may have about the project and my participation. My consent is given freely.

3. Although I understand the purpose of the research project, it has also been explained that my involvement may not be of any benefit to me.

4. I agree to participate in the activities outlined in the participant information sheet.

5. I agree to be:
   Audio recorded ☐ Yes ☐ No

   Video recorded ☐ Yes ☐ No

6. I understand that I am free to withdraw from the project at any time.

7. I have been informed that the information gained in the project may be published in a book/journal article/thesis/conference presentations/ etc.

8. I have been informed that while I will not be named in the published materials, it may not be possible to guarantee my anonymity given the nature of the study and/or small number of participants involved.
   ☐ Yes ☐ No

9. I agree to my information being used for future research undertaken by the same researcher (s).
   ☐ Yes ☐ No

10. I understand my information will only be disclosed according to the consent provided, except where disclosure is required by law.

11. I am aware that I should keep a copy of this Consent Form, when completed, and the attached Information Sheet.

Participant to complete:

Name: ________________________ Signature: ___________________________ Date: ______________________________

Researcher/Witness to complete:

I have described the nature of the research to ____

(print name of participant)

and in my opinion, she/he understood the explanation.

Signature: ______________________ Position:_____________________________ Date: ______________________________

Appendix G – Participant consent form: Industry participants

Human Research Ethics Committee (HREC)

CONSENT FORM FOR INDUSTRY PARTICIPANTS

12. I have read the attached Information Sheet and agree to take part in the following research project:

Title:	**Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia**
Ethics Approval Number:	**H-2020-244**

13. I have had the project, so far as it affects me, and the potential risks and burdens fully explained to my satisfaction by the research worker. I have had the opportunity to ask any questions I may have about the project and my participation. My consent is given freely.

14. Although I understand the purpose of the research project, it has also been explained that my involvement may not be of any benefit to me.

15. I agree to participate in the activities outlined in the participant information sheet.

16. I agree to be:

    Audio recorded ☐ Yes ☐ No

    Video recorded ☐ Yes ☐ No

17. I understand that I am free to withdraw from the project at any time.

18. I have been informed that the information gained in the project may be published in a book/journal article/thesis/conference presentations/ etc.

19. I have been informed that while I will not be named in the published materials, it may not be possible to guarantee my anonymity given the nature of the study and/or small number of participants involved.
    ☐ Yes ☐ No

20. I agree to my information being used for future research undertaken by the same researcher (s).
    ☐ Yes ☐ No

21. I understand my information will only be disclosed according to the consent provided, except where disclosure is required by law.

22. I am aware that I should keep a copy of this Consent Form, when completed, and the attached Information Sheet.

Participant to complete:

Name: ________________________ Signature: ___________________________ Date: ______________________________

Researcher/Witness to complete:

I have described the nature of the research to ____

(print name of participant)

and in my opinion, she/he understood the explanation.

Signature: ______________________ Position:_____________________________ Date: ______________________________

Appendix H – Participant consent form: Fieldwork

Human Research Ethics Committee (HREC)

CONSENT FORM FOR FIELD STUDIES

23. I have read the attached Information Sheet and agree to take part in the following research project:

Title:	**Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia**
Ethics Approval Number:	**H-2020-244**

24. I have had the project, so far as it affects me, and the potential risks and burdens fully explained to my satisfaction by the research worker. I have had the opportunity to ask any questions I may have about the project and my participation. My consent is given freely.

25. Although I understand the purpose of the research project, it has also been explained that my involvement may not be of any benefit to me.

26. I agree to participate in the activities outlined in the participant information sheet.

27. I agree to be:
    Audio recorded ☐ Yes ☐ No

    Video recorded ☐ Yes ☐ No

    Photographed ☐ Yes ☐ No

28. I understand that I am free to withdraw from the project at any time.

29. I have been informed that the information gained in the project may be published in a book/journal article/thesis/conference presentations/ etc.

30. I have been informed that while I will not be named in the published materials, it may not be possible to guarantee my anonymity given the nature of the study and/or small number of participants involved.
    ☐ Yes ☐ No

31. I agree to my information being used for future research undertaken by the same researcher (s).
    ☐ Yes ☐ No

32. I understand my information will only be disclosed according to the consent provided, except where disclosure is required by law.

33. I am aware that I should keep a copy of this Consent Form, when completed, and the attached Information Sheet.

Participant to complete:

Name: ________________________ Signature: ___________________________ Date:
____

Researcher/Witness to complete:

I have described the nature of the research to
____

(print name of participant)

and in my opinion, she/he understood the explanation.

Signature: ______________________ Position:_____________________________ Date:
____

Appendix I – Participant information sheet: Government participants

PARTICIPANT INFORMATION SHEET

PROJECT TITLE: Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia
HUMAN RESEARCH ETHICS COMMITTEE APPROVAL NUMBER: H-2020-244
PRINCIPAL INVESTIGATOR: Prof. Jian Zuo
STUDENT RESEARCHER: Daniel Oteng
STUDENT'S DEGREE: Doctor of Philosophy
Target Group: Government/Consultants

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?

There is a rapid growth of the solar photovoltaic (PV) panel installations globally which will keep rising sharply in the coming years. Solar PV systems are commonly chosen to address the need for reducing the greenhouse gas emissions and life cycle energy use of buildings. However, the large exploitation of solar PV could lead to undesirable impacts on the environment in terms of waste disposal. Australia has the highest penetration of solar PV in the residential sector in the developed world. As the normal useful life of the panels is 25 to 30 years, the waste from solar panels will soon become a major issue as they will require disposal in the coming years. This study therefore, seeks to explore the management practices of solar PV waste in addressing a sustainable waste policy in Australia. To achieve the aim of the research, the following objectives are devised:

1. To examine the current practice of dealing with waste from solar photovoltaic panels in the Australian residential sector.
2. To assess the impact of the waste from solar photovoltaic panels in the Australian residential sector.
3. To provide policy suggestions on the management of waste from solar photovoltaic panels in Australia.

