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Review

Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review

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A B S T R A C T

Distributed solar photovoltaic (PV) systems are a low-cost form of renewable energy technology that has had an exponential rate of uptake globally in the last decade. However, little attention has been paid to the potential environmental and human health related impacts associated with PV systems, if not managed properly at the end-of-life (EoL). Rare materials such as ruthenium, gallium, indium, and tellurium are essential components in PV panels, while battery energy storage systems (BESS) are composed of various chemistries (i.e. lithium-ion, lead acid, nickel cadmium, salt water, and flow batteries). An appropriate EoL management strategy for solar photovoltaic systems (i.e. PV modules, BESS) is necessary, not only to prevent and/or mitigate future environmental problems but also to reduce demand on rare earth materials. Drawn from a portfolio of 191 papers collected from Scopus and Web of Science databases between 2000 and 2018 (by 30 June 2018), a systematic quantitative literature review on solar energy systems EoL studies was conducted to examine the temporal trend of current research as well as methodological and geographical distributions of the published articles. Research has been concentrated within Europe, some parts of Asia, and North America, with experimental and modelling/simulation methods being mostly applied. The focus of this study was to compile and synthesise reported drivers, barriers, and enablers to EoL management of PV panels and BESS in the context of the circular economy. A conceptual framework is proposed to facilitate the transition of current PV system material flows and supply chain management practices to circular economy concepts. This paper also presents a future research agenda.

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1. Introduction

1.1. The inevitable waste problem of photovoltaic system boom

Photovoltaic (PV) systems are recognised as being a reliable, efficient, and environmentally-friendly source of energy. Despite the typical low impact operation, it does not necessarily mean that solar energy is completely free from environmental and human health related impacts throughout its life-cycle. Once PV panels, inverters and battery energy storage system (BESS) have reached the end of their individual life-cycles, they will form a large amount of electronic waste. PV panel and BESS contain hazardous materials such as lead, lithium, tin, and cadmium (Cucchiella et al., 2015a) which can harm the environment and human health if they are not properly managed at the end of life-cycle. They also contain valuable materials such as ruthenium, gallium, indium, and tellurium (Anctil and Fthenakis, 2013) which are scarce and worth recovering. Appropriate end-of-life (EoL) management (i.e. refurbishment, reuse, or recycle) of this technology is required, not only to mitigate environmental problems but also to avoid a shortage of critical materials to meet future resource demands. Appropriate EoL strategic planning will drive circular economy and enable more effective material recovery.

A considerable number of solar PV systems have reached the end of their life-cycle (Xu et al., 2018). Considering the exponential growth of consumer demand, the waste problem of PV panels and BESS is inevitable without an effective EoL management strategy. The global projection of installation capacity and future waste generation of PV panels and BESS is depicted on Fig. 1. The installation capacity in 2017 for PV panels is 390 GW (IRENA, 2017a), whilst BESS is 11 GWh (IRENA, 2017b). PV installation capacity will experience an exponential increase until 2030, but the growth rate will start to level-off afterwards. 4,133 GW of installed PV panels and 10,968 GWh of BESS (see Supplementary Material A for calculation details) can be expected by 2050. Although the quantity of waste PV panels is still relatively small over the next few years, a significant increase can be expected from approximately 2028. Considering an average lifetime of 20 years (Cucchiella et al., 2015a), 195,332 kilo tonnes of PV panel waste is projected by 2050. On the other hand, the recent adoption of BESS will experience a gradual increase until 2030 and substantially increase thereafter. The EoL BESS stock will accumulate at a faster rate as a result of shorter life-cycle of this system accessories[1] (May et al., 2018). This study projected 12,659 kilo tonnes of BESS waste by 2050.

1.2. End-of-life photovoltaic systems: what's next?

The current linear "*take-make-consume-dispose*" economic system practiced within PV systems will inevitably undermine the renewable status of this technology without an effective EoL management strategy (Sica et al., 2018). EoL PV systems management is only beginning to surface on the radar of government policy, with few countries (e.g. European countries) having well-established policy and regulation for post-consumption waste management (Xu et al., 2018). Circular economy philosophy attempts to close the supply chain loop by reducing the need for virgin materials via reuse or recycle of existing materials (Sica et al., 2018). The paradigm uses eco-design and *"Reduce, Reuse, Recycle"* principles to minimise waste throughout a product's life-cycle (Kalmykova et al., 2018). Integrating the life-cycle perspective within the circular economy paradigm will shape PV systems as a truly sustainable source of energy.

Several key issues at different stages of current linear supply chain practices are highlighted on Fig. 2. The manufacturing process of PV systems use rare materials; while both PV and BESS contain hazardous materials. At the manufacturing stage, few PV and BESS manufacturers have taken consideration into the design for environment (e.g. product design that allows removal of broken PV modules and replace them without damaging other parts). Enabling design for environment will prevent stockpiling of hazardous wastes by replacing broken parts or inefficient modules before they reach their maximum life-cycle. The implementation of product-service system remains limited to date especially due to the design challenges as well as the lack of knowledge and supply chain transparency (Reim et al., 2015). Within PV systems supply chain, only a few original equipment manufacturers (OEMs) have implemented take-back systems and/or established internal recycling infrastructure such as *First Solar* and *SolarWorld* (Besiou and Van Wassenhove, 2016). Additionally, a growing number of third-

[1] BESS has different lifespan depending on the type of batteries and a number of environmental factors (i.e. operating temperature). However, lithium-ion battery which is the most common type for stationary application have an average lifetime of 5–15 years (May et al., 2018).

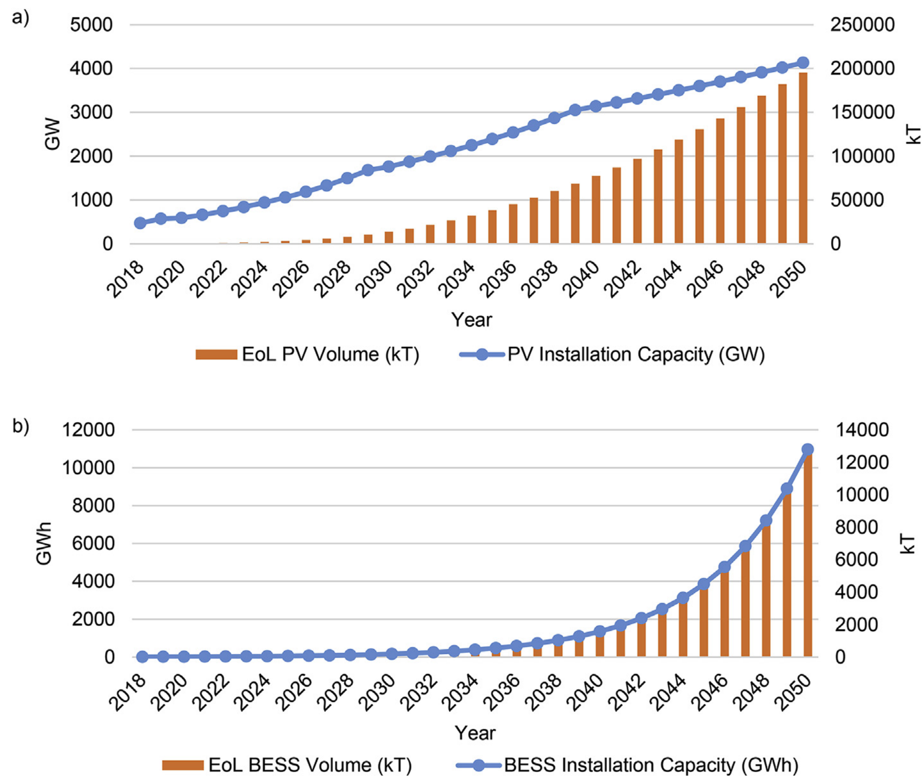

Fig. 1. Cumulative installation capacity and waste projection from 2018 to 2050; a) PV panels and b) BESS.

party recyclers have engaged with PV and BESS recycling on behalf of OEMs such as *PV CYCLE*, *Umicore*, etc. that allow OEMs and other liable parties to obtain a membership for voluntary or mandated recycling of EoL PV and BESS. A general lack of consumers' awareness and participation of recycling electronic waste (Tanskanen, 2013) is prevalent within PV and BESS supply chain. Many consumers and OEMs typically prefer to dispose the EoL products if the landfill costs cheaper than recycling (Besiou and Van Wassenhove, 2016). Informal recyclers can be a prevalent problem to effective EoL PV systems management in some countries (Yu et al., 2010) where they generally have lack of know-how to recycle the products, thus only a small fraction of parts and modules can be recovered.

The transition to a circular supply chain will unlock the untapped opportunities for each stakeholder along the supply chain. Enabling EoL management of PV panels and BESS may help to prevent shortage of rare materials to meet the future demand of solar PV systems. Manufactures may cut their production cost by reusing materials and reducing their dependency on import of raw materials (Kalmykova et al., 2018). Distributors and installers can achieve competitive advantage via increased green image and better customer trust (Reim et al., 2015). Within social perspectives, the circular transition of PV panels and BESS supply chain will allow job creation in collection and recycling sectors as well as reduced human health risks and environmental damages (Dominiguez and Geyer, 2017).

In order to shift from a linear to circular economy for the solar PV system supply chain, appropriate regulations and incentives are required to encourage actors along the supply chain to take proactive and collaborative actions. The circular solar PV systems supply chain configuration is depicted on Fig. 2. Product stewardship approaches such as extended producer responsibility (EPR), mandatory joint collection and recycling schemes, and shared responsibility among stakeholders are some of the possible strategies to promote participation in EoL collection and recycling activities (McDonald and Pearce, 2010). In addition, these approaches must offer flexibility between companies who intend to collect and recycle the products internally and through a joint recycling program with third-party providers (Malandrino et al., 2017). Furthermore, an innovative PV system circular business model, such as buy-back (Fthenakis, 2000), deposit-refund system, product-service system (Kalmykova et al., 2018), etc., is required to promote industry development and transition towards a circular economy. This business model may prioritise access rather than ownership arrangements, such as a contract or lease (Sica et al., 2018), to ensure a higher return rate once the contract has ended. Collection and recycling infrastructures also need to be decentralised to cater for the highly decentralised nature of PV system installations (Weckend et al., 2016).

This paper used the systematic quantitative literature review approach by Pickering et al. (2015) to reveal the future research directions within the discipline of EoL management of PV panels and BESS by examining the methodological and geographical trends of current literature from 2000 to 2018 (by 30 June 2018). The study then compiled and synthesised the drivers, barriers, and enablers to EoL management of solar PV and BESS, with the goal to develop a conceptual framework for transitioning the current PV system material flows and supply chain management practices to circular supply chain. Although a primary component to PV systems, inverter was excluded in this study because the part contain few hazardous materials (Kannan et al., 2006) and can be easily refurbished at the end of its life-cycle (Zweibel, 2010).

2. Material and methods

The systematic quantitative literature review method allows a reliable assessment to examine the current progress of a specific research topic and to identify the research gap for future research. Fig. 3 presents the overview of methodology used in this research.

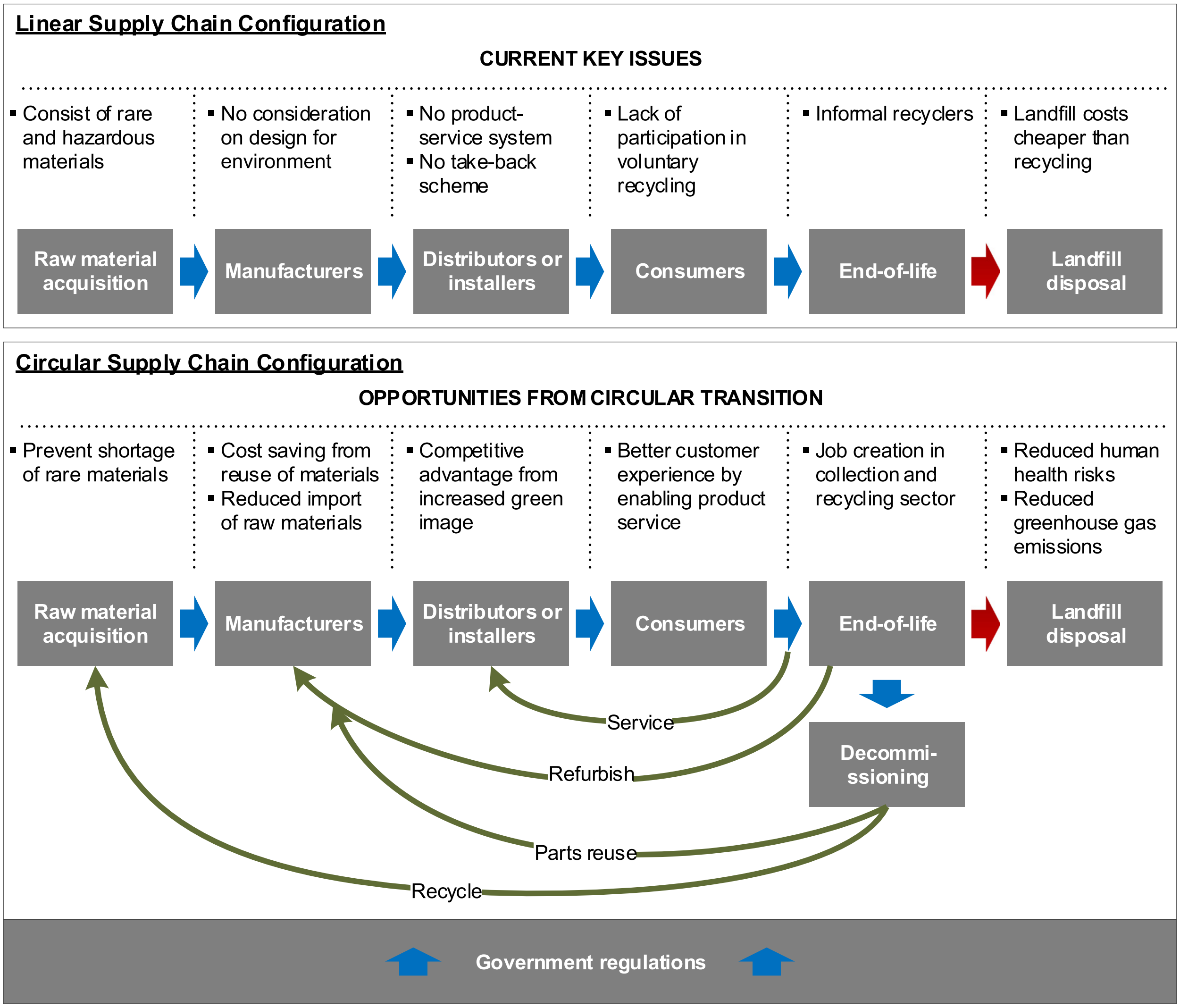

Fig. 2. Linear and circular supply chains of photovoltaic systems.

Firstly, the search criteria needs to be establish, including research questions, search keywords, databases, etc. Based on the established criteria, the researcher utilises databases for an articles search. Furthermore, the collected articles will be assessed according to their relevance on the topic. Irrelevant articles, duplicates, and references without full-text will be excluded from the analysis. The last step is to perform the content analysis to examine the temporal, geographical, and methodological distributions of the published articles as well as to synthesise the drivers, barriers, and enablers within the studied literature.

2.1. Search criteria

Search criteria were established in the first instance to develop a systematic guide to determine which articles need to be included in or excluded from the content analysis and the synthesis of barriers and enablers. The following criteria are used to conduct the articles search:

- The search query used is: *"end of life" OR recycl* AND (solar panel) OR photovoltaic OR (battery energy storage).*
- The scholarly databases used in this study were Scopus and Web of Science.
- This study only considers articles focus on EoL solar PV and BESS which refers to the waste generated during the post-consumption stage. Thus, studies on waste generated within the upstream supply chain are excluded from the analysis.
- The study period is limited from 2000 to 2018 (as of 30 June 2018).
- The search results are limited only to articles published in English language.

The search resulted in 844 articles from Web of Science and 1209 articles from Scopus. Academic literature included in this study consisted of relevant papers in refereed scientific journals, conference papers, books, and book chapters. Government and industry reports as well as other grey literature were excluded due to the difficulties to be collected systematically. Records from both databases were combined and 699 duplicates were subsequently removed, thus resulting in 1354 records.

2.2. Articles screening and eligibility assessment

The records were screened to eliminate articles without full-text, leaving 817 records available for eligibility assessment. In order to provide a rigorous process for the inclusion or exclusion of

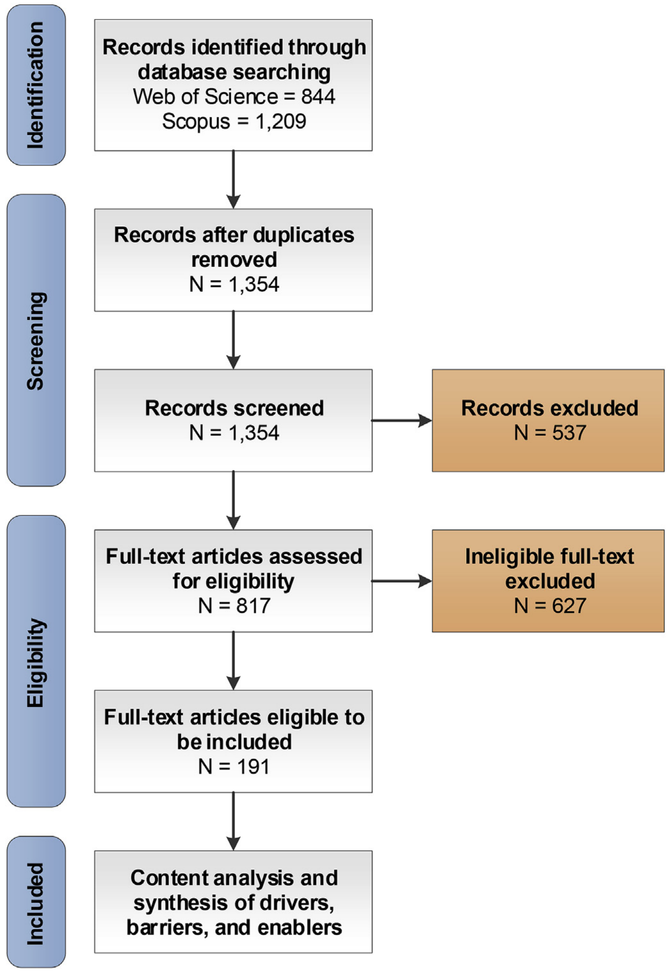

Fig. 3. Methodology overview.

articles, the eligibility assessment method is adapted from Hansen et al. (2015) and Salim et al. (2018). Four phases of assessment hurdles are employed in this research: title, keywords, abstract, and full-text (see Fig. 4). Specifically, the first assessment option is to examine the title of the article in the first instance. If the title is sufficient, then the paper can be included for content analysis. Otherwise, the keywords need to be examined, whether or not the article is relevant to the study. However, if the authors perceived that there is not enough evidence to include the papers based on the title and keywords, then they have to examine the abstract and full-text respectively. The included papers should address the issue of EoL PV panels and BESS (post-consumption waste), but also papers which discuss different type of renewable energies (e.g. solar energy, wind, hydropower, etc.) as long as it includes discussion on EoL PV systems. Due to the wide range of BESS applications (e.g. solar energy, wind, electric vehicle, etc.), this research only included EoL BESS from solar PV application. Otherwise, they will be excluded (e.g. waste generated during the production stage, recovery strategies of BESS for other applications such as electric vehicle, etc.). The assessment resulted in 191 articles being eligible to be included for content analysis and the synthesis of barriers and enablers. The list of articles, content analysis, and data synthesis is provided in the Supplementary Material B.

2.3. Content analysis

In this stage, each publication was further categorised according to its research subject, methodology used in the paper, as well as the geographical location of the first author's research institution. There are four research subjects identified after reading the articles: PV panel, BESS, both PV panel and BESS, and multiple renewable energy technologies (e.g. wