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Anthony Halog, Lauren Mcgavin

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Policy design for solar waste management in a decarbonised, circular economy: a systematic review

Anthony HALOG

School of the Environment, The University of Queensland
a.halog@uq.edu.au

Lauren MCGAVIN

School of the Environment, The University of Queensland
l.mcgavin@uq.net.au



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Policy Design for Solar Waste Management in a Decarbonised, Circular Economy: A Systematic Review

Abstract

The most significant barriers to solar panel recycling at present are lack of incentives and regulations, transportation costs, extraction costs, purity of extracted materials, fossil fuel use, environmental impacts of recycling processes, lack of stakeholder engagement and a lack of available data regarding solar panel recycling facilities. Whilst several studies suggest that recycling end-of-life (EoL) solar panels may not offer sufficient profitability yet, there is a strong consensus that recycling does mitigate social and environmental harm and is an inevitable requirement in the transition to a sustainable and decarbonised circular economy (CE). However, upscaling solar technologies to meet global renewable energy demand will necessitate government interventions to promote R&D of improved recycling processes and stakeholder participation.

This systematic review explores how life cycle assessment (LCA) and systems thinking method (STM), integrating insights from environmental science, engineering, economics, and policy studies, can be used for policy design for solar panel waste management (SPWM). LCA effectively identifies environmental impacts and hotspots within various SPWM scenarios and can aid in decision-making processes. Through LCA the need for mandatory recycling recovery rates, landfill bans and renewable energy use in recycling scenarios have been identified. STMs focus on complex, dynamic, non-linear systems and emphasise the requirement of effective stakeholder engagement. A hybrid LCA and STM approach combined with principles of sustainable development (SD) and CE can offer comprehensive insight to decision-makers when designing SPWM policies. These policies can facilitate the recirculation of valuable resources, stimulate new jobs, and minimise harm to human and environmental health.

Keywords: Policy Design, Renewable Energy, Environment, Systems Thinking, Life Cycle Assessment, Waste Management, Solar Panels, Circular Economy, Sustainable Development

Introduction

Australia is renowned for having the highest per-capita solar power uptake in the world, with around 1 in 3 houses having solar panel systems installed, the equivalent of 3.52 million installations across the country [1-2]. Australia's reported installed solar capacity in January 2023 (30,511,489kW) had increased by nearly 200% compared to capacity levels in January 2003 (4,689kW) [1]. Whilst Australia has embraced solar technology in its bid to decarbonise, an emerging issue that raises pressing concerns about health and environmental impacts. Thus far in the clean energy transition, little attention has been directed towards the managing these technologies once they decline in efficiency and approach the end of their operational life cycles. In order to transition to a decarbonised CE, Australia and other countries must ensure energy generation is clean and sustainable, and that waste is managed responsibly with environmental, social, and economic impacts taken into consideration.

Whilst solar panels have contributed to reducing dependency on GHGs, a unique challenge arises in managing this complex and valuable technology at its EoL. The average life span of solar panels manufactured today in Australia is 25-35 years; for older models manufactured in the early 2000s, lifespan may only extend to approximately 20 years [3-5]. Most solar panels are still entirely functional when decommissioned. Upon approaching their EoL, solar panels are generally still operating at just under 80% of their original capacity but are decommissioned as solar panel manufacturers classify solar systems as EoL and waste where the maximum power loss is higher than 20% [4,6]. The exponential growth of the industry has seen a mounting challenge in the case of SPWM. Solar waste has begun accumulating in landfills as the first generation of solar panels installed during the early 2000s solar boom is being retired. With the industry only projected to grow, forecasts show that Australian solar power waste (SPW) could amount to 145,000 tonnes in 2030 and 450,000 tonnes in 2040 [7-8]. This issue is of paramount importance due to the critical environmental, economic, and social challenges SPWM presents. There is a strong imperative to devise SPWM policies and address the paradox whereby solar panels benefit the environment and reduce GHG emissions during their operation life, end up discarded in landfills upon retirement. In these landfills, critical minerals and other valuable materials are squandered and laid to waste, giving rise to new environmental issues such as heavy metal leaching. Current estimations indicate that as much as 96% of the materials used in solar panels have the potential to be recycled [7, 9].

Due to the relatively recent emergence of this issue, research has only started to gain traction within the last five years, with minimal academic literature available prior to 2018. Solar energy adoption has been extensively discussed in numerous government documents such as low emissions technology statement (LETs 21), yet acknowledgement of EoL management has been disproportionately minimal. These recent surges in solar adoption underscore the need for urgent action and emphasise that policy intervention will be required to redirect solar panels from landfills and ensure these valuable technologies are recycled.

Research Question & Objectives

This systematic review seeks to answer the following research question:

How are life cycle assessment (LCA) and systems thinking methods (STM) being utilized to improve solar panel waste management processes?

The objective of this review is to identify how LCA & STM have been utilised in previously published studies, the major barriers inherent in SPWM and discern potential policy imperatives for effective management.

LCA & Systems Thinking Methods

This paper seeks to build upon the foundations and concepts of sustainable development (SD) and circular economy (CE) presented in existing literature through integrating LCA and STM tools and applying them to the research question. These tools have been used separately and in combination with other evaluation tools throughout literature; however, the utilisation of an integrated approach when discussing SPWM has not been previously explored. Using LCA and STM in a hybrid approach will serve to improve the accuracy and reliability of any findings, as LCA can help to mitigate and address the limitations of STM and vice versa.

LCA and STM are established tools that have been utilised in various different areas of environmental studies and provide several compelling advantages [10]. Both of these tools facilitate comprehensive analysis and holistic evaluation of the social, environmental, and economic impacts a product can pose throughout its entire life cycle, including product design, manufacturing, installation, use and EoL disposal. Due to the long operational lives of solar panels, waste management is a long-term issue. LCA and STM are beneficial in this aspect as they encourage policymakers to consider the long-term effects of current SPWM decisions and design policies that account for the extended lifespans of these technologies. Changes to current SPWM process will require the involvement of multiple stakeholders, processes, and technologies.

Consequently, there should be a requirement from policymakers to ensure that there are guidelines, standards, incentives, and consequences in place to govern SPWM effectively. STM can assist researchers and policymakers to understand the interdependence and connectiveness of the complex variables impacting SPWM and seek solutions. STM also promotes adaptable policies that can evolve with changing circumstances, technologies, and future generations of policy. SPWM requires collaborations and insights from a large variety of disciplines and stakeholders, underpinning the importance of a holistic, systems thinking approach when moving away from the linear economy model.

Both LCA and STM facilitate the principles of sustainable development in policy design and decision-making by prioritising the well-being of the environment, economy, and communities through complex issue analysis, consideration of long-term impacts, promoting of adaptable policies, interdisciplinary insights, stakeholder engagement and data-backed decision-making.

Utilising these particular approaches will facilitate the identification of the factors impeding improved SPWM processes and explore policy incentives capable of delivering effective and sustainable solutions that advance the transition to a CE.

Literature Review Organisation

Drawing from disciplines including environmental science, engineering, and public policy, this review seeks to explore the challenges surrounding SPWM in Australia and illuminate the importance of this issue with respect to Australia's global commitment to reduce emissions to 43% below 2005 levels by 2030 and achieve net-zero emissions by 2050. Sustainable development and circular economy principles will be briefly discussed, followed by an overview of current SPWM in Australia, the application of LCA and STM to SPWM and how they can be integrated to inform decision-making processes will then be evaluated. The implications of these strategies on policy will be detailed and deconstructed to determine what policy measures are required to ensure Australia is not only generating clean and renewable energy but also conducting responsible waste management practices to reduce environmental harm. Following this, recommendations and avenues for future research will be proposed before presenting the final conclusions.

Methodology

A systematic review was conducted to analyse existing literature, summarise this knowledge and identify research gaps whilst also examining the approaches that have been successful and effective in the research area of solar panel end-of-life management. A thorough scoping review was performed to determine keywords and phrases and assess the suitability of the available and current literature pertaining to the research question.