Through the interviews and data from previous assessments, a framework will be developed to determine the environmental, economic and health impact of these practices through life cycle impact analysis. In transitioning towards a sustainable PV policy, the results of this research will inform government and the private sector on the impacts of the current management practices and guidelines will be provided to support decision making towards a sustainable PV waste management in Australia.

Who is undertaking the project?

This project is being conducted by Daniel Oteng. This research will form the basis for the degree of Doctor of Philosophy at the University of Adelaide under the supervision of Prof. Jian Zuo and Dr. Ehsan Sharifi.

Why am I being invited to participate?

You are being invited as you fall within the following group:

- Have a minimum of 2 years work experience
- Member of government organizations or spokesperson (Australian Renewable Energy Agency, Clean Energy Regulator, Department of Energy and Water, Dept. of Agriculture, Water and the Environment/Environment Protection Authority, National Waste and Recycling Industry Council, Green Industry SA).
- Member of institutions/consultants (Australia Photovoltaic Institute, Waste Management and Resource Recovery Association of Australia).

What am I being invited to do?

You are being invited to take part in an interview. The interviews are being conducted with experts within the solar photovoltaic industry or related government positions. The interviews are designed to collect the following information as shown below:

- Developments in solar PV technologies in Australia
- Policies and regulations on solar photovoltaics in Australia
- Strategies and initiatives of PV waste treatment pathways

The interview will be recorded under your approved consent either through Zoom or phone. The recording will then be analysed using Nvivo. However, the transcript of the interview will be shared with you for any review or corrections before it is finally used for analysis. Because of the issue with Covid-19, the interview will be conducted virtually through Zoom or the phone. Your preference will be taken into consideration.

How much time will my involvement in the project take?

The interview is expected to take 1 hour, in which case will be recorded for transcription. A voluntary follow-up interview may be requested, which you are allowed to refuse or participate. In this case the researcher will contact you using the personal information provided, which again will not be part of the analysis. After the transcription of the interviews, it will be returned to the participants to review and confirm what has been produced. The participants will have one week to review and give their feedback.

Are there any risks associated with participating in this project?

The participants will be made to feel comfortable through the asking of relevant questions related to the research which would have already be sent to them. This is unlikely to cause any harm or discomfort as the selected participants will be experts in this field. The time spent is kept to a minimal, the meeting will be conducted virtually or through the phone because of the restrictions on Covid-19 which will help reduce any potential discomfort. The participants will have the option to withdraw or reschedule the interview should they feel uncomfortable or any discomfort. Therefore, the risks for both researchers and participants will be minimal.

The global pandemic (Covid-19) has caused some fear when it comes to physical contact. The interviews will therefore be conducted through zoom or phone at the appropriate schedule or convenience of the participants. Most importantly, they will have options to reschedule the meetings to their convenient times as well as end the meeting in case of any discomfort. Breaks will be taken throughout the interview to ensure that participants are relaxed and comfortable. With these protocols in place, risks will be minimized and mitigated.

What are the potential benefits of the research project?

The research may not offer any benefit to the participant as it is for academic purposes. However, the research may result in producing guidelines for solar photovoltaic waste policies in Australia. The research will benefit the participants indirectly by contributing to the body of knowledge in the research field as well as give recommendations on policies to government and policy makers which will one way or the other affect their operations. The findings of the research will also be published in conference proceedings and journal publications.

Can I withdraw from the project?

Participation in this project is completely voluntary. If you agree to participate, you can withdraw from the study anytime the participant feels uncomfortable before or during the interview. Withdrawal may not be possible during the analysis of the data which will start around May, 2020.

What will happen to my information?

Digital-data will be processed and stored securely. The information will be stored in an encrypted university hard drive and servers which will be stored in the principal investigator's office 4073 Barr Smith South as well as the University of Adelaide database (The data will be accessed via the University of Adelaide PC located on Level 3 of Horace Lamb Building), and will only be accessible to the researchers. All data will be backed up to reduce the risk of losing the data. All backed up data will not be stored on personal drives as the university makes backups of all data.

Non- digital data will be secured and stored in a lockable filing cabinet during the data collection and recruitment phase. The filing cabinet is in a secure and accessible location in the Horace Lamb Building.

A final data management plan will be prepared after completing the research. Before thesis submission, all the original data or primary research materials will be deposited with the principal investigator. The data will then be lodged in the University of Adelaide Figshare after the completion of the study. The data and records of the studies will be retained by the University for a minimum of 5 years from the completion of the projects.

Sensitive and confidential information will not be included when storing data on Figshare. Details of participant will be anonymized and identified with a unique code. Your information will only be used as described in this participant information sheet and it will only be disclosed according to the consent provided, except as required by law.

Who do I contact if I have questions about the project?

To contact the participants please see below:

Supervisors: Prof. Jian Zuo (Ph: +61 8 8313 0217; Email: jian.zuo@adelaide.edu.au)

Dr. Ehsan Sharifi (Ph: +61 8 8313 0317; Email: ehsan.sharifi@adelaide.edu.au)
Researcher: Daniel Oteng (Ph: +61 8 8313 4038; Email: daniel.oteng@adelaide.edu.au)

What if I have a complaint or any concerns?

