Systems approach to end-of-life management of residential photovoltaic panels and battery energy storage system in Australia

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Abstract

Understanding the complexities around managing the end-of-life (EoL) residential solar photovoltaic (PV) and battery energy storage systems (BESS) is a precursor to a better decision-making process that mitigates unintended product life-cycle impacts. In this paper, a participatory Systems Thinking approach was utilised to build a causal loop diagram (CLD) for this system based on the collective knowledge of stakeholders. The developed CLD was categorised into three sub-systems: (1) waste flows; (2) regulatory aspects; and (3) industry strategies and government incentives. Two main system archetypes were identified in a reflection to the CLD, namely fixes that fail and drifting goals. The identified feedback loops indicate the need to introduce a comprehensive national product stewardship scheme, complimentary landfill restrictions, and provide sufficient incentives to industries for promoting recovery activities within residential PV panels and BESS sectors. An effective waste management system for these renewable energy technologies is most effective if industries are required to participate through regulation which also specifies certain targets, such as product and material recovery rates and establishes a sustainable funding model to meet operational requirements and future needs. The increasingly prohibitive overseas waste export market will require local industries and governments to collaboratively improve domestic recycling capability and capacity. In this light, the failure to build an effective EoL management system for residential PV and BESS will result in valuable and hazardous materials in both technologies to be disposed of in the landfill, stockpiled or illegally dumped; consequently, reinforcing unintended and adverse environmental impacts.

Highlights

- Causal loop diagram mapped the complexity of EoL management system of PV and BESS.

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Stakeholders were consulted to develop and validate the conceptual model.

Conceptual model is governed by three subsystems and 13 feedback loops.

Two system archetypes were identified, namely fixes that fail and drifting goals.

Keywords: end-of-life, solar photovoltaic, battery energy storage system, causal loop diagram, systems thinking, Australia

Word count: 6,979 words (abstract and article body only)

List of abbreviations

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>ACT</td>
<td>Australian Capital Territory</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery energy storage system</td>
</tr>
<tr>
<td>CLD</td>
<td>Causal loop diagram</td>
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<tr>
<td>EoL</td>
<td>End-of-life</td>
</tr>
<tr>
<td>NSW</td>
<td>New South Wales</td>
</tr>
<tr>
<td>PSO</td>
<td>Product stewardship organisation</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>QLD</td>
<td>Queensland</td>
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<tr>
<td>SD</td>
<td>System dynamics</td>
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<td>ST</td>
<td>Systems thinking</td>
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<tr>
<td>VIC</td>
<td>Victoria</td>
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1 Introduction

The rapid growth of solar photovoltaic (PV) systems uptake internationally and in countries like Australia will create an impending electronic waste crisis. Residential-scale PV in Australia makes up the highest (80.2%) solar energy generation in 2018 [1]. Moreover, the declining cost of battery energy storage system (BESS) will lead to an exponential increase in their solar energy applications in the coming decade [2]. Salim et al. [3] projected that end-of-life (EoL) residential PV panels in Australia will increase at an exponential rate from 2.7 kilo tonnes in 2018 to 1,532 kilo tonnes in 2050. Residential EoL BESS will start to emerge as a significant waste stream in 2025 (1.6 kilo tonnes) and will surge dramatically to 99.1 kilo tonnes in 2050. With valuable and critical materials (i.e. ruthenium, gallium, indium, tellurium, lead, and lithium) present in both PV panels [4] and BESS [5], enabling an appropriate policy to promote the recovery process is necessary to conserve and recirculate these materials to meet the future demand of solar energy [6].
A product stewardship scheme for PV systems (i.e. PV panels, BESS, and auxiliary components) is being investigated by the Australian government [3]. This scheme aims to establish a voluntary, co-regulatory, or mandatory approach to manage a product throughout its life-cycle, from the product design to EoL stage. It acknowledges that all participants involved in the design, importation, distribution, manufacturing and use of the product as having a shared responsibility to ensure negative environmental and human health impacts evident throughout the value chain can be reduced. Despite being considered under the same product class in 2017 [7], a recent government report stated that a product stewardship scheme will likely be separated between PV panels and BESS, whereas auxiliary components will be excluded from the schemes [8]. This is mainly because BESS applications overlap across electric vehicles and other renewable energy storage systems.

Determining an appropriate EoL management strategy for PV panels and BESS in Australia is extremely complex as it is characterised by multiple stakeholder objectives [9]. Particularly in the case of the residential sector, the collection of EoL products tends to be more challenging as it requires more operational efforts and incentives to create and promote consumer awareness compared with typical electronic waste management such as televisions and computers [10]. A fundamental gap in the academic literature is an assessment of transition pathways using a systemic approach to capture the complexity and dynamics of the EoL management system of residential PV and BESS in Australia [11]. Despite being frequently conceptualised as a techno-economic and environmental phenomenon in previous studies, EoL PV and BESS value chain is also driven by socio-technical aspects [11]. Systems Thinking (ST) modelling is a suitable approach to capture the complexity of this particular problem. It has been widely applied in various environmental studies such as solid waste management [12] and water resource management [13]. The traditional econometric approach that assumes exogeneity of a problem fails to identify the complex structure and parameters of a system from its observed behaviour [14].