Inclusion/Exclusion Criteria

When examining how LCA or STM techniques had been utilised in end-of-life management of SPW, studies had to meet the following eligibility criteria:

1. Published within the last five years (2019-2023)
2. Journal article or review paper only
3. Published in English.
4. Peer-reviewed

Whilst most of the documents on the Web of Science database are peer-reviewed, Web of Science does not enable you to filter by peer-review status; hence, if any articles were found that had not been peer-reviewed, they were excluded.

Information Sources

Electronic searches within the Scopus and Web of Science (WoS) databases were conducted to find eligible studies. These databases were selected for use due to their focus in the field of science, their enormous collection of rigorously vetted, peer-reviewed journals and the availability of analytical tools.

Search Strategy

An initial scoping search within 'Article title, Abstract, Keywords' or 'Topic' was performed for the words ("solar panel*" AND waste) in both Scopus and WoS, 622 and 371 results were returned for each database, respectively. From this search it was found that there were many alternative keywords being used to describe solar panels and waste that may be limiting results. The following search: ((e-waste OR waste* OR landfill* OR dispos* OR recycl* OR "end-of-life") AND ("Solar panel*" OR "solar technolog*" OR photovoltaic*)) in Scopus and WoS using all identified alternative keywords returned 6,204 documents and 4,189 documents for each respective database. Proximity operators were then utilised in the above search query to further refine the search; ((e-waste OR waste* OR landfill* OR dispos* OR recycl* OR "end-of-life" OR retir*) NEAR/8 ("Solar panel*" OR "solar technolog*" OR photovoltaic*)) 1,514 results were returned in Scopus, and 1,174 were returned in WoS. The following scoping search of LCA literature ("life cycle assess*" OR "life cycle analys*" OR "life cycle sustain*" OR "life cycle impact*") returned 48,589 results in Scopus and 43,525 results in WoS. A scoping search of STM literature using the query: ("system thinking" OR "system dynamic*" OR "system method*" OR "systems thinking" OR "systems dynamic*" OR "systems method*") returned 94,857 results in Scopus and 58,409 results in WoS. The proximity search for keywords pertaining to solar panels and waste was then combined using advanced search features with the scoping queries pertaining to LCA and STM which returned a total of 132 documents in Scopus and 125 in WoS. A final result of 257 documents were identified across both of the databases. Searches were going to initially be limited to studies discussing Australia, however the addition of the search; (*Australia* OR Queensland* OR "South-East Queensland" OR Tasmania* OR Victoria* OR "Western Australia*" OR "South Australia*" OR "New South Wales" OR "Australian Capital Territor*" OR "Northern Territor*" OR Pacific*) to the above advanced search query saw 7 results returned in Scopus and 4 results from WoS. Table 1 below summarises the search queries used in the databases and the number of results returned.

Table 1 – Boolean Operator Keyword search summaries

Search Query	Number of Results in Scopus	Number of Results in WoS
“solar panel*” AND waste	622	371
((e-waste OR waste* OR landfill* OR dispos* OR recycl* OR "end-of-life") AND ("Solar panel*" OR "solar technolog*" OR photovoltaic*))	6,204	4,189
((e-waste OR waste* OR landfill* OR dispos* OR recycl* OR "end-of-life" OR retir*) NEAR/8 ("Solar panel*" OR "solar technolog*" OR photovoltaic*))	1,514	1,174
("life cycle assess*" OR "life cycle analys*" OR "life cycle sustain*" OR "life cycle impact*")	48,589	43,525
("system thinking" OR "system dynamic*" OR "systemmethod*" OR "systems thinking" OR "systems dynamic*" OR "systems method*")	94,857	58,409
((e-waste OR waste* OR landfill* OR dispos* OR recycl* OR "end-of-life" OR retir*) NEAR/8 ("Solar panel*" OR "solar technolog*" OR photovoltaic*)) AND ("life cycle assess*" OR "life cycle analys*" OR "life cycle sustain*" OR "life cycle impact*") AND ("system thinking" OR "system dynamic*" OR "system method*" OR "systems thinking" OR "systems dynamic*" OR "systems method*")	132	125
((e-waste OR waste* OR landfill* OR dispos* OR recycl* OR "end-of-life" OR retir*) NEAR/8 ("Solar panel*" OR "solar technolog*" OR photovoltaic*)) AND ("life cycle assess*" OR "life cycle analys*" OR "life cycle sustain*" OR "life cycle impact*") AND ("system thinking" OR "system dynamic*" OR "system method*" OR "systems thinking" OR "systems dynamic*" OR "systems method*") AND (*Australia* OR Queensland* OR "South-East Queensland" OR Tasmania* OR Victoria* OR "Western Australia*" OR "South Australia*" OR "New South Wales" OR "Australian Capital Territor*" OR "Northern Territor*" OR Pacific*)	7	4

Further methodologies recommended under the PRISMA 2020 framework, including data items and study risks of bias assessments were not performed due to their limited relevance to the review and/or time constraints.

Results

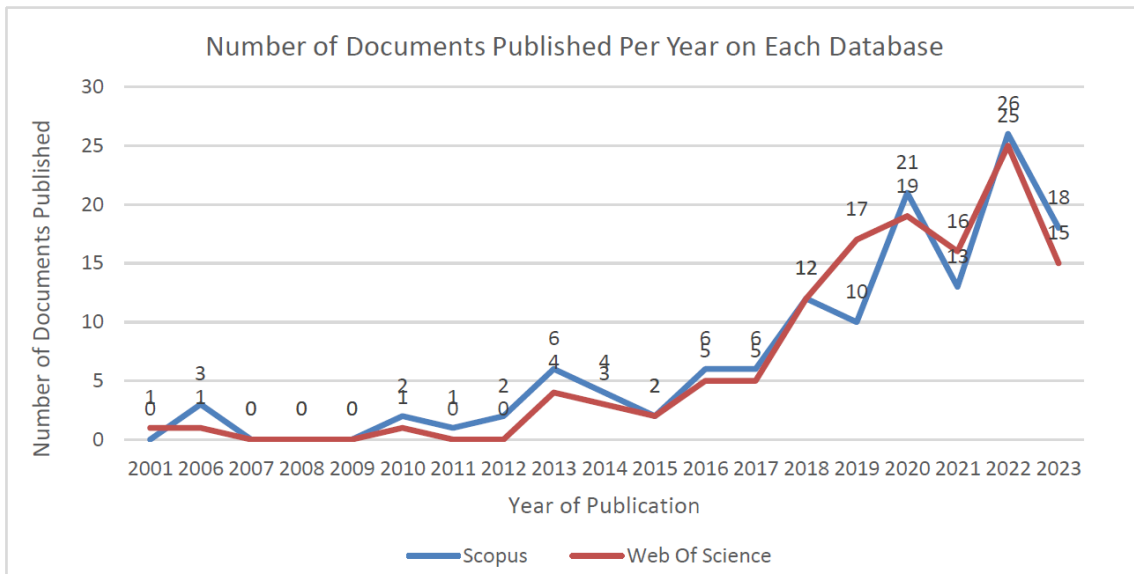
Study Selection

Of the 257 documents retrieved, 132 were found through Scopus and 125 through WoS. All 257 documents were uploaded into the Covidence systematic review software for screening. Prior to screening 99 records were removed due to being duplicates. The titles, authors, and abstracts of 158 articles were then screened from which 80 records were excluded and 78 records were sought for retrieval. 77 full texts were retrieved and independently screened and assessed for eligibility. A total of 42 studies obtained from databases were included in the review. The documents were exclusively reviewed, and notes were recorded in an Excel worksheet that summarised the keywords, main findings, relevant quotations, limitations, and suggestions of the papers.