The study has been approved by the Human Research Ethics Committee at the University of Adelaide (approval number H-2020-244). This research project will be conducted according to the NHMRC National Statement on Ethical Conduct in Human Research 2007 (Updated 2018). If you have questions or problems associated with the practical aspects of your participation in the project, or wish to raise a concern or complaint about the project, then you should consult the Principal Investigator. If you wish to speak with an independent person regarding concerns or a complaint, the University's policy on research involving human participants, or your rights as a participant, please contact the Human Research Ethics Committee's Secretariat on:

Phone: +61 8 8313 6028
Email: hrec@adelaide.edu.au
Post: Level 4, Rundle Mall Plaza, 50 Rundle Mall, ADELAIDE SA 5000

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

If I want to participate, what do I do?

To participate in this study, please contact Daniel Oteng by email. A consent form will be emailed to you for signing in which you will return it to the research. An interview time will then be scheduled. Daniel's email: daniel.oteng@adelaide.edu.au

Yours sincerely,
Researcher: Daniel Oteng
Supervisors: Prof. Jian Zuo; Dr. Ehsan Sharifi

Appendix J – Participant information sheet Industry participants

PARTICIPANT INFORMATION SHEET

PROJECT TITLE: Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia
HUMAN RESEARCH ETHICS COMMITTEE APPROVAL NUMBER: H-2020-244
PRINCIPAL INVESTIGATOR: Prof. Jian Zuo
STUDENT RESEARCHER: Daniel Oteng
STUDENT'S DEGREE: Doctor of Philosophy
Target Group: Industry Professionals

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?
There is a rapid growth of the solar photovoltaic (PV) panel installations globally which will keep rising sharply in the coming years. Solar PV systems are commonly chosen to address the need for reducing the greenhouse gas emissions and life cycle energy use of buildings. However, the large exploitation of solar PV could lead to undesirable impacts on the environment in terms of waste disposal. Australia has the highest penetration of solar PV in the residential sector in the developed world. As the normal useful life of the panels is 25 to 30 years, the waste from solar panels will soon become a major issue as they will require disposal in the coming years. This study therefore, seeks to explore the management practices of solar PV waste in addressing a sustainable waste policy in Australia. To achieve the aim of the research, the following objectives are devised:

4. To examine the current practice of dealing with waste from solar photovoltaic panels in the Australian residential sector.
5. To assess the impact of the waste from solar photovoltaic panels in the Australian residential sector.
6. To provide policy suggestions on the management of waste from solar photovoltaic panels in Australia.

Through the interviews and data from previous assessments, a framework will be developed to determine the environmental, economic and health impacts of these practices through life cycle impact analysis. In transitioning towards a sustainable PV policy, the results of this research will inform government and the private sector on the impacts of the current management practices and guidelines will be provided to support decision making towards a sustainable PV waste management in Australia.

Who is undertaking the project?

This project is being conducted by Daniel Oteng. This research will form the basis for the degree of Doctor of Philosophy at the University of Adelaide under the supervision of Prof. Jian Zuo and Dr. Ehsan Sharifi.

Why am I being invited to participate?

You are being invited as you fall within the following group:

- Have a minimum of 2 years work experience
- Spokesperson of Manufacturers/Distributors (This will be retrieved from the member list of clean energy council approved retailers and crossed check using the Australian Business Register (ABN) Lookup).
- Recovery and Recycling experts

What am I being invited to do?

You are being invited to take part in an interview. The interviews are being conducted with experts within the solar photovoltaic industry or related government positions. The interviews are designed to collect the following information as shown below:

- Developments in solar PV technologies in Australia
- Policies and regulations on solar photovoltaics in Australia
- Strategies and initiatives of PV waste treatment pathways

The interview will be recorded under your approved consent either through Zoom or phone. The recording will then be analysed using Nvivo. However, the transcript of the interview will be shared with you for any review or corrections before it is finally used for analysis. Because of the issue with Covid-19, the interview will be conducted virtually through Zoom or the phone. Your preference will be taken into consideration.

How much time will my involvement in the project take?

The interview is expected to take 1 hour, in which case will be recorded for transcription. A voluntary follow-up interview may be requested, which you are allowed to refuse or participate. In this case the researcher will contact you using the personal information provided, which again will not be part of the analysis. After the transcription of the interviews, it will be returned to the participants to review and confirm what has been produced. The participants will have one week to review and give their feedback.

Are there any risks associated with participating in this project?

The participants will be made to feel comfortable through the asking of relevant questions related to the research which would have already be sent to them. This is unlikely to cause any harm or discomfort as the selected participants will be experts in this field. The time spent is kept to a minimal, the meeting will be conducted virtually or through the phone because of the restrictions on Covid-19 which will help reduce any potential discomfort. The participants will have the option to withdraw or reschedule the interview should they feel uncomfortable or any discomfort. Therefore, the risks for both researchers and participants will be minimal.

The global pandemic (Covid-19) has caused some fear when it comes to physical contact. The interviews will therefore be conducted through zoom or phone at the appropriate schedule or convenience of the participants. Most importantly, they will have options to reschedule the meetings to their convenient times as well as end the meeting in case of any discomfort. Breaks will be taken throughout the interview to ensure that participants are relaxed and comfortable. With these protocols in place, risks will be minimized and mitigated.

What are the potential benefits of the research project?

The research may not offer any benefit to the participant as it is for academic purposes. However, the research may result in producing guidelines for solar photovoltaic waste policies in Australia. The research will benefit the participants indirectly by contributing to the body of knowledge in the research field as well as give recommendations on policies to government and policy makers which will one way or the other affect their operations. The findings of the research will also be published in conference proceedings and journal publications.