Effective System Dynamics (SD) modelling is accomplished by establishing a clear picture of the problem a priori through a conceptual model [14] through an ST approach. The application of ST for complex environmental issues necessitates extensive consultation with relevant stakeholders to ensure that a robust model is formulated [15]. Therefore, this study presents a policy-oriented dynamic hypothesis using a causal loop diagram (CLD) that applies the factors reported by the authors in a recent study [3] using a participatory ST approach. This paper builds a knowledge base underpinning a decision-making tool using the SD modelling approach by mapping the complexity of the interrelationship between key drivers, barriers, and enablers influencing the EoL management system for residential solar PV and BESS in Australia. The CLD was further refined in stakeholder workshops to ensure that variables and relationships are relevant and valid. Despite the potential
product stewardship scheme separation between PV panels and BESS, coupling the discussion is of
importance to understand how the adoption of solar PV systems will increase the complexity of the
whole EoL BESS supply chain (i.e. including electric vehicle and other renewable energy
applications).

2 Material and methods

Systems thinking approach uses feedback theory to develop a dynamic hypothesis that explains and
predicts past and future system behaviour [14]. The strength of the CLD is that it helps stakeholders
to challenge entrenched mental models and test assumptions; thus, leading to an important and
counterintuitive understanding about system structure and behaviour [16]. Following an integrated
participatory modelling approach allowed the researchers to capture different stakeholder perceptions
in the developed conceptual model [17]. The approach is based on the notion that people who reside
and work in a particular system may be better informed about its process and problems and will have
deeper system awareness than academics [18]. Several advantages have been reported as a result of
a participatory modelling approach including the validity of model outputs [19], facilitation of a
stakeholder learning process [15], and elicitation of possible policy options [20].

There are two main steps in developing the conceptual model: problem scoping and CLD modelling
(Table 1). Problem scoping helps to clarify the purpose of the research while defining the scope of
the model by identifying the key drivers, barriers, and enablers [14]. Enabling a comparative analysis
between different stakeholder groups is imperative to capture conflicting strategic goals in the system.
CLD modelling is a process to depict the causal relationships and feedback loops between key system
variables identified in the problem scoping stage. CLD allows the identification of system archetypes
which visualise a generic system structure where appropriate leverage points and policy interventions
can be proposed to overcome the problem [21].

Table 1. Participatory systems thinking approach

<table>
<thead>
<tr>
<th>Stage</th>
<th>Time</th>
<th>Process</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem scoping</td>
<td>Aug – Sep 2018</td>
<td>Expert review</td>
<td>• Validate the list of drivers, barriers, and enablers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Discuss the problematic situations and potential solutions</td>
</tr>
<tr>
<td></td>
<td>Oct – Dec 2018</td>
<td>Stakeholder survey</td>
<td>• Quantify and compare stakeholder perceptions on the drivers, barriers, and enablers</td>
</tr>
<tr>
<td>Conceptual model development</td>
<td>Oct 2018</td>
<td>Pre-conceptualisation workshop</td>
<td>• Present the expert review results</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Initiate discussion around the problematic situations and potential solutions</td>
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</tbody>
</table>
### 2.1 Problem scoping

The problem scoping phase aims to define the purpose of the research and understand the boundary of the model. This process helps to capture the mental models from relevant stakeholders on how a particular system works, the supply chain works, current challenges and drivers, as well as plausible management strategies [22]. In this research, the initial list of drivers, barriers, and enablers retrieved from the systematic literature review process presented in Salim et al. [11] were confirmed with eight experts from different stakeholder groups (i.e. recyclers, academics, governments, non-governmental organisations, and manufacturers). This process helped to ensure the comprehensiveness, relevance, and clarity of the factors. A stakeholder survey round was then conducted to quantify and compare the perceived drivers, barriers, and enablers to EoL management of PV and BESS in Australia across different stakeholder categories. The survey was responded by 57 stakeholders, including governments, academics, consultants, distributors/installers, manufacturers, and non-governmental organisations. Given that this research is an emerging area, it was deemed that an adequate sample size has been achieved due to the range of sampling approaches employed, including purposive sampling approach and snowball sampling approach. Detailed methodology of the problem scoping stage was reported in Salim et al. [3]. The focus of this present paper is on the conceptual model development phase of this research program.

### 2.2 Conceptual model development

The conceptual model development process involved the identification of variables, development of the preliminary CLD, and refinement of the CLD in two stakeholder workshop sessions. The following sub-sections detail these model development activities.
2.2.1 Variables identification

The authors relied on the expert review and stakeholder survey results as well as relevant literature (i.e., academic articles, government and consultancy reports) as a primary source of data to identify and select relevant system variables. The lead author also presented the expert review results and initiated some discussion around the problematic situations and potential solutions during the pre-conceptualisation workshop in October 2018 to determine the model scope and identify important variables. Qualitative data from the expert review process were coded using grounded theory techniques to support the identification of the model scope and variables. This approach was used to systematically analyse the theory or themes from the data by extracting and grouping concepts, or codes from the interview data [23]. The concepts extracted from this analysis are presented in Table 2. In addition, quantitative data from the stakeholder survey were also utilised by analysing the most highly ranked drivers, barriers, and enablers. Key drivers, barriers, and enablers is summarised in Table 3. We triangulated variables extracted from these data with the previous literature and government reports to confirm the commonly used term and description of each factor.

Table 2. Concepts extracted from the grounded theory approach

<table>
<thead>
<tr>
<th>Governments</th>
<th>Academics</th>
<th>Consultant</th>
<th>Product Stewardship Arrangement Parties¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Product stewardship scheme</td>
<td>• Landfill ban</td>
<td>• Product stewardship scheme</td>
<td>• Industry development</td>
</tr>
<tr>
<td>• Fair and equitable costs across stakeholders</td>
<td>• Fire risk</td>
<td>• Rare materials</td>
<td>• Material recovery rate</td>
</tr>
<tr>
<td>• Inconsistent labelling of batteries</td>
<td>• Consumer/installer awareness</td>
<td>• Landfill ban</td>
<td>• Reasonable access requirement</td>
</tr>
<tr>
<td>• Incentives to encourage participation</td>
<td>• Research and development of recycling technologies</td>
<td>• Consumer/installer awareness</td>
<td>• Internal recycling</td>
</tr>
<tr>
<td>• Enforcement of landfill ban</td>
<td>• Profitability to recycle</td>
<td>• Fire risk</td>
<td>• Scheme target</td>
</tr>
<tr>
<td>• Reasonable access requirement</td>
<td>• Environmental impacts of recycling</td>
<td></td>
<td>• Landfill ban</td>
</tr>
<tr>
<td>• Consumer/installer awareness</td>
<td></td>
<td></td>
<td>• Consumer/installer awareness</td>
</tr>
</tbody>
</table>

¹ Product stewardship arrangement parties include a manufacturer, a recycler, and a product stewardship organisation that were interviewed

Table 3. Summary of the core drivers, barriers and enablers utilised in conceptual model

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Barriers</th>
<th>Enablers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain the integrity of green products</td>
<td>No regulations in place</td>
<td>Strict regulations and policies such as product stewardship</td>
</tr>
<tr>
<td>Ensure appropriate EoL management strategies via evidence of product and material impacts</td>
<td>Lack of economic incentives for collection and recycling</td>
<td>Implementing business model for take-back/collection scheme</td>
</tr>
</tbody>
</table>
Conserve and recirculate rare materials
Lack of profitability to recycle
Lack of incentives for installers to participate in a stewardship scheme
Lack of consumer and/or system installer awareness around available EoL disposal
Provide economic incentives to increase collection and recycling
Research and development on new efficient recycling technologies
Optimal number of collection centres and recycling plants

2.2.2 Causal loop diagram development

In producing the preliminary CLD, there are two types of causal relationships which reflect the direction of a pair of variables. A positive (+) causal relationship indicates that the cause and effect variables are moving in the same direction (i.e. when the cause variable increases, then the effect variable will increase). A negative (-) causal relationship indicates that the cause and effect variables are moving in the opposite direction (i.e. when the cause variable increases, then the effect variable will decrease). Double lines across the arrows represent information delay, that is, the time lag between the cause and effect. Certain causal relationships between pairs of variables may lead to a feedback loop, where the loop starts and ends at the same variable.

Understanding feedback loops can provide useful insights into the structure and functioning of the studied system as well as facilitate the identification of appropriate intervention strategies. Feedback loops can be described as reinforcing (R) or balancing (B) loops [14]. Reinforcing loop characterises the acceleration of growth or decline [24]. On the other hand, the balancing loop will counteract change within a system and produce a stabilising system behaviour or an oscillating trend [25]. The dominance of balancing loops indicates that numerous potential sources can limit growth in system performance that needs to be addressed, whereas the dominance of reinforcing loops indicates more sources of growth, erosion, and collapse in the system [14].

Preliminary system archetypes were also identified in a reflection of the CLD as a diagnostic tool for systemic issues to solve a problem symptom. Once systemic structures that are responsible for the problem symptom are identified, high leverage interventions can be proposed to create a fundamental change [26]. An archetype consists of various combinations of reinforcing loops, balancing loops, and information delays [27]. According to Senge [28], there are eight typical system archetypes: fixes that fail, limits to growth, growth and underinvestment, success to the successful, eroding goals, shifting the burden, tragedy of the commons, and escalation.