Analysis of Results

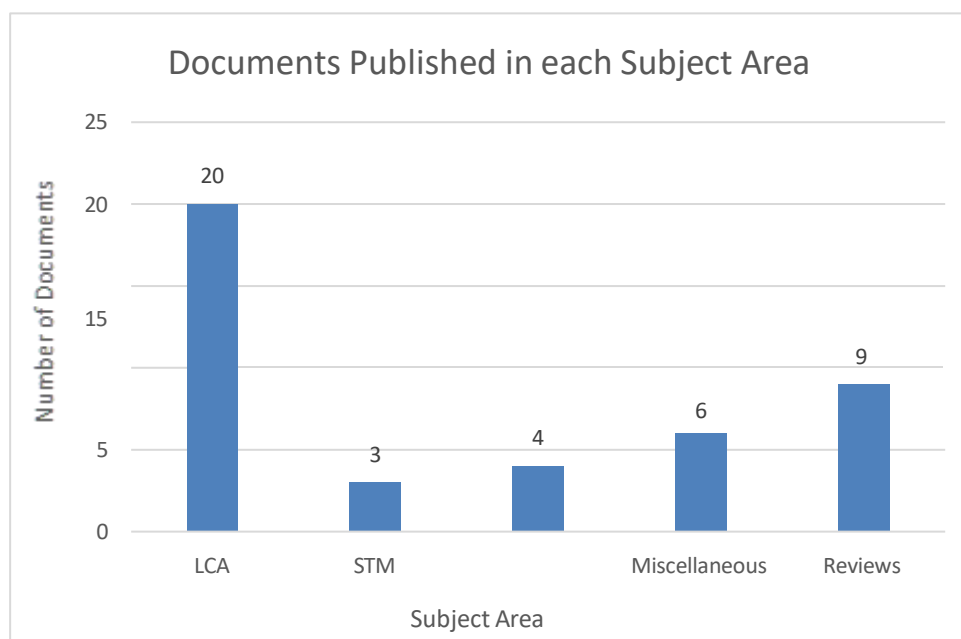
The documents were reviewed by looking at the number of documents published per year, the main subject areas and the number of documents published per year within each subject area. The number of documents published each year is shown in Figure 1 below which highlights the novelty of this subject area with the first document in 2001 being a conference proceeding that briefly mentions photovoltaic systems as a case study for using LCA and Geographic Information Systems (GIS) as decision support systems [11]. Figure 1 highlights how research regarding solar photovoltaic waste has only demonstrated marked growth in the last five years. From 2001-2018, 78 documents were published across both databases, this figure has more than doubled to 180 documents published across the databases during the five-year period between 2019-2023. The dramatic increase in publications within the last five years can be attributed to the recent identification of SPWM as an emerging issue.

Figure 1: Number of documents published per year from 2001-2023 in the Scopus and Web of Science Databases



The highest number of publications employed LCA in empirical studies of SPWM, with 20 documents utilising the methodology. A higher number of publications focused on principles of CE pertaining to SPWM than STM, with four and three studies published in each area, respectively. Six studies were classed as miscellaneous for employing methods other than LCA or STM to approach the SPWM challenge. Of the 42 publications sought for extraction, nine studies were reviews that received recycling methodologies or challenges or management approaches.

Figure 2: Number of documents published in each subject area.



Importance of a Transition to a Decarbonised, Circular Economy

Growing concerns about the rising levels of solar panel waste (SPW) in landfills and alarming projections of future waste generation, driven by the global interest in green hydrogen production, have highlighted the negative social, environmental, and economic consequences of SPW mismanagement. In response, experts are advocating for the adoption of sustainable development (SD) and circular economy (CE) principles to mitigate these adverse impacts.

Sustainable Development & Circular Economy Concepts

The concept of sustainable development (SD) has garnered significant attention in recent years at a global scale as the world recognises the urgent and drastic measures required to confront the most significant and formidable challenge humans has ever faced, the climate crisis. SD is a conceptual framework rather than a single, rigidly defined principle. It is dynamic and encompasses a collection of goals, principles and values that can guide policymakers whilst facilitating concepts to adapt and evolve over time to address changing circumstances and new challenges. SD, as a broad concept, involves integrated considerations of social, economic, and environmental impacts in relation to development requirements. Additionally, there is a strong focus on promoting stakeholder participation and emphasising intra-generational equity to ensure that present-day actions and needs do not jeopardise future generation's ability to fulfil their respective needs.

CE synergistically complements SD principles as a decarbonised, CE prioritises the reduction of GHGs and waste minimisation. This is achieved through the adoption of renewable energy sources and comprehensive evaluations of a product's full life cycle, all with the aim of closing the loop on resource use through efficient and effective resource management, and responsible consumption practices. At all levels, local, national, and global, a paradigm shift away from linear economies is required. The life and value of resources must be extended and fully utilised through recycling, reusing, and recovering materials. Whilst recycling is reserved as the final option for products under CE principles, currently, implementation of reuse, repair, and refurbishment for SPW is more limited than recycling as a solution to SPWM due to a lack of economic feasibility and solar panel design flaws [12]. For Australia, CE will help address critical environmental challenges such as land clearing, resource consumption, pollution, and climate change whilst also creating new social and economic opportunities and fostering innovation.

The Role of Sustainable Practices and Waste Management in Achieving the CE Transition

Currently, EoL solar panels primarily end up in landfill due to economic feasibility and waste stream constraints, which limit demand for recycling options. Whilst market demand for these recovered materials is undeniably important in recycling solar panels, it should not be the primary factor guiding SPWM principles. In alignment with the principles of SD and CE, equal attention should be devoted to prioritising SPWM decisions as a means to mitigate the harm and hazards that arise as a result of not recycling these products. This review aims to identify SD and CE principles that can be utilised in policy design to provide a balanced evaluation of environmental and socio-economic impacts rather than focusing solely on the economic impacts of SPWM strategies. This will aid CE transitions through promotion of a more sustainable

and circular system that minimises resource consumption and waste production by prioritising principles of reducing, reusing, and recycling.

Overview of the Current State of SPWM in Australia

Solar panels accounted for 14% of Australia’s total energy generation in 2022, equating to 12,349 gigawatt hours (GWh) of power [13]. Given the Government’s commitment to increase renewable energy production including the growing interest in green hydrogen and reduce GHGs through solar technologies, solar panel usage will continue to increase exponentially for the near future, creating a looming waste management crisis. The Australian Government’s Second LETS 21 pitch highlights ultra-low-cost solar as a priority technology for decarbonisation efforts [14]. Yet, in the most recent white paper from the Australian Government’s Australian Renewable Energy Agency, discussing the ultra-low-cost solar rollout, just over 100 words were dedicated to discussing end-of-life management of solar panels. The report acknowledges that it is an emerging issue; however, no clear methods or policy interventions for managing solar waste were mentioned or discussed [15]. Solar panels have been on the Government’s product stewardship priority list for over six years with increasing calls for manufacturers to claim some of the responsibility and economic impacts of recycling the technology [16]. Two suggested actions for the management of photovoltaic waste were supposed to have been achieved by June 2022 and June 2023, respectively and yet limited progress has been achieved to date. The expected actions included:

- “An industry agreed, nationwide scheme design by June 2022 (Limited progress achieved to date)” [17]
- “An operational scheme including an approach to deal with legacy panels by June 2023 (Limited progress achieved to date)” [17]

At present, the Australian Government does not have any formal national legislation or regulatory frameworks that exclusively guide SPWM procedures [3, 18]. There are some guidelines in place that discuss the management of solar panels as electronic waste (e-waste), such as in the states of Victoria and South Australia where e-waste can no longer be dumped at landfills. However, there is still a notable absence of policy in these states to guide comprehensive and sustainable management of SPW [16]. In Victoria, solar panels were banned from entering landfills effective 1 July 2019, with the state Government investing \$16.5 million to upgrade e-waste storage and collection facilities where the technologies must now be deposited at the end of their operational life [5].

In terms of international progress, Australia is lagging behind compared to other countries such as member states of the European Union (EU) where the Waste Electrical and Electronic Equipment (WEEE) Directive legislated in 2012 that solar photovoltaic manufacturers are responsible for the disposal and recycling of the solar modules they sell as a part of their mandatory extended producer responsibility (MEPR) scheme [19]. These regions have clear rules for the disposal or recycling of solar panels with recycling incentives to promote the recovery of valuable materials and reuse of these materials in new panels. One of the recycling frameworks that has emerged in response to the WEEE Directive is the Full Recycling EoL Procedure (FRELP), a standardised recycling procedure produced by the EU for SPWM. FRELP outlines a clear

framework for producers on the collection, transport, sorting, dismantling, treatment, and treatment of SPW under the MEPR scheme as well as their legal liabilities and compliance requirements [9].