Can I withdraw from the project?

Participation in this project is completely voluntary. If you agree to participate, you can withdraw from the study anytime the participant feels uncomfortable before or during the interview. Withdrawal may not be possible during the analysis of the data which will start around May, 2020.

What will happen to my information?

Digital-data will be processed and stored securely. The information will be stored in an encrypted hard drive which will be stored in the principal investigator's office 4073 Barr Smith South as well as the University of Adelaide database (The data will be accessed via the University of Adelaide PC located on Level 3 of Horace Lamb Building), and will only be accessible to the researchers. All data will be backed up to reduce the risk of losing the data. All backed up data will not be stored on personal drives as the university makes backups of all data.

Non- digital data will be secured and stored in a lockable filing cabinet during the data collection and recruitment phase. The filing cabinet is in a secure and accessible location in the Horace Lamb Building.

A final data management plan will be prepared after completing the research. Before thesis submission, all the original data or primary research materials will be deposited with the principal investigator. The data will then be lodged in the University of Adelaide Figshare after the completion of the study. The data and records of the studies will be retained by the University for a minimum of 5 years from the completion of the projects.

Sensitive and confidential information will not be included when storing data on Figshare. Details of participant will be anonymized and identified with a unique code. Your information will only be used as described in this participant information sheet and it will only be disclosed according to the consent provided, except as required by law.

Who do I contact if I have questions about the project?

To contact the participants please see below:
Supervisors: Prof. Jian Zuo (Ph: +61 8 8313 0217; Email: jian.zuo@adelaide.edu.au)
Dr. Ehsan Sharifi (Ph: +61 8 8313 0317; Email: ehsan.sharifi@adelaide.edu.au)
Researcher: Daniel Oteng (Ph: +61 8 8313 4038; Email: daniel.oteng@adelaide.edu.au)

What if I have a complaint or any concerns?

The study has been approved by the Human Research Ethics Committee at the University of Adelaide (approval number H-2020-244). This research project will be conducted according to the NHMRC National Statement on Ethical Conduct in Human Research 2007 (Updated 2018). If you have questions or problems associated with the practical aspects of your participation in the project, or wish to raise a concern or complaint about the project, then you should consult the Principal Investigator. If you wish to speak with an independent person regarding concerns or a complaint, the University's policy on research involving human participants, or your rights as a participant, please contact the Human Research Ethics Committee's Secretariat on:

Phone: +61 8 8313 6028
Email: hrec@adelaide.edu.au
Post: Level 4, Rundle Mall Plaza, 50 Rundle Mall, ADELAIDE SA 5000

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

If I want to participate, what do I do?

To participate in this study, please contact Daniel Oteng by email. A consent form will be emailed to you for signing in which you will return it to the research. An interview time will then be scheduled. Daniel's email: daniel.oteng@adelaide.edu.au

Yours sincerely,
Researcher: Daniel Oteng
Supervisors: Prof. Jian Zuo; Dr. Ehsan Sharifi

Appendix K – Participant information sheet: Fieldwork

PARTICIPANT INFORMATION SHEET

PROJECT TITLE: Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia
HUMAN RESEARCH ETHICS COMMITTEE APPROVAL NUMBER: H-2020-244
PRINCIPAL INVESTIGATOR: Prof. Jian Zuo
STUDENT RESEARCHER: Daniel Oteng
STUDENT'S DEGREE: Doctor of Philosophy
Target Group: Recycling Facilities

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?

There is a rapid growth of the solar photovoltaic (PV) panel installations globally which will keep rising sharply in the coming years. Solar PV systems are commonly chosen to address the need for reducing the greenhouse gas emissions and life cycle energy use of buildings. However, the large exploitation of solar PV could lead to undesirable impacts on the environment in terms of waste disposal. Australia has the highest penetration of solar PV in the residential sector in the developed world. As the normal useful life of the panels is 25 to 30 years, the waste from solar panels will soon become a major issue as they will require disposal in the coming years. This study therefore, seeks to explore the management practices of solar PV waste in addressing a sustainable waste policy in Australia. To achieve the aim of the research, the following objectives are devised:

7. To examine the current practice of dealing with waste from solar photovoltaic panels in the Australian residential sector.
8. To assess the impact of the waste from solar photovoltaic panels in the Australian residential sector.
9. To provide policy suggestions on the management of waste from solar photovoltaic panels in Australia.

Through the interviews and data from previous assessments, a framework will be developed to determine the environmental, economic and health impacts of these practices through life cycle impact analysis. In transitioning towards a sustainable PV policy, the results of this research will inform government and the private sector on the impacts of the current management practices and guidelines will be provided to support decision making towards a sustainable PV waste management in Australia.

Who is undertaking the project?

This project is being conducted by Daniel Oteng. This research will form the basis for the degree of Doctor of Philosophy at the University of Adelaide under the supervision of Prof. Jian Zuo and Dr. Ehsan Sharifi.

Why am I being invited to participate?

You are being invited as you fall within the following group:

- Have a minimum of 2 years work experience
- Recycling facility processing solar PV waste materials.

What am I being invited to do?

You are being invited to take part in an interview. The interviews are being conducted to collect operational data of the recycling facility for life cycle assessment of solar PV waste in Australia. The interviews are designed to collect information such as:

- Capacity data of the recycling facility
- Operational data of the recycling facility
- Emission data on the recycling facility

The interview will be recorded under your approved consent either through Zoom or phone. The recording will then be analysed manually to create a local life cycle inventory data for life cycle assessment. However, the transcript of the interview will be shared with you for any review or corrections before it is finally used for analysis. Because of the issue with Covid-19, the interview will be conducted virtually through Zoom or the phone, however, the researcher may visit the facility for observational input if it is required and if approval is given by the facility manager. Your preference will be taken into consideration.