2.2.3 Stakeholder identification

Stakeholder involvement is central to the conceptual model development to support model validity. This is because environmental problems generally involve complex socio-economic and technical
aspects and the multi-faceted nature of stakeholders, uncertainty, value conflicts, as well as ecosystem and social dynamics [29]. Videira and Antunes [30] provided a guideline to conducting a stakeholder engagement process in a system dynamics approach. A workshop is the most common form of stakeholder engagement in the modelling process [31].

There is no standardised approach to identify and select participants for a participatory ST approach [18]. However, an effort should be made to foster an inclusive environment for diverse interests and background. We used the same pool of potential respondents with the stakeholder survey phase which consists of 287 potential respondents with an additional four stakeholder contacts suggested during the survey phase. Potential participants were identified based on a purposive sampling approach by conducting a systematic search in websites, relevant institutions, organisations and working groups [32] to avoid marginalisation of stakeholders [33]. In the case of this research, a diverse group of study participants was ensured by targeting all relevant stakeholders along the supply chain [18], including recyclers, governments, non-governmental organisations, system installers, academics, and consultants. Consumers, however, were not consulted as they are not typically involved in the preliminary strategic assessment of a new product stewardship scheme. Participants needed to have a general knowledge on end-of-life aspects of PV panels and BESS as well as product stewardship systems, but did not require any prior knowledge or experience in ST or systems modelling.

2.2.4 Causal loop diagram validation workshop

In this study, the stakeholder workshop aims to confirm and refine the variables and the feedback mechanisms between variables with stakeholders to ensure that they are relevant, comprehensive, and reflecting the actual system. A workshop gives the modeller an opportunity to build a consensus among stakeholders about the causal relationships and variables depicted in the diagram [2]. Two CLD validation workshops were conducted in the city of Melbourne (State of Victoria) and the city of Brisbane (State of Queensland), respectively, following the development of a preliminary CLD. The workshops aimed to validate the preliminary CLD and discuss the system archetypes. 11 stakeholders attended the first CLD validation workshop held in Melbourne, which included stakeholders from the States of Victoria and New South Wales, as well as the Australian Capital Territory. The second CLD validation workshop was held in Brisbane, which captured stakeholder perceptions from six attendees based in various parts of this State.

The workshop participants’ profile is summarised in Table 4. Important stakeholders have been consulted during the workshops, including governments, academics, recyclers, non-governmental organisations, and solar installers. Each workshop lasted for three hours and was divided into three sessions which serve to: 1) develop a shared understanding of the ST approach, 2) discuss and refine
the CLD, and 3) discuss the identified predominant system archetypes within the CLD. Despite stakeholders’ unfamiliarity with the ST approach, they demonstrated an understanding of the approach during an introductory tutorial session conducted prior to the CLD validation session. Besides, the discussion among stakeholders has been very inclusive and insightful due to the manageable size of participants.

Table 4. Profile of workshop attendees

<table>
<thead>
<tr>
<th>Location</th>
<th>No.</th>
<th>Stakeholder Group</th>
<th>Position</th>
<th>Years of Experience</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melbourne, VIC</td>
<td>1</td>
<td>Government</td>
<td>Strategic Lead (Product Stewardship)</td>
<td>3 years</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Government</td>
<td>Project Officer (Industry)</td>
<td>1 year</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Government</td>
<td>Specialist Applied Scientist – Waste Management</td>
<td>10 years</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Government</td>
<td>Assistant Director, Waste Policy</td>
<td>1 year</td>
<td>ACT</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Government</td>
<td>Project Manager</td>
<td>6 years</td>
<td>ACT</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Government</td>
<td>Policy Officer</td>
<td>1 year</td>
<td>NSW</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Academic</td>
<td>Head of School</td>
<td>10 years</td>
<td>NSW</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Recycler</td>
<td>Chief Executive Officer</td>
<td>28 years</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Recycler</td>
<td>National Development Manager</td>
<td>3 years</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Non-governmental organisation</td>
<td>Project and Policy Manager</td>
<td>5 years</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Consultant</td>
<td>Managing Director</td>
<td>10 years</td>
<td>VIC</td>
</tr>
<tr>
<td>Brisbane, QLD</td>
<td>1</td>
<td>Government</td>
<td>Senior Waste Operations Officer</td>
<td>1 year</td>
<td>QLD</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Government</td>
<td>Senior Policy Officer</td>
<td>3 years</td>
<td>QLD</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Government</td>
<td>Senior Policy Officer</td>
<td>5 years</td>
<td>QLD</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Government</td>
<td>Waste Minimisation Manager</td>
<td>6 years</td>
<td>QLD</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Installer</td>
<td>Systems Manager</td>
<td>7 years</td>
<td>QLD</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Non-governmental organisation</td>
<td>Director</td>
<td>8 years</td>
<td>QLD</td>
</tr>
</tbody>
</table>

Note: VIC: Victoria; NSW: New South Wales; QLD: Queensland; ACT: Australian Capital Territory

After completion of the two CLD validation workshops, the research team utilised the stakeholder comments and inputs to refine the CLD and the archetypes. CLD refinement tasks included adding and modifying variables, as well as adjusting causal relationships and feedback loops. Some stakeholder suggestions that were considered outside of the research scope were not integrated into the refined conceptual model.
3 Analysis and Findings

In this section, we provide the identified model scope and discuss the three primary subsystems in the final CLD depicting the complex interrelationship of managing EoL residential PV panels and BESS in Australia, namely (1) waste flows, (2) regulatory aspects, and (3) industry strategies and government incentives.

3.1 Conceptual model’s scope

The variables used in the CLD mainly focused on the policy and economic aspects (i.e. regulations, economic incentives, business models, investment in developing recycling capability and capacity, etc.) of the studied system. A few cost-related variables from commercial and industrial PV/BESS scale perspectives were also integrated into the conceptual model since residential, commercial, and industrial-scale activities will likely have similar recycling dynamics, despite having different generation, collection, and business model dynamics. It should be noted here for readers, that the herein model has purposely focused on residential-scale solar PV and BESS as this sector presently accounts for the largest amount (80.2%) of solar electricity generation in Australia compared to the commercial and industrial sectors [1]. Moreover, it is also the most challenging sector for collection activities due to the geographically dispersed nature of solar PV installations across Australian states and territories.

3.2 Causal loop diagram

The refined CLD for EoL management of residential solar PV and BESS in Australia is presented in (Fig. 1). Although PV panels and BESS are two different technologies with very different recycling regimes at the operational and processing level, their strategic product stewardship management will be relatively similar. Thus, this study combined the CLD for PV panels and BESS and used the variables interchangeably. This CLD is a product of collective mental models of stakeholders involved in the study through interviews, stakeholder surveys, and literature reviews. The final CLD was refined using information solicited at the two CLD validation workshops to ensure that its variables, causal relationships and feedback loops, are appropriately represented. The CLD can be explained in three sub-systems which were coded using different colour schemes. The green coloured area shows the PV panels and BESS waste flows dynamics. Blue coloured areas indicate regulatory aspects to manage EoL PV and BESS. The orange coloured area is indicative of the industry (e.g. product stewardship organisations, recyclers, and system installers) response to regulations and government incentives to support industries.
3.2.1 Subsystem 1 – Waste flows

The first subsystem captures the interrelationships between variables associated with the adoption and waste flows of residential PV and BESS. The model captured the positive influence of the installed residential PV systems on the consequent generation of EoL PV panels and BESS, given the time delay of the lifespan of respective technologies [34]. It is expected that the adoption of rooftop PV and BESS will increase significantly due to the declining cost of technologies and subsidies.
offered by some state governments. This is represented as a payback period which refers to the time required for consumers to recover the cost of purchasing PV panels [2]. In this light, the amount of EoL PV panels entering the waste stream is starting to increase significantly, whereas EoL BESS will start to reach a substantial level within a decade [3]. Critical and hazardous materials present in both technologies means that recovery process is necessary to avoid shortage of material supply for meeting future demand of PV systems and avoid negative impacts on the environment and human health [3].

The CLD depicts two possible pathways for EoL PV panels and BESS which can either be collected for recovery or disposed in the landfill. According to the mental model of stakeholders, if the cost to landfill disposal remains a legal and affordable option, recycling activities will become economically unfavourable. The lack of available pathways to recover PV panels and BESS have caused improper disposal of these technologies (loop B1). Reclaim PV (a South Australian-based company) and PV Industries (based in New South Wales) offer services to collect and recycle PV nationally. However, they are currently still working on establishing appropriate recycling technologies to achieve the highest material recovery rate [6]. Despite studies suggesting that 90% of the components in PV panels can be recovered [35], there is presently no economic incentive to recycle those components if a product stewardship scheme is not in place and the market for recovered materials has not been well-developed. Solar panels primarily consist of glass [34] that has a low commodity value. It is currently challenging to effectively recover the more valuable rare materials within PV panels without generating substantial environmental impacts as it requires extensive chemical usage [36]. A pilot study by Cutting and Gietman [37] also found that there is a limited market for recycled backing layers of the panels.

Despite a considerable number of BESS recyclers available in the major states of Australia [38], there is limited coordination and visibility of collection and recycling activities due to unavailable product stewardship scheme [3]. Lead-acid based batteries have an established industry in Australia [39] with around 99% of the materials capable of being recycled [40]. From a technical perspective, the recovery technologies for lithium-ion batteries are still immature and require extensive development to achieve a sufficiently high material recovery rate [41]. Envirostream is the only recycler in Australia which has a facility for pre-treatment processes of lithium-ion batteries. Likewise, from a regulatory perspective, there is currently no product stewardship scheme in place for BESS, where logistics and recycling activities are being led by industries voluntarily or supported by a few state governments [42].