The Australian Government announced a new ‘Ministerial Advisory Group on the Circular Economy’ in late 2022 that has been established to aid Australia in transitioning to a CE by 2030. This group will seek to design out waste at the manufacturing stage and improve resource recovery in collaboration with state Governments and industry stakeholders [20]. This is important in the context of SPWM as many of the issues associated with solar panels have arisen due to a lack of consideration for potential disassembly and recycling during the design and manufacturing stages.

Social, Environmental and Economic Impacts of SPW in Australia

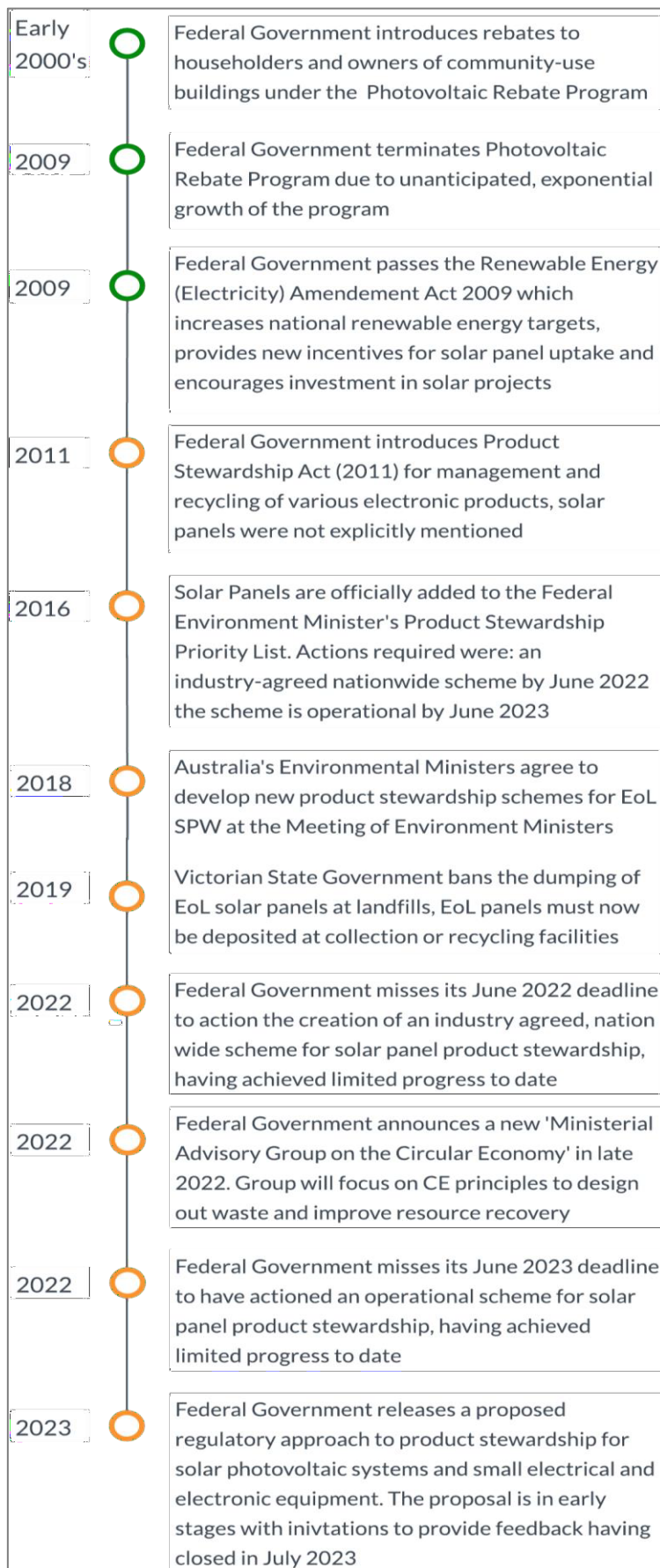
Victorian landfill bans were prompted by the growing concerns over escalating waste and the potential for hazardous substances to leach into soil and groundwater supplies posing harm to both human and environmental health whilst also contributing to high externality costs [12, 21-22]. These dangerous contaminants, such as cadmium, lead and nickel can also be emitted into the air if SPW is subjected to incineration, compounding the social and environmental health risks associated with improper solar waste disposal methods [18,22]. The materials found within solar panels should be recovered for utilisation in new products or incorporated into the production of subsequent generations of solar panels. This approach would help to mitigate resource depletion, land-use change and degradation, and other environmental challenges that arise from the mining of these raw materials [22].

Whilst Australia has made some progress in adopting SD and CE principles, they have often demonstrated a lack of ambition and even lobbied against efforts to reduce GHG emissions and acknowledge the impacts of climate change that are necessitating the transition to a decarbonised CE. Yet, from an economic perspective, Australia stands to incur significant losses due to the potential threats posed by climate change to its natural assets. Changes to the climate will threaten Australia’s prominent agricultural industry, disrupt water resources, increase the frequency and severity of extreme weather events such as bushfires, droughts, heatwaves, and floods, and devalue its tourism industry [23].

Figure 3 below depicts the Australian Governments’ historical actions regarding solar panel adoption incentives and waste management actions.

Figure 3: Chronology of the Australian Government’s Policies and Actions surrounding solar panel uptake and EoL waste management.

Solar panel uptake policies/actions are represented by green bullet points, whilst solar panel waste management policies/actions are represented by orange bullet points.



Whilst there are impacts associated with the recycling of SPW, numerous studies have demonstrated that the benefits outweigh the disadvantages [24-27]. Recycling solar panels is a superior solution that aligns with Australia's SD and CE commitments and mitigates EoL solar panel impacts, making it an environmentally friendlier option compared to dumping the panels in landfill.

Utilisation of LCA in SPWM

LCA Background and Methodology

Life cycle assessments are a crucial component of SD and CE as they can facilitate the quantification of resource consumption, waste production, and environmental impact, as well as the economic costs of a project throughout the product's entire life cycle, from cradle-to-grave. There are generally five given stages in a product's life cycle:

1. Product design
2. Resource extraction
3. Manufacture
4. Product used/consumed
5. Product disposed/recycled/reused

These life stages all have various impacts, however, much of a product's environmental impact is locked in at the design phase. Hence, LCAs can help promote optimisation and reduce harm through evaluation and quantification of material flow, energy use, and consideration of a product's fate at the end of its life [28]. LCAs can be used to assist in adhering to regulations, developing sustainable products, addressing consumer demand for sustainability, as well as optimising supply chain management and minimising costs. LCAs promote consumer responsibility and prevent the outsourcing of emissions to nations with more lenient regulations or lower climate action commitments [29]. LCAs are used across a variety of industries due to their adaptability as a tool and cross-disciplinary applications that allow for broad comparisons and questions to be considered. They are also effective in preventing the negating of responsibility from one stage in a product's life cycle to another or rectifying one environmental impact whilst simultaneously creating another [30].

Due to the versatility of LCAs and their ability to be utilised across a variety of disciplines and industries, LCAs are subject to the International Organisation for Standardisation (ISO). Based on the outlined ISO guidelines, there are four clearly defined stages within a LCA [31]:

1. Determining goal and scope of the LCA
2. Inventory analysis phase
3. Impact assessment phase
4. Interpretation phase

LCA methodologies have undergone intense improvement in recent years. These advancements have emerged due to the recognition of problems with older life cycle assessment (LCA) methodologies and the introduction of new innovations [30]. Initially, LCAs focused purely on the environmental impacts of products, as traditionally, the environment was excluded from consideration. Now some LCA methods can also consider social and economic impacts in line with the three pillars of sustainable development [30].

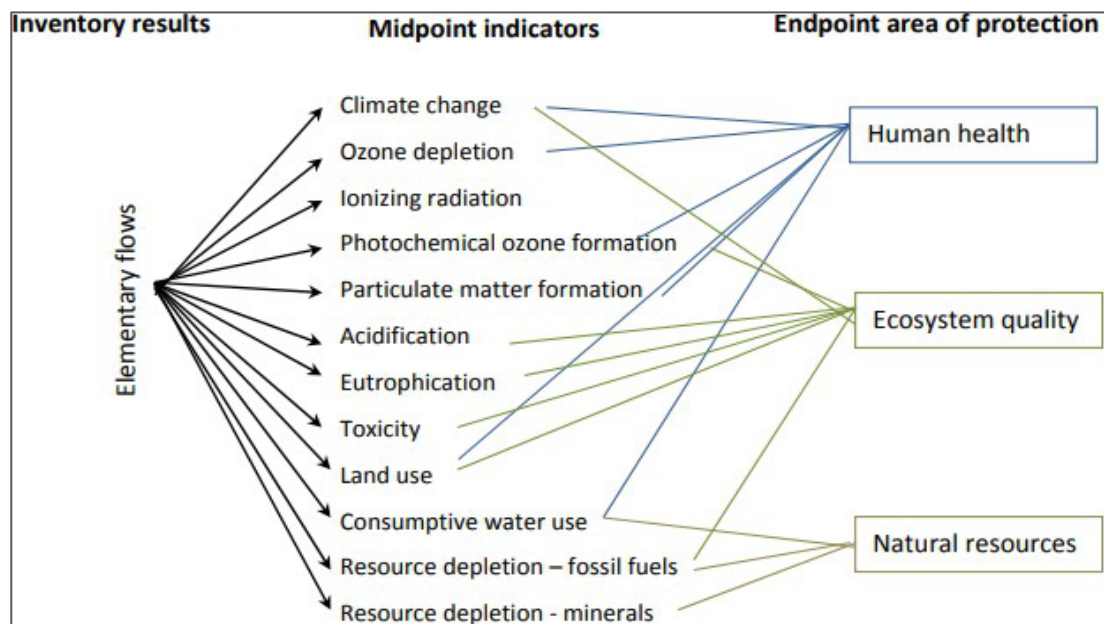
The establishment of the ISO's standards for LCA in the late 1990s provided a framework for LCA's that improved the reliability and credibility of results and facilitated their incorporation into decision-making processes. LCA has exhibited a resurgence as concerns surrounding the environment and climate crisis call for evaluations of environmental impacts, further compounded by calls for the adoption of SD and CE principles. LCA has risen from obscurity to become a mainstream tool that governments and industries alike can employ to evaluate impacts across various diverse applications, such as individual products, entire supply chains, or even waste management policies. Whilst LCA is a robust and comprehensive tool, it can still be used in combination with other methodologies such as Multi-Criteria Decision Analysis and STM to aid policymakers in assessing and interpreting the environmental and economic impacts of SPWM [32].

Previous Studies Using LCA

The literature on SPWM employs a variety of LCA methodologies, including traditional LCA, anticipatory LCA, simplified LCA, Life Cycle Costing and more. Through evaluation of this literature, no single methodology was identified as being more effective in addressing the topic of SPWM in Australia. Instead, each methodology was utilised due to the unique results and analysis that it could provide to inform research and policy design in the context of SPWM.

There are a number of frequently used key mid-point impact categories, or 'indicators' used in stage three of LCA's to assess the environmental and economic impacts of SPWM scenarios. The Australian Life Cycle Assessment Society (ALCAS) recognises 12 midpoint indicators which all have an effect on one or more of the three endpoint indicators. Figure 4 below shows the mid and endpoint indicators as outlined by ALCAS.

Figure 4: ALCAS Mid and endpoint impact indicators. Image source: [33]



SPWM scenarios can have associated impacts across all mid-point impact categories and hence many studies evaluate impacts across all categories. However, the most relevant SPWM indicators are climate change, eutrophication, resource depletion – minerals, and toxicity [20, 34]. The ‘climate change’ impact category quantifies anthropogenic effects on the climate through the release of GHG emissions. Most LCA’s solely consider GHGs effect on climate without accounting for factors such as reduced albedo or production of soot [50]. The climate change indicator can impact both human and ecosystem endpoint indicators. The ‘Eutrophication’ impact category refers to the impacts of escaped macronutrients on aquatic and terrestrial ecosystem health, impacting the ecosystem quality endpoint indicator. The ‘resource depletion – minerals’ (RD-M) impact category describes the extraction of minerals resulting in the depletion of reserves impacting the natural resources endpoint indicator. The ‘toxicity’ impact category refers to both human and ecotoxicity, characterising the effects of chemicals on human health and the environment at varying levels of organisation; hence, toxicity can affect both human health and ecosystem quality endpoint indicators. These impact categories are the most frequently cited and generally exhibit the largest impact reduction in LCA scenarios due to impacts associated with energy use from fossil fuel powered energy-intensive processes, chemical usage, long travel distances and externality costs of mineral use. The most commonly applied impact assessment methodology in literature was the ReCiPe method; however, in the context of Australian SPWM, the ALCAS recommends CML methodology as best practice for a number of impact categories, including eutrophication and RD-M [33].

When using LCA to evaluate midpoint impacts, most studies looked at one or both of the following recycling methods; laminated glass recycling facilities (LGRF) or FRELP. In cases where the LGRF approach is used, only glass, aluminium and copper are recovered for reuse, with all other materials being disposed of. Whilst LGRF has some advantages such as the ability to utilise existing glass recycling facilities, eliminating the need for dedicated solar panel recycling plants, the most valuable materials found within the solar cells are not recovered from this process [35]. Under EU directives, FRELP was developed to meet resource

recovery targets and seeks to achieve maximum resource recovery rates. Due to the numerous chemical and mechanical processes, the methodology is energy-intensive, necessitating dedicated recycling plants to accommodate the energy-intensive procedures and specialised processes required for material separation.

Most studies using LCA methodologies to evaluate SPWM aim to assess the feasibility of secondary resource recovery and identify hotspots within the recycling process where impacts and burdens could further be reduced. Ansanelli et al. (22) conducted an LCA for the materials recovery process for a solar panel plant in Italy and identified heat treatment to be the most impacting phase relative to the selected midpoint indicators. Abatement systems and other infrastructures were the next most impacting phase, having an impact on all 10 of the midpoint indicators selected for analysis. Transport was also identified as a sensitive input and a factor impacting the environmental sustainability of the recycling process when using national distance averages; numerous other studies have identified and reported transportation as having a notable impact [6,22]. Oteng et al. (3) reports that using averages or assumptions for transport distances is a major limitation and gap in LCA and is an issue in environmental impact assessment (EIA) due to the massive burdens transport contributes to the recycling process. Oteng et al. (3) suggests bridging this gap through application of a formula that utilises estimated travel distances through calculating the hotspot analysis of waste sources. Literature consensus outlines transportation, in conjunction with chemical usage and energy consumption from fossil fuel sources as the main hotspots of EoL solar panel recycling processes [22,36].

Both Ansanelli et al. (22) and Rossi et al. (27) identified the recovery and recycling of aluminium from SPW as having a significant impact in reducing the GWP and other associated midpoint impacts of SPW. This implies the significance of recovering metals from EoL panels, as in a scenario where 100% of materials are recycled, the GWP impacts of a solar panel across its lifecycle can be reduced by up to 53%. Over 80% of these reductions were attributed to the recovery and recycling of metals [44]. In terms of the transition to SD and CE practices, recycling plants must prioritise recycling the entire solar panel which contains critical minerals and has an enormous impact on the RD-M indicator. This approach contrasts LGRF which seeks to retrieve only the easily recovered materials such as glass and the aluminium junction box. The recycling of all recoverable materials in a solar panel reduces RD-M impacts by 34%, of which non-metal material recycling accounts for 84% of the harm reductions within the system, highlighting the importance of minimising primary resource extraction and prioritising secondary resource recovery of both metals and non-metal materials, including silicon [27]. Reuse of recovered secondary silicon wafers from EoL solar panels in new generations of panels has demonstrated a decrease of around 70% of the energy required in the production of primary silicon wafers [3]. Appropriate measures to ensure contamination of recovered silicon remains under 2.5% ensures equivalent performance of solar cells in their second life and reduces production costs by up to 20% [37]. There is an identified need to ensure secondary silicon procured from EoL solar panels maintains its quality and value to prevent the downcycling of this material and instead retain material quality for reincorporation into new generations of solar panels [38]. Therefore, LGRF would not be a viable solution for SPWM

in line with SD and CE concepts, as silicon and other non-metals are disposed of when utilising LGRF pathways.

The construction and establishment of dedicated recycling plant infrastructure could have potential adverse impacts; however, no papers using LCA to quantify the social, environmental, and economic impacts of building and operating these facilities were identified. This gap has been previously recognised in the literature and is yet to be addressed due to the recent emergence of SPWM as an issue and a lack of available data on the few existing solar panel recycling plants [9]. As a result, the construction and operation of the recycling plant is often excluded from LCA evaluations of solar panel recycling scenarios which could impact the feasibility of recycling plants as a SPWM solution.

Literature has also identified an issue in the utilisation of LCA where key cost drivers are routinely under-represented where models do not accurately represent the economic costs associated with development aspects such as research, investment, overheads, and marketing [24]. This could potentially indicate that recycling processes are being represented as more economically viable than is accurate, with some papers reporting that recycling EoL panels has a positive environmental impact but is not always economically profitable [36,39]. However, in the case of Dias et al. (39), where the authors report a lack of economic feasibility, this pertains to studies where no policy measures or government interventions have been implemented, influencing the lower reported costs of landfilling compared to recycling methods. Recycling EoL panels could potentially present economic feasibility with no policy intervention in developing countries with lax environmental laws and low labour costs; however, there is a risk of generating new environmental and social issues if recycling facilities are not managed responsibly [39]. Additionally, there are concerns that exploitative labour practices, akin to modern-day slavery, could be engaged to operate said facilities [39]. Such concerns highlight the need for policy interventions to ensure responsible domestic processing of SPW with stringent social and environmental guidelines and incentivised industry compliance. LCA studies have been conducted to evaluate the potential effectiveness of government interventions. Using LCA, Oteng et al. (3) demonstrated that a mandatory product stewardship (MPS) scheme could improve the GWP for both monocrystalline and polycrystalline solar panels. A MPS scheme where 100% of SPW is recycled saw GWP for the two solar modules decrease by $-1\text{E}+06$ kgCO₂-eq and $-2\text{E}+06$ kgCO₂-eq respectively, compared to a scenario where 100% of SPW is landfilled, resulting in an increased GWP of $1\text{E}+05$ kgCO₂-eq for both types of modules [3].

Multiple studies showed using LCA that different EoL recycling scenarios had lower environmental impacts when compared to the current conventional approach of dumping SPW in landfill [22,39]. Despite associated impacts with the transportation and recycling of EoL panels, literature has still concluded that recycling is superior to landfilling and that impacts generated during these processes are offset by the harm reductions gained from recirculating secondary raw materials [40].

Applications & Limitations of LCA to SPWM in Australia

Numerous papers have identified a lack of LCA studies that present a case study or are Australia-specific [6,9,24,41]. Of the 45 publications retrieved for full-text screening only four present case studies or examples in Australia; furthermore, only three of the studies discuss LCA. Singh et al. (9) highlighted that in conjunction with a lack of Australia-specific LCA studies, the few existing studies have limited the ability of their results to be compared to other technologies or procedures by using a different functional unit (FU) than is standard. Typically, most LCA's use the FU of energy in this research context, which makes it difficult to draw conclusions and make direct comparisons when an alternative FU is employed. However, when considering the end-of-life (EoL) impacts specific to photovoltaic (PV) modules, traditional LCA may be limited due to the chosen functional units. To better address PV EoL issues, alternative functional units such as 'peak power/installed capacity' or 'number of PV panels of a given power/energy rating' should be considered. Additionally, narrowing down LCA to gate-to-grave or solely EoL lifecycle phases can bring EoL impacts to the forefront and provide more precise insights for policymakers.

Mahmoudi et al. [41] acknowledges a concerning lack of comprehensive policy in Australia and performs a modified pilot recycling procedure for domestic treatment EoL SPW, utilising LCA and an economic feasibility analysis. The findings of this study found the domestic treatment of EoL SPW would be economically feasible and reduce environmental impacts. Recycling plants would have high-profit margins where the annual waste flow of EoL solar panels equates to 20,000 tonnes or more, with no government intervention [41]. A plant with reduced capacity processing around 10,000 tonnes per year would not exhibit profitability unless new policy measures were implemented by the Australian Government [41]. Whilst profitability is a crucial consideration in any industry, government mandates and incentives need to be introduced now. Waiting for the issue to become profitable before acting is neither socially nor environmentally feasible. Recycling facilities need to be established now to prepare for the expected increase in future waste due to the growing global interest in green hydrogen production. A proactive approach to establishing recycling programs ensures that facilities will be able to effectively handle the future waste streams without encountering operational challenges.

Singh et al. [9] conducts a comparative LCA for three different disposal scenarios in Australia, LGRF, FRELP and landfill scenario using a solar panel operational lifetime of 30 years. The study found impacts scores and CO₂ emissions reduced by 7% and 8% respectively for LGRF and 26% and 22% respectively for FRELP when compared to the impacts and CO₂ emissions of the landfilling scenario [9]. The study also considered how future R&D would improve the operational lives of solar panels and found that increasing solar panel lifespan to 50 and 100 years would reduce ReCiPe endpoint score impacts by 40% and 70% respectively [9]. The study also emphasised the importance of mandating circular designs and industry standardisation alongside the implementation of a MPS scheme [9].

Suyanto et al. [24] found using simplified LCA that a modified FRELP scenario could be more economically feasible for Australian applications due to the focus on recovering solar-grade silicon over silver in the regular FRELP scenario. The paper proposed that an interim

approach similar to what is currently employed in the EU where only the bulk materials, aluminium, glass, and copper, are sought for retrieval is a temporary solution whilst SPW mass is still relatively low and difficult to scale [24].

LCA has identified a need to improve the design stages for solar panels; adoption of circular design strategies could enable the reuse, repair and refurbishment of solar panels and see the development of a standardised design and manufacturing process [12]. This standardisation, in turn, could facilitate uniform management and recycling procedures, streamlining the recycling process, reducing costs and energy requirements, and promoting SD and circularity principles in SPWM [12]. Improving the durability of solar panels was also suggested as a means to increase operational lifetimes of solar panels, with Singh et al. [9] suggesting that in conjunction to improving designs and standardisation for circularity and SD, operational lifetimes should also be increased to effectively address environmental concerns.

There is an identified gap in the number of published studies pertaining to LCA of c-Si SPWM scenarios, and this is attributed to limited data availability due to the scale of SPWM with most research still in the pilot or laboratory stages [6]. Whilst there are some limitations to the LCA methodology, LCA still provides valuable information that supports the transition a decarbonised economy by providing valuable insights to policymakers and various stakeholders for the creation of robust and long-lasting policy that supports the principles of SD and CE.

Applications of STMs in SPWM

STM Background & Methodologies

Many of the issues surrounding the linear economy, i.e., pollution, resource depletion, GHG emissions are inherently systemic and therefore, in the future, STM's will be fundamental in aiding the transition to a decarbonised CE. At a rudimentary level, systems thinking (ST) refers to how individual parts fit together and consolidate to form a larger system whilst still considering the interactions between the individual parts. STMs serve to help us identify strengths, weaknesses, challenges, and opportunities within systems, whilst facilitating the evaluation of environmental impacts on various scales and challenging world views by expanding awareness through a requirement to consider wider and multiple perspectives. STMs focus heavily on integration and consideration of stakeholder values. A ST approach to decarbonisation would consider how policy design can have an impact on multiple fronts, including the environment, economy, society, stakeholders, etc. Systems thinking approaches have been gaining traction in both the academic and decision-making fields as much current research and policy fails to achieve and sustain their desired objective/s [42-44].

Whilst traditional reductionist thinking methodologies have served scientific discovery well, they are not effective in systems with high levels of interdependence and interconnectedness; designing effective policies will require a shift towards looking at systems holistically. STMs take a non-linear approach that analyses the connection between and within individual systems, acknowledging that cause and effect may not necessarily be related as they are in traditional linear systems. STMs tools include causal loop diagrams (CLDs), systems dynamics,

soft systems methodology, social network analysis and computer modelling. A paper by Laimon et al. [45] identified STMs as an effective tool for policy design to minimise policy resistance and produce long-term solutions whilst avoiding unwanted repercussions and short-term fixes. Whilst STMs have been used to effectively model long-term policymaking decisions, they have demonstrated a limited ability to identify short-term impacts within long-term modelling systems due to the large scope of the models [42,45]. STM approaches can help to combat a commonly encountered issue known as Goodhart's Law, which refers to situations where decisions are based on predicted effects rather than the ability to achieve the original objectives that it was proposed to deliver [46].

STMs will play a vital role in future policy design due to the highly interconnected nature of policy and issues surrounding decarbonisation. STM terminology and techniques must be shared and explained to remove barriers between STM practitioners and policymakers, stakeholders, and the public so as to increase understanding and facilitate informed decision-making processes that create effective and long-lasting policies [47].

Previous Studies Using STM

Systems dynamics have been applied extensively to research surrounding solar photovoltaics and policy, but few studies have utilised systems approaches to integrate these research areas and investigate EoL solar panel waste management [18,40]. Of the 44 results retrieved from Scopus and WoS databases, only four of these papers had a primary focus on applying STMs to SPW. The empirical methodologies utilised in these papers included: causal loop diagrams, stocks and flows diagrams and policy- simulation models.

Marcuzzo et al. [18] aimed to evaluate the potential destinations strategies for EoL solar waste, landfill, and recycling facilities. Through systems dynamics modelling, Marcuzzo et al. [18] employed comparative analyses to aid policymakers in identifying best potential practices for SPWM and the development of instruments and incentives to regulate SPW. Salim et al. [10] utilised STM to incorporate stakeholder feedback and identified the need for a comprehensive national product stewardship scheme and incentives to manage SPW. The paper also showed that SPWM is most effective wherein industries are required to participate through regulation that establishes targets such as minimum product and material recovery rates [10]. Marcuzzo et al. [18] also emphasised the need for interconnection between local, state, and federal governments to develop the recycling facilities required to meet the speed of solar panel retirement. Using systems dynamics methods, Zhang et al. [40] demonstrated that recycling return on investments (ROIs) are higher in scenarios with government interventions such as recycling subsidies which improve the economic feasibility of SPW recycling operations. The paper employed stock and flow models and a systems dynamics approach to develop policy-simulation models designed to evaluate the impact of various policies on economic viability of recycling as a SPWM solution for a case study in China. El-Khawad et al. [12]'s analysis of transforming the solar panel industry into a closed-loop system recognised a current lack of economic feasibility in achieving full material recovery in solar panel recycling facilities without government intervention. However, a holistic consideration of the system recognises the exponential growth of the industry and large future waste streams which will improve

future feasibility, emphasising the need for actions to be implemented now in order to successfully transition the industry to a closed loop, circular system, and account for future needs. El-Khawad et al. [12] suggests that producers will play a crucial role in enabling this transition and there is a compelling requirement for them to adopt circular design and recovery principles into their planning and manufacturing processes if EoL solar panels are to be repaired, refurbished, and recycled on large scales.

Application of STM to SPWM

Whilst some of these papers have focused on specific case studies such as China and Germany, the dynamic nature of STM and the similarities in the challenges posed by SPWM mean that the findings can be readily adapted and applied to other countries [12,40].

Salim et al. [10] was the only identified paper to apply STM to SPWM in Australia, the researchers present a CLD that depicts the complex interrelationships between drivers, barriers, and enablers of managing residential SPW in Australia. The qualitative model captures the interactions between the waste flow dynamics of SPW, regulatory instruments for SPWM and industry responses to regulation. As previously highlighted in LCA studies, the researchers express concerns relating to the challenges of collecting and transporting EoL solar panels, environmental impacts of inadequate SPWM, potential weaknesses of ineffective policies and the importance of a national MPS scheme.

STMs are one of the most effective methodologies in considering the relationships between stakeholders and a system, as well as obtaining stakeholder perspectives regarding systems behaviours and impacts. Effective policy implementation will depend on extensive stakeholder engagement, particularly in an Australian context where transportation distances of SPW can vary due to relatively low population density and dispersed urban areas. Stakeholder participation is crucial due to high sensitivities of variables such as transportation distances on the environmental footprint of recycled SPW. Stakeholder participation extends beyond the industrial sector, encompassing the general public as consumers of solar panels for residential use. Existing MPS schemes often incentivise consumers to deposit EoL products at designated collection points [48]. This approach has already been implemented in Australia under MPS schemes for tyres and other e-waste products such as televisions and laptops and could be readily adapted to have consumers drop off EoL panels at local retailers or installers.

STMs facilitate short and long-term impact evaluations. This is particularly important as research and development (R&D) may see the average operational lifecycle of solar panels increased to 40+ years, necessitating dynamic and adaptable policies that are equipped to respond to Australia's growing SPW problem. Whilst increasing the lifecycle of a product is a crucial factor in SD and CE transitions, such improvements could inadvertently inhibit support for SPW recycling pathways by reducing future waste streams. Reduced waste streams could limit the development of economies of scale, reducing the profitability of recycling pathways. Such challenges further emphasise the importance of future perspectives and dynamic policies when addressing SPWM [18]. A MPS scheme incorporating additional interventions such as landfill bans would function as a balancing measure to inhibit the current reinforcing waste

accumulation loop where solar panels are decommissioned and dumped at landfills, resulting in the installation of new panels manufactured using virgin materials.

Despite a limited number of published studies in the research context, existing literature has employed STMs to underscore the importance of industry standards and participation and MPS schemes in creating policies that promote CE principles and sustainable SPWM. STMs demonstrate the importance of not only improving waste management processes but also identifying holistic, sustainable, and circular solutions to address and resolve the underlying issues contributing to the mismanagement of SPW. This involves enhancing the design and manufacturing phases to reduce resource consumption and minimise the environmental impacts of solar panels throughout their entire life cycle.

Integration of LCA & STM - Policy Implications and Recommendations

Key Policy Implications

Landfilling is the current preferred SPWM strategy employed by producers who are only considering economic factors, underscoring the requirement for government intervention to prohibit landfilling and introduce MPS schemes and recycling incentives [6]. Voluntary approaches for product stewardship have been found in literature to be ineffective in regulating e-waste, hence mandating is recommended [3].

In recent years, LCA has been effectively employed to environmental hotspots throughout the entire life cycle of solar panels. Although studies in the SPWM context are limited, LCA has still proven to be an effective tool in evaluating and comparing the environmental impacts of EoL solar panels under various management scenarios. Whilst many studies are still in pilot or laboratory stages, LCA has been instrumental in finding inefficiencies and shortcomings in proposed recycling scenarios. Identification of environmental hotspots through LCA can help policymakers determine where intervention is required to have the most significant reduction in adverse impacts. Such interventions should involve mandatory recovery rates for materials, landfill bans, or requirements for the use of renewable energy sources to power recycling plants. In conjunction to aiding policy interventions, LCA also facilitates ongoing monitoring of SPWM and can be used to develop reporting standards for, and through, collaboration with stakeholders to ensure accountability and evaluate progress. Policymakers would also be required to fund or incentivise research and development in stages of the recycling process that are particularly harmful or legislate industry-wide adoption of existing processes that have been demonstrated to be less harmful. As SPW recycling infrastructure increases and the processing capabilities of recycling facilities evolve and change, LCA can continue to be utilised as a holistic impact quantification and evaluation tool with dynamic applications to inform decision-making processes. However, Ganesan & Valderrama (6) identify that most existing LCA frameworks for SPWM are dependent on detailed data which is only available from mature systems, and they take retrospective approaches, limiting their ability to assess emerging generations of solar technology and new recycling processes, as well as informing policymakers [6]. To address this limitation, Ganesan & Valderrama (6) propose the adoption of anticipatory LCA (a-LCA) to facilitate policymakers in evaluating modern technologies and different EoL SPWM strategies with various sustainability indicators. However, the authors

acknowledge that their novel approach may be limited by its overreliance on stakeholder feedback and recommend careful selection of relevant stakeholders for engagement as a means to compensate for this potential limitation [6].

Systems dynamics is credited for its ability to portray and facilitate analysis of complex, non-linear systems under different policy scenarios and understand the causes of particular outcomes [40]. STMs have identified a necessary decoupling of recovery rate targets from weight as this leads to the extraction of the heaviest and easily recovered resources and does not incentivise the recovery of all materials, particularly rarer minerals such as copper and silver [34]. Whilst rarer minerals constitute an exceptionally low percentage of a solar panel's weight, they hold significant economic value, and their recovery plays a critical role in reducing the social and environmental impacts of solar panels over their life cycle. The waste electrical and electronic equipment (WEEE) Directive legislates resource recovery targets using weight, resulting in recycling facilities prioritising glass recovery which comprises 75% of a solar panel's weight but represents only 8% of its value, but can be readily recovered and facilitates easy attainment of WEEE targets [12]. Literature emphasises a high recyclability of c-Si cells with potential material recovery rates for c-Si modules reported to be 96% of material components and 99% by weight in 2020, emphasising the value of recycling methods, a requirement to increase weight recovery targets, and the merit of diverting SPW from landfill [6,9]. Current estimations indicate that as much as 96% of the materials used in solar panels have the potential to be recycled. However, the recycled mass/materials ratio, which is a broad indicator, does not reflect the critical issues with recovering micrograms of essential materials like Ag, Pd, and Ti from each panel. High-quality, low-entropy recycling of these resources is crucial for the long-term scalability and sustainability of PV manufacturing, highlighting the need for more targeted recycling technologies and policies. LCA found that panels manufactured using recovered secondary materials from EoL panels have been determined to have a significantly reduced energy payback time of ~1.6 years compared to that of solar panels manufactured using virgin materials (~3.8 years) [12]. Despite remarkable advancements in the extraction processes and high resource recovery rates, commercial-scale recovery of these high-value materials has been hindered by a lack of collection networks and investment in recycling scenarios [49].

Stakeholder participation is primarily motivated by economic impacts, improving the rate of investment (ROI) of SPW recycling through policy interventions would increase stakeholder participation and thereby increase the mass of collected and recycled EoL panels. Improved recovery rates lead to higher ROI's which encourages stakeholders to invest in R&D, creating a reinforcing loop between R&D and ROI [40]. This can be balanced by scaling back or abolishing implemented policies over time once the market for recycled SPW has established itself and stakeholders can still make a reasonable profit without government policies [40]. Implementing policy measures within the next few years to incentivise necessary R&D which will be crucial to sustainably develop the solar panel recycling industry and improve ROI as SPWM will continue to burgeon into a significant issue as SPW accumulates. Using STMs, Zhang et al. [40] found that standard subsidies for used electronic products and foreign EoL solar panels sit between 1-3% of the product price. Whilst a higher subsidy rate will motivate rapid stakeholder participation and support R&D, long-term impacts must still be considered.

Over time, fixed subsidy rates will beget a ballooning effect on policy costs as market dynamics shift and evolve in response to industry growth and scaling of facilities driven by increasing supplies of SPW. Recycling costs will decrease with improved R&D as profit margins increase, emphasising the necessity of a subsidy retreat mechanism in this context [40].

Literature recommends the implementation of a tracking system such as a serial number registrar to ensure industry compliance with a MPS scheme to facilitate the evaluation of the solar panel market dynamics [64]. This registry would monitor solar panel type, installation date, estimated decommissioning date and location of the installation. This information is invaluable to recyclers and policymakers who can use systems thinking approaches to forecast waste projections and prepare appropriate frameworks or policy solutions to effectively manage SPW [12].

Whilst a large number of literature articles identify the requirement for integration of sustainability assessment methodologies for a successful transition to a decarbonised, circular economy, there is a limited number of papers discussing the use of integrating certain methods to aid policy design. To date, no papers have been found to explicitly discuss the integration of LCA and STMs to aid policy design for SPWM. A review by Onat et al. [47] identified that the integration of LCA and STM's would serve to help address limitations observed during the use of these techniques independently. Many papers have identified the need for integration of multiple techniques or highlighted that further research is required to examine how various techniques would interact and serve to aid the transition towards a CE but there is limited empirical literature [50]. Thus, due to the lack of literature currently available, there is a demonstrated need to assess the integration of LCA and STM's and their use in informing policy design. Further research in this area will guide the creation of decarbonization policies that promote the sustainable growth of the solar panel industry and support the global interest in green hydrogen production. These policies should encourage responsible management, prioritize environmental values, and consider the perspectives of all stakeholders. This approach will help implement transformative policies that will shape and inform future policy decisions for generations to come.

Incorporation of CE Framework in SPWM Policy

Australia has made progress towards incorporating CE frameworks into key industries with \$83.1 million in expenditures announced for use over the next five years. This funding will be used in part for policy measures that promote cleaner energy, reduced GHG emissions, improved efficient relating to resource use, extended producer responsibility schemes, and superior operational lifetimes of products [51]. With photovoltaics having been on the Ministers Priority List for over six years and in line with the measures previously listed, it is expected that some of these measures will address SPWM.

Deconstructable solar panel designs to facilitate recycling and CE principles such as repair and refurbish exist and highlight progress made towards SD [12]. However, there has been limited adoption of said designs, restricting opportunities for repair or refurbishment, suggesting a lack of producer responsibility and accountability within the industry. Industry stakeholders have expressed concerns over identified policy loopholes that are contributing to the

premature decommissioning of functional solar panels [8]. Policy intervention will be required to reduce the premature decommissioning of solar panel systems driven by flaws in existing incentive schemes and warranty and insurance claim procedures. Up to 80% of SPW can contain defects acquired within the first four years of their operational life, of these waste panels, between 45-65% could potentially be repaired or refurbished, indicating the need for not only SPWM programmes but a larger need for repair and refurbishment services to reinject these valuable technologies back into the system [6]. The repair of damaged solar panels underpins essential concepts of CE to minimise waste, extend product longevity, and conserve resources. However, considerations need to be paid regarding the current lack of formal standards pertaining to the repairs of damaged solar panels as there are no characterisation, reliability tests, certifications, or labelling standards to support consumer confidence that creates a market for second-life solar panels (SLSPs) [6]. These issues underscore the importance of implementing a MPS scheme in conjunction with regulating design and manufacturing stages of solar panel production to drive sustainable and effective solar panel design. Policy requirements for manufacturer reporting on material circularity index and material reutilisation scores are suggested as means to enforce industry action and compliance with circular designs of solar panels [9]. Whilst SLSPs manufactured from recycled SPW have been shown to demonstrate similar power generation capabilities as new solar panels, government endorsement will be required to bring them to the mainstream market. Policy measures outlining targets for incorporation of secondary materials recovered from EoL panels into new solar panels could serve as powerful incentives for resource recovery, promoting recycling of decommissioned panels, whilst also encouraging the acceptance of new panels manufactured using secondary materials.

Conclusion

The implications of the above stated strategies on policy will need to be deconstructed to determine what measures are required to ensure Australia is not only generating clean and renewable energy but also conducting responsible waste management practices to reduce environmental harm. To inform policymakers, below are specific recommendations to facilitate effective solar panel waste management (SPWM):

1. *Mandatory Recycling Rates:* Implementing mandatory recycling recovery rates is essential to ensure a higher percentage of solar panel materials are recycled and diverted from landfills. By setting and enforcing these targets, Australia can significantly reduce the environmental impact of solar panel waste, promoting a circular economy and conserving valuable resources.
2. *Incentives for Research and Development:* Providing governmental incentives for research and development in recycling technologies is crucial for advancing the efficiency and cost-effectiveness of solar panel recycling techniques. By investing in innovative R&D, Australia can lead the way in developing cutting-edge recycling processes, making it economically viable to recycle solar panels on a large scale.

3. *Stakeholder Engagement Programs*: Establishing comprehensive programs for stakeholder engagement, including manufacturers, recyclers, and policymakers, is vital for collaboratively addressing SPWM challenges. These programs will foster dialogue and cooperation among all parties involved, encouraging the development of best practices and the adoption of new technologies in recycling.

By adopting these policy measures, Australia can ensure that its commitment to clean energy extends beyond just generation to encompass the entire lifecycle of solar panels. This holistic approach will not only minimize environmental harm but also position Australia as a leader in sustainable energy and waste management practices.

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Directrice de publication :

Anne Revillard

Comité de rédaction :

Ariane Lacaze, Andreana Khristova

Sciences Po - LIEPP
27 rue Saint Guillaume
75007 Paris - France
+33(0)1.45.49.83.61
liepp@sciencespo.fr