How much time will my involvement in the project take?

The interview is expected to take 1 hour, in which case will be recorded for transcription. A voluntary follow-up interview may be requested, which you are allowed to refuse or participate. In this case the researcher will contact you using the personal information provided, which again will not be part of the analysis. After the transcription of the interviews, it will be returned to the participants to review and confirm what has been produced. The participants will have one week to review and give their feedback.

Are there any risks associated with participating in this project?

The participants will be made to feel comfortable through the asking of relevant questions related to the research which would have already be sent to them. This is unlikely to cause any harm or discomfort as the selected participants will be experts in this field. The time spent is kept to a minimal, the meeting will be conducted virtually or through the phone because of the restrictions on Covid-19 which will help reduce any potential discomfort. The participants will have the option to withdraw or reschedule the interview should they feel uncomfortable or any discomfort. Therefore, the risks for both researchers and participants will be minimal.

The global pandemic (Covid-19) has caused some fear when it comes to physical contact. The interviews will therefore be conducted through zoom or phone at the appropriate schedule or convenience of the participants, however, the researcher may visit the facility for observational input if it is required and if approval is given by the facility manager. Most importantly, they will have options to reschedule the meetings to their convenient times as well as end the meeting in case of any discomfort. Breaks will be taken throughout the interview to ensure that participants are relaxed and comfortable. With these protocols in place, risks will be minimized and mitigated.

What are the potential benefits of the research project?

The research may not offer any benefit to the participant as it is for academic purposes. However, the research may result in producing guidelines for solar photovoltaic waste policies in Australia. The research will benefit the participants indirectly by contributing to the body of knowledge in the research field as well as give recommendations on policies to government and policy makers which will one way or the other affect their operations. The findings of the research will also be published in conference proceedings and journal publications.

Can I withdraw from the project?

Participation in this project is completely voluntary. If you agree to participate, you can withdraw from the study anytime the participant feels uncomfortable before or during the interview. Withdrawal may not be possible during the analysis of the data which will start around May, 2020.

What will happen to my information?

Digital-data will be processed and stored securely. The information will be stored in an encrypted hard drive which will be stored in the principal investigator's office 4073 Barr Smith South as well as the University of Adelaide database (The data will be accessed via the University of Adelaide PC located on Level 3 of Horace Lamb Building), and will only be accessible to the researchers. All data will be backed up to reduce the risk of losing the data. All backed up data will not be stored on personal drives as the university makes backups of all data.

Non- digital data will be secured and stored in a lockable filing cabinet during the data collection and recruitment phase. The filing cabinet is in a secure and accessible location in the Horace Lamb Building.

A final data management plan will be prepared after completing the research. Before thesis submission, all the original data or primary research materials will be deposited with the principal investigator. The data will then be lodged in the University of Adelaide Figshare after the completion of the study. The data and records of the studies will be retained by the University for a minimum of 5 years from the completion of the projects.

Sensitive and confidential information will not be included when storing data on Figshare. Details of participant will be anonymized and identified with a unique code. Your information will only be used as described in this participant information sheet and it will only be disclosed according to the consent provided, except as required by law.

Who do I contact if I have questions about the project?

To contact the participants please see below:
Supervisors: Prof. Jian Zuo (Ph: +61 8 8313 0217; Email: jian.zuo@adelaide.edu.au)
Dr. Ehsan Sharifi (Ph: +61 8 8313 0317; Email: ehsan.sharifi@adelaide.edu.au)
Researcher: Daniel Oteng (Ph: +61 8 8313 4038; Email: daniel.oteng@adelaide.edu.au)

What if I have a complaint or any concerns?

The study has been approved by the Human Research Ethics Committee at the University of Adelaide (approval number H-2020-244). This research project will be conducted according to the NHMRC National Statement on Ethical Conduct in Human Research 2007 (Updated 2018). If you have questions or problems associated with the practical aspects of your participation in the project, or wish to raise a concern or complaint about the project, then you should consult the Principal Investigator. If you wish to speak with an independent person regarding concerns or a complaint, the University's policy on research involving human participants, or your rights as a participant, please contact the Human Research Ethics Committee's Secretariat on:

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Email: hrec@adelaide.edu.au
Post: Level 4, Rundle Mall Plaza, 50 Rundle Mall, ADELAIDE SA 5000

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

If I want to participate, what do I do?

To participate in this study, please contact Daniel Oteng by email. A consent form will be emailed to you for signing in which you will return it to the research. An interview time will then be scheduled. Daniel's email: daniel.oteng@adelaide.edu.au

Yours sincerely,
Researcher: Daniel Oteng
Supervisors: Prof. Jian Zuo; Dr. Ehsan Sharifi

Appendix L – Protocol for interviews: Government participants

THE UNIVERSITY of ADELAIDE

School of Architecture and Civil Engineering

Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia

HREC Approval Number: H-2020-244

RESEARCH INFORMATION

There is a rapid growth of the solar photovoltaic (PV) panel installations globally which will keep rising sharply in the coming years. Solar PV systems are commonly chosen to address the need for reducing the greenhouse gas emissions and life cycle energy use of buildings. However, the large exploitation of solar PV could lead to undesirable impacts on the environment in terms of waste disposal. Australia has the highest penetration of solar PV in the residential sector in the developed world. As the normal useful life of the panels is 25 to 30 years, the waste from solar panels will soon become a major issue as they will require disposal in the coming years. This study therefore, seeks to explore the management practices of solar PV waste to address sustainable waste policy in Australia. Interviews will be conducted with government, production and recycling industry stakeholders to ascertain the current waste management practices of solar PV systems. An assessment framework will then be developed to determine the environmental, economic and health impact of these practices through life cycle impact analysis. In transitioning towards a sustainable PV policy, the results of this research will inform government and the private sector on the impacts of the current management practices and guidelines will be provided to support decision making towards a sustainable PV waste management in Australia.

RESEARCH OBJECTIVES

The aim of the research is to explore the management practices of solar photovoltaic waste towards a sustainable waste policy in Australia. To achieve the aim of the research, the following objectives are devised:

- *To examine the current practice of dealing with waste from solar photovoltaic panels in the Australian residential sector.*
- *To assess the impact of the waste from solar photovoltaic panels in the Australian residential sector.*
- *To provide policy suggestions on the management of waste from solar photovoltaic panels in Australia.*

FOR FURTHER ENQUIRIES

RESEARCHER

Daniel Oteng

daniel.oteng@adelaide.edu.au

0424277615

SUPERVISORS

Prof. Jian Zuo

Dr. Ehsan Sharifi

CRICOS 00123M

Interview: Towards a sustainable PV waste policy: Exploring the management practices of solar photovoltaic waste in Australia

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Purpose of Interview

The purpose of this interview is to gather information on your perception of the current practices of dealing with waste from solar photovoltaic panels in the Australian residential sector. This interview will inform the researcher on the current management practices of waste from solar photovoltaics in Australia.

Interviewer: *Daniel Oteng*

Duration: *1 hr*

SECTION A

Name: ………………………………………………………………………….

Position: …………………………………………………………………………..

Experience in PV systems: ☐ Less than 2 years ☐ More than 2 years

State: ☐ Victoria ☐ New South Wales ☐ Australia Capital Territory

☐ Queensland ☐ South Australia ☐ Western Australia

☐ Northern Territory ☐ Tasmania

Type of organisation: ☐ Government ☐ Non-governmental Organisations

☐ Waste Consultant ☐ Other, please specify: ________________

Interview: Towards a sustainable PV waste policy: Exploring the management practices of solar photovoltaic waste in Australia

SECTION B

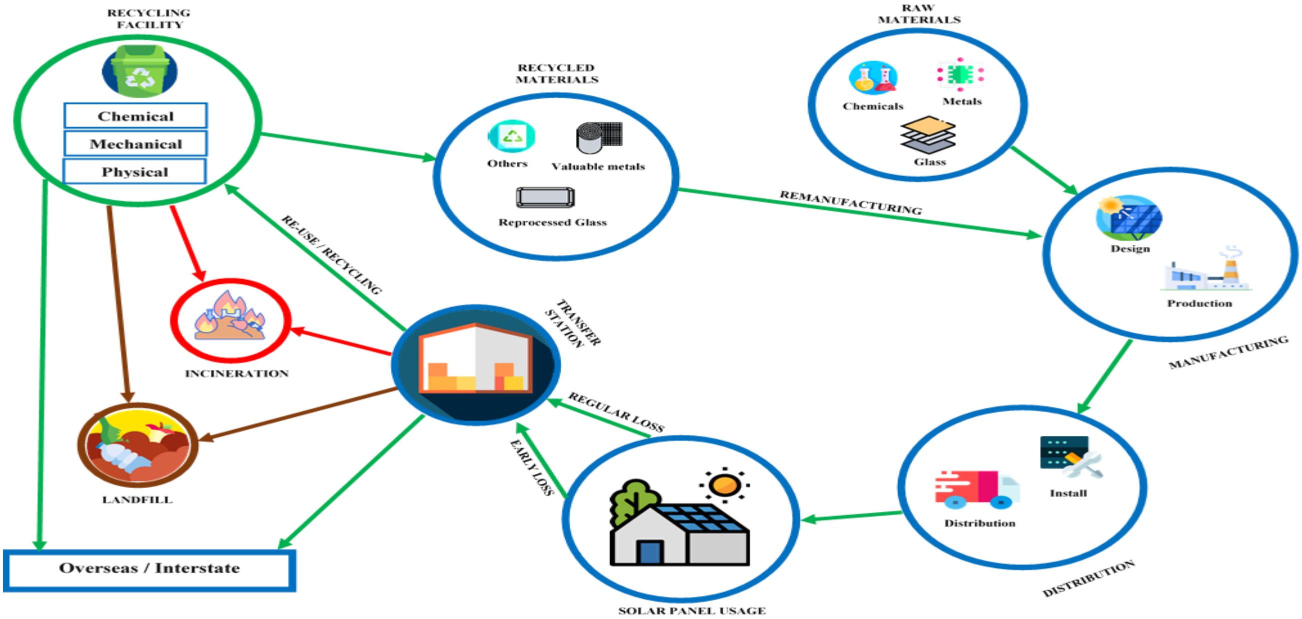

Fig.1: Solar photovoltaic supply chain

1. Are you aware of the popular types of solar panels available in the Australian market, and why?
2. Are you aware of any new technologies on the market and do you think we will continue to have new technologies in the coming years?
3. Are you aware of any policies and regulations (take back system/treatment systems) on solar PV recycling in Australia, what are they?
4. Are the policies effective in terms of subsidies, behavioural attitude towards the policies, ban of panels to landfill? If not, how can it be improved?
5. Are you aware of any tracking and movement (Monitoring system) of PV waste within/out of Australia?
6. Do you think the government is well equipped to handle solar PV waste now? If yes, why do you think that is, if no when do you think that will be?
7. What are some of the initiatives developed by the government to reduce emissions when it comes solar PV waste?
8. What is the government’s role in achieving a comprehensive product stewardship (take-back initiative) for solar PV waste to help reduce its impact on the environment?
9. What are some of the drivers to solar PV waste recycling infrastructure needs?
10. What are some of the barriers to solar PV waste recycling infrastructure needs?

Appendix M – Protocol for interviews: Industry participant

School of Architecture and Civil Engineering

Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia

HREC Approval Number: H-2020-244

RESEARCH INFORMATION

There is a rapid growth of the solar photovoltaic (PV) panel installations globally which will keep rising sharply in the coming years. Solar PV systems are commonly chosen to address the need for reducing the greenhouse gas emissions and life cycle energy use of buildings. However, the large exploitation of solar PV could lead to undesirable impacts on the environment in terms of waste disposal. Australia has the highest penetration of solar PV in the residential sector in the developed world. As the normal useful life of the panels is 25 to 30 years, the waste from solar panels will soon become a major issue as they will require disposal in the coming years. This study therefore, seeks to explore the management practices of solar PV waste to address sustainable waste policy in Australia. Interviews will be conducted with government, production and recycling industry stakeholders to ascertain the current waste management practices of solar PV systems. An assessment framework will then be developed to determine the environmental, economic and health impact of these practices through life cycle impact analysis. In transitioning towards a sustainable PV policy, the results of this research will inform government and the private sector on the impacts of the current management practices and guidelines will be provided to support decision making towards a sustainable PV waste management in Australia.

RESEARCH OBJECTIVES

The aim of the research is to explore the management practices of solar photovoltaic waste towards a sustainable waste policy in Australia. To achieve the aim of the research, the following objectives are devised:

- *To examine the current practice of dealing with waste from solar photovoltaic panels in the Australian residential sector.*
- *To assess the impact of the waste from solar photovoltaic panels in the Australian residential sector.*
- *To provide policy suggestions on the management of waste from solar photovoltaic panels in Australia.*

FOR FURTHER ENQUIRIES

RESEARCHER

Daniel Oteng

daniel.oteng@adelaide.edu.au

0424277615

SUPERVISORS

Prof. Jian Zuo

Dr. Ehsan Sharifi

CRICOS 00123M

Fieldwork: Towards a sustainable PV waste policy: Exploring the management practices of solar photovoltaic waste in Australia

---

Purpose of Interview

The purpose of this interview is to gather information on your perception of the current practices of dealing with waste from solar photovoltaic panels in the Australian residential sector. This interview will inform the researcher on the current management practices of waste from solar photovoltaics in Australia.

Interviewer: *Daniel Oteng*

Duration: *1 hr*

SECTION A

Name: ………………………………………………………………………….

Position: …………………………………………………………………………..

Experience in PV systems: ☐ Less than 2 years ☐ More than 2 years

State: ☐ Victoria ☐ New South Wales ☐ Australia Capital Territory

☐ Queensland ☐ South Australia ☐ Western Australia

☐ Northern Territory ☐ Tasmania

Type of organisation: ☐ Manufacturer ☐ Distributor/installers ☐ Recyclers

☐ Other, please specify: _______________

SECTION B

THE UNIVERSITY *of* ADELAIDE

Fieldwork: Towards a sustainable PV waste policy: Exploring the management practices of solar photovoltaic waste in Australia

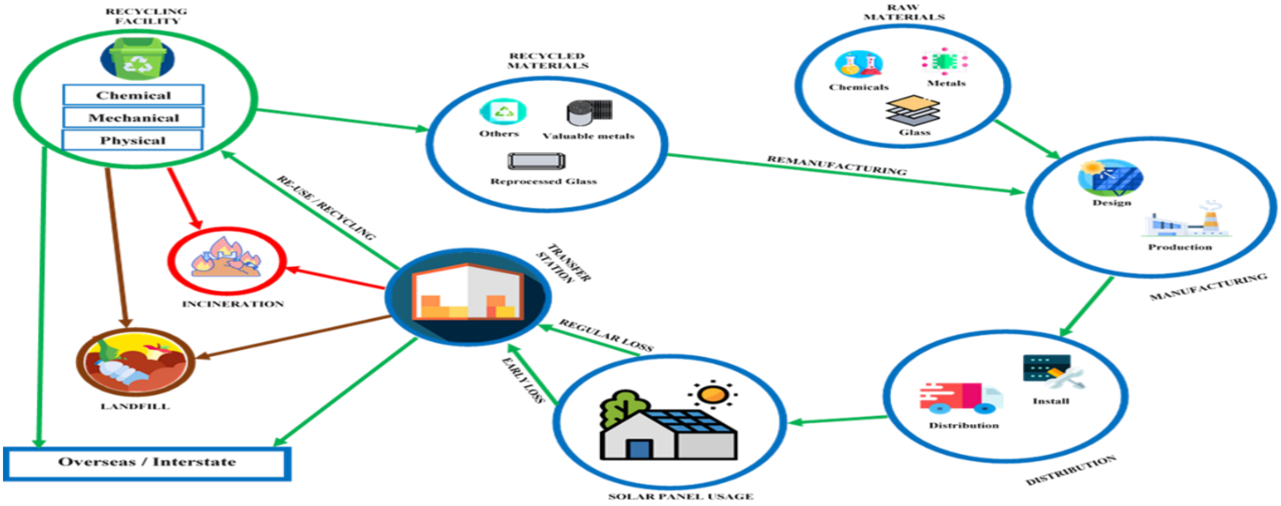

Fig.1: Solar photovoltaic supply chain

1. What are the popular types of solar panels installed on the Australian market, which ones do you do distribute?
2. What are the new technologies on the market and do you think we will continue to have new technologies in the coming years
3. What are the recycling capabilities of the new technologies compared to previous modules?
4. Has your company adopted any take-back systems? if yes, how does the company operate it?
5. Are you aware of any tracking and movement (Monitoring system) of PV waste within/out of Australia?
6. Does the design and manufacturing processes of solar panels have any implications on its recycling capabilities at the end-of-life, how can this be achieved? Can the government help in this aspect?
7. Are you aware of any of these treatment pathways: Landfilling, Recycling, Reuse/Reconditioning, Incineration, Others? If you are aware of any other practices, how do they work?
8. Does your company have its own approach in treating solar PV waste, how is this done? (upstream and downstream supply chain, remanufacturing)
9. Which one of these factors affect your company’s decision to recycle solar panels and why? (Cost benefits/Distance to collection centre/Government Initiatives/Environmental benefits/other reasons).
10. What is the best treatment pathway for Australia when it comes to solar PV waste, and why?

Appendix N – Procedure: Fieldwork

THE UNIVERSITY of ADELAIDE

School of Architecture and Civil Engineering

Towards a Sustainable PV Waste Policy: Exploring the management practices of solar photovoltaic waste in Australia

HREC Approval Number: H-2020-244

RESEARCH INFORMATION

There is a rapid growth of the solar photovoltaic (PV) panel installations globally which will keep rising sharply in the coming years. Solar PV systems are commonly chosen to address the need for reducing the greenhouse gas emissions and life cycle energy use of buildings. However, the large exploitation of solar PV could lead to undesirable impacts on the environment in terms of waste disposal. Australia has the highest penetration of solar PV in the residential sector in the developed world. As the normal useful life of the panels is 25 to 30 years, the waste from solar panels will soon become a major issue as they will require disposal in the coming years. This study therefore, seeks to explore the management practices of solar PV waste to address sustainable waste policy in Australia. Interviews will be conducted with government, production and recycling industry stakeholders to ascertain the current waste management practices of solar PV systems. An assessment framework will then be developed to determine the environmental, economic and health impact of these practices through life cycle impact analysis. In transitioning towards a sustainable PV policy, the results of this research will inform government and the private sector on the impacts of the current management practices and guidelines will be provided to support decision making towards a sustainable PV waste management in Australia.

RESEARCH OBJECTIVES

The aim of the research is to explore the management practices of solar photovoltaic waste towards a sustainable waste policy in Australia. To achieve the aim of the research, the following objectives are devised:

- *To examine the current practice of dealing with waste from solar photovoltaic panels in the Australian residential sector.*
- *To assess the impact of the waste from solar photovoltaic panels in the Australian residential sector.*
- *To provide policy suggestions on the management of waste from solar photovoltaic panels in Australia.*

FOR FURTHER ENQUIRIES

RESEARCHER

Daniel Oteng

daniel.oteng@adelaide.edu.au

0424277615

SUPERVISORS

Prof. Jian Zuo

Dr. Ehsan Sharifi

CRICOS 00123M

Interview: Towards a sustainable PV waste policy: Exploring the management practices of solar photovoltaic waste in Australia

---

Purpose of Fieldwork

The purpose of this fieldwork is to gather information on the recycling processes of this facility as an input and output data (life cycle inventory) for life cycle impact assessment of solar PV waste recycling in Australia. This fieldwork will provide the researcher with primary inventory data for PV waste recycling in Australia to aid in accessing the current management practices of waste from solar photovoltaics in Australia.

Interviewer: *Daniel Oteng*

Duration: *1 hr*

SECTION A

Recycling Facility: ………………………………………………………………………………

Location:

………………………………………………………………………………..

Years in Operation: ……………………………………………………………………………...

State: ☐ Victoria ☐ New South Wales ☐ Australia Capital Territory

☐ Queensland ☐ South Australia ☐ Western Australia

☐ Northern Territory ☐ Tasmania

Interview: Towards a sustainable PV waste policy: Exploring the management practices of solar photovoltaic waste in Australia

SECTION B

11. Types of solar PV panels that are processed in the facility.
12. Source (where the solar panels are collected for processing) of PV waste for recycling (transfer stations, bins, collection points).
13. Amount of PV waste received monthly/annually.
14. Type of transportation for delivering PV waste to the facility (By road, rail, flight).
15. Capacity of recycling plant (ton/year).
16. Annual electricity consumption for the PV waste processing and the type of energy used.
17. Cost of running the plant annually (A$) in relation to employees, equipment usage, electricity and whether there are any subsidies from the government.
18. Type of technology used in recycling the PV waste (such as mechanical/chemical treatment or automatic/physical separation).
19. Description of the operation (process flow) of the plant and inputs (Product/Technosphere) to the processes.

    (Electricity, Water Fuel (Diesel), Chemicals)
20. What kind of emission are released during the operation of the recycling plant (tonnes)?

    (Emissions to air, Waste to landfill, Energy recovery)
21. What valuable materials are salvaged after the recycling process (output)?

    (Glass, Solar-grade Silicon, Aluminium, Copper, Tin, Silver, Lead)
22. Market for the new recycled products (overseas, interstate, within state).
23. Can the recycled materials be used for remanufacturing (upstream) and/or does the facility practice upcycling of the solar PV waste?