The CLD also suggests that a higher collection rate will lead to a higher total collection cost, despite reducing the unit collection cost. Collected EoL PV panels and BESS may not always make it into
recycling (loop B2a) or repair/refurbishment process (loop B2b) as waste stockpiling can occur (loop B3) due to the limited availability of recycling technologies and infrastructures [43]. There is only a small number of PV panels are currently being recycled domestically with low level of recovery (i.e. aluminium frames) [8]. Despite the potential of promoting refurbishment activities for PV panels [35], developing refurbishment capability domestically will remain a big challenge. This is because the majority of PV panels in Australia are imported, whilst manufacturers have different product standardisation and design which will add complexity into the refurbishing process. There are also several barriers to the development of a local reuse and repair market including, such as the requirement for PV panels to be registered on the Clean Energy Council (CEC) approved product list in order for panels to be reintegrated with the energy grid, insurance limitations for replacing second-hand panels and inability to claim or transfer solar credits from the small-scale renewable energy certificate (STC) scheme.

Reinforcing loop R3 further explained the recycling flows between domestic and overseas processing pathways which is influenced by recyclers’ domestic recycling capacity. Both activities will result in a higher total cost of recycling, despite reducing the unit recycling cost. In other words, the higher total recycling costs derives from further treatment required (e.g. thermal treatment or chemical treatment) if a recycler intends to achieve a high material recovery rate. However, the signatory to the transboundary movement of hazardous materials raises a concern into stockpiling issues of lithium-ion batteries and solar panels (loop B3) given the absence of domestic recycling infrastructures for these products and the impossibility to export hazardous waste [42].

Landfill disposal, stockpiling, and illegal dumping of PV panels and BESS will contribute to high externality costs as both technologies consist of a considerable amount of heavy metals [44]. These externality costs include the opportunity cost of land and costs related to land pollution. Potential leachate of heavy metals in the landfill will also trigger direct costs for the government to prevent and manage the leachate as well as amenity costs [45], as well as costs emerged as a result of fire prevention due to stockpiling [42].

3.2.2 Subsystem 2 – Regulatory aspects

The second sub-system presents regulatory approaches to promote EoL management activities for residential PV and BESS in Australia. The CLD captured governments’ effort to introduce landfill ban or levy to divert hazardous waste from landfill including PV panels and BESS (loop B1). Despite ostensibly reducing landfill disposal, it may promote stockpiling activities (loop B3) without proper incentives for businesses to develop local recycling capability. Especially, considering many countries are increasingly placing a ban on receiving exported waste, including electronic waste. This
situation reflects the ‘fixes that fail’ archetype (Fig. 2) where an initial fix seems to overcome the problem symptom in the short run, but unintended consequences will follow after a time delay. In this case, stockpiling battery (particularly lithium-ion) will pose more fire risks than PV panels which will further exacerbate externality costs.

![Diagram of Waste stockpiling problem as fixes that fail archetype](image)

**Fig. 2. Waste stockpiling problem as fixes that fail archetype**

In order to avoid such a potential policy pitfall, landfill restrictions should be coupled with the introduction of a product stewardship scheme to incentivise industries to collect and recycle solar PV and BESS. There are three approaches in a product stewardship scheme, including voluntary, co-regulatory, and mandatory [46]. A voluntary approach is characterised by voluntary participation from consumers and industries to manage product life-cycle impacts. A co-regulatory approach requires the establishment and compliance of scheme participants to participate in the scheme and product stewardship organisations (PSOs) to provide collection and recycling services to scheme participants. A mandatory approach places a legal obligation on certain parties to take actions in regards to collection and recycling; however there is little or no discretion to industries on how requirements should be met. Typically, as scheme stringency increases, costs to government will increase which includes costs for policy design and implementation, staffing requirements, as well as government administration for monitoring and reporting the operationalisation and outcomes of the scheme [45].

In the case of co-regulatory and mandatory approach, regulatory impact statement of a scheme may differ from one product to another in regards to sharing responsibility across stakeholders along the supply chain and its funding model. The scheme may require the establishment of approved PSOs to organise collection and recycling services for scheme participants\(^1\) as well as scheme recycling target

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1 Scheme participants may include importers, manufacturers, distributors, and users, depending on the regulatory impact statement.
An example in the case of PV panels’ collection, PSOs may have to coordinate with PV installers to provide safe uninstallation services to residential consumers and to dispose them into designated collection points for recycling. A traditional collection approach to BESS (i.e. establishing reasonable access of collection points) can be utilised as they do not require a complex uninstallation process.

The funding model for co-regulatory and mandatory approach will also be determined by the government in close consultation with industries which can either be fully-funded by industries or shared costs between consumers and industries. The cost could be in the form of an upfront payment covering EoL uninstallation cost or as a service request charged at the end-of-life. Such a payment could be embedded in the purchase costs of PV modules and batteries and be covered by consumers or can be funded by industries. This funding should be managed by industry associations or PSOs in coordination with approved solar installers in order to ensure accountability. However, such a funding model should be implemented without rendering an uncompetitive price of PV panels and BESS.

The recovery target refers to the amount of liability of scheme participants which is calculated based on the scheme target in a particular period and the average number of products they imported or manufactured between the required lengths of liability period (e.g. 20 years) and may also include material recovery target in its calculation in the case of co-regulatory and mandatory approach. In practice, a scaling factor is used to scale down the amount of liability as not all of the manufactured and imported products along with the waste will end up in the domestic market. However, since this conceptual model is dealing with the projection of the domestic installation of residential PV/BESS, a scaling factor was not included in the model.

Establishing a threshold will be an effective strategy to create a sustainable product stewardship scheme. It aims to exclude small PV panel and BESS industries from being categorised as liable parties as they do not have a substantial market share to fund the product stewardship scheme. This type of intervention aims to minimise the financial burden of regulation on small businesses, but also to reduce costs to government as it minimises the scope of enforcement. A threshold can be determined on the basis of company size (e.g. employee size and annual turnover) or based on their activities (e.g. number of imports or manufactured products). In the case of PV panels and BESS, establishing a threshold based on the number of imports or manufactured products sounds more reasonable as small companies may import a large number of products or the other way around.
3.2.3 Subsystem 3 – Industry strategies and government incentives

The final subsystem represents industry strategies in response to the regulations enforced by the government as well as government incentives to promote investment and capacity building. PV panel and BESS industries are potential scheme participants which may or may not decide to participate in the scheme. Unless under co-regulatory and mandatory approach, eligible PV and BESS industries must comply as scheme participants. A voluntary approach that allows a high proportion of free-riders to scheme participation will result in fewer industry players taking financial responsibilities. In a situation where there are only a few manufacturers, importers and distributors that are willing to voluntarily participate in the stewardship scheme (i.e. voluntarily participate), other industry players may also be discouraged to participate as they would bear the financial and administrative burden for free-riders. Stakeholders argued that it is imperative to address free-riding problems in the case of EoL PV panels and BESS as economies of scale cannot be achieved if there is no substantial waste is being collected and processed (loop R5); thus, will likely result in a more expensive scheme. In this light, an important feedback loop in the CLD is the trade-off between scheme participants and free-riders\(^2\) (loop R4).

Under the co-regulatory or mandatory scheme, the lack of efforts’ improvement from PSOs to promote collection and recycling activities will cause a supply shortfall (i.e. the gap between the actual recycling and scheme recycling target) to a PSO. Although, however, supply surplus could potentially lead to a waste stockpiling problem as there is no funding available to process the remaining collected waste outside liability amount. This situation reflects the *drifting goals* archetype (Fig. 3). If there is a gap between the recovery target and the total recovered PV, PSOs and scheme participants may put pressure on the government to reduce the recycling target. To prevent eroding goals, the government must proactively raise a political pressure (e.g. administer penalties) for PSOs to improve if a certain PSO does not meet the target and supporting PSOs with various incentives. The PSO will then have to improve its effort to meet the recycling target in the following financial year and address the recycling shortfall carried forward. Otherwise, its authority as a PSO will be revoked if there is a continuous non-compliance [49].

\(^2\) A free-rider is defined as an industry who avoid to participate in the product stewardship scheme and being liable for the waste generated in the market.
Stakeholders argued that improving accessibility of uninstallation services and reachability of collection points throughout metropolitan, regional, and remote locations would be necessary to cover solar PV and BESS installation across different geographical areas (loop B6). PSOs can also increase their promotional effort (loop B4) to increase solar installers and consumers’ awareness of nearby collection points or solar panels uninstallation services. PSOs may also work together with the government and industry associations to incentivise industries or scheme participants to undertake circular business model (loop B5) to ensure that PV and BESS can be collected at the end of life-cycle. Examples include product-as-service, lease, and deposit-refund. These types of business models should be managed by PSOs or industry associations to ensure that they are sustainable.

Scheme participants become part of a PSO and will be liable to fund collection and/or recycling services. The cost to participate in the scheme largely depends on the recycling cost, the cost of PV de-installation or BESS collection, and whether or not the funding model will be industry-funded. PSOs’ administration cost may be funded using a fixed fee, in proportion to market share, or a combination of both, depending on their marketing strategy [48]. A comprehensive industry-funded scheme (from de-installation, collection, to recycling) would attract more consumers to safely dispose EoL PV and BESS. However, this could potentially create an unsustainable PV and BESS industries as the cost to scheme participants will be expensive. On the other hand, if consumers are required to absorb all of the costs to collect and recycle EoL PV and BESS this could lead to an unsatisfactory collection rate as second-hand market is a cheaper disposal option.

A PSO has a network of recyclers or internal recycling facility where the collected waste will be distributed across member recyclers. The CLD depicts the positive effect of member recyclers on the domestic recycling capacity. Member recyclers also ensure that EoL PV panels and BESS can be properly handled and recycled to achieve the highest level of recycling efficiency. On the other hand, there may be solar panels and batteries that will be collected and reprocessed outside the scheme (i.e. processed by recyclers that are not part of a PSO). Recyclers that are not part of PSOs may not have adequate recycling technologies to achieve the highest material recovery rate.
The decision to process PV panels and BESS materials domestically or internationally (loop R3) depends on the extent of the current domestic recycling capacity and capability and EoL volumes available. Domestic recycling capacity reflects the amount (i.e. mass) of materials which can be recycled domestically, whereas domestic recycling capability refers to the fraction of materials that can be recycled domestically. Australia’s current electronic waste recycling capability can only deal with steel, aluminium, copper, glass, and lead-acid batteries, whereas polymers, cables, and other batteries are being processed overseas [39]. Local recyclers are still developing their capability to recycle PV cells [8].

Despite the current ability to export non-hazardous materials overseas for recycling, there is an increasing trend of overseas waste export bans. In this light, there will be an increasing government’s pressure to improve domestic recycling capability (loop B8) in order to reduce the gap between domestic recycling capacity and the recycled waste (i.e. preventing future stockpiling problems). Recyclers’ decision to invest in developing local capability depends on a number of factors. However, this model focuses on the effect of the economic viability of specific materials to be recycled locally (loop B7). The economic viability is measured by looking at evidence of how improving domestic capability will affect the unit cost of recycling. This initiative should be coupled with various incentives such as infrastructure grants as well as research and development funding to support recycler investment ability as well as tax credits to reduce recyclers’ operational costs. However, technological development will also present industries with a new set of challenges as there will be potential material changes [50]. Thus, the development of recycling technologies should be adaptive to potential changes in materials. This loop is also reinforced by the economies of scale through sufficient development of domestic recycling capability and capacity which will reduces the unit recycling cost (loop R5). However, this reinforcing loop will remain weak until sufficient PV panels and BESS waste have been generated.

4 Conclusion and future directions

This research used a participatory ST approach by utilising various stakeholder engagement approach throughout the modelling process. One of the main advantages of the participatory approach utilised in this study is that problematic situations and opportunities can be identified from both stakeholder interviews and surveys. This approach enables triangulation of knowledge, mental models, and potential solutions from a wide range of stakeholders across Australian jurisdictions to construct the preliminary conceptual model. Problematic situations and potential solutions were identified through a systematic literature review, an iterative expert review process, and stakeholder survey. A
A preliminary CLD was developed on the basis of the key system variables identified from the problem scoping stage.

Two stakeholder workshop sessions were conducted in Australia in order to refine and validate the preliminary CLD. The final CLD can be explained in three parts: 1) waste flows; 2) regulatory aspects; and 3) industry strategies and government incentives. The conceptual model is governed by 13 feedback loops, consisting of eight balancing loops and five reinforcing loops. The CLD depicts the interplay between waste flows and different stakeholder roles and objectives. The role of government will be critical to introduce and monitor regulations as well as to determine an effective funding model for collection and recycling, leading to an optimal collection rate. PSOs will play a critical role in organising collection and recycling activities on behalf of scheme participants. In the event of co-regulatory and mandatory approaches, PSOs will also be responsible to ensure that the recycled waste meets the scheme target. Recyclers and system installers will be part of a PSO to deliver recycling services and PV uninstallation respectively on behalf of the PSO.

Two system archetypes were identified on the basis of the CLD, including *fixes that fail* and *drifting goals*. Several leverage points can be identified as key strategies to improve feedback loops. Coupling landfill restrictions and product stewardship scheme is an effective intervention to promote collection and recycling activities. A clear, consistent, and informative education and awareness that is accessible to diverse communities should form a major part of any product stewardship approach. However, incentives and recycler investments are required to develop domestic capability and capacity to avoid stockpiling issues. PSOs’ effort can be improved by increasing promotional activities, improving accessibility of uninstallation services and collection points, as well as implementing circular business models. Establishing a threshold is also necessary to avoid financial burden on small businesses which do not have a sufficient market share to fund the scheme.

Nonetheless, the dynamic behaviour of the system cannot be inferred from a qualitative model exclusively as it only depicts the collective knowledge of stakeholders. Future work involves the development of a quantitative SD model based on the CLD developed in this study. Such a model will be useful to evaluate different transition pathways towards an effective EoL management system of residential PV and BESS in Australia. SD model should be developed separately for these technologies as a separate product stewardship scheme will be considered by the government. Evaluation of how accurate the model replicates the real system behaviour can be comprehensively evaluated once the model has been quantified and simulated under certain parameters. Finally, although this paper focused on Australia as a case study, the discussions and recommendations are also applicable to other countries that are transitioning toward greater producer responsibility for electronic waste streams.
Acknowledgement

The authors would like to acknowledge Michael Dudley, a Senior Policy Officer at Australia New Zealand Recycling Platform (ANZRP) Limited for contributing to and supporting this research project. Hengky K. Salim would like to acknowledge Griffith University for funding this research project through the Griffith University Postgraduate Research Scholarship (GUPRS). Finally, the authors would also like to acknowledge Cities Research Institute, Griffith University through their internal Strategic Grant Development Initiatives.

References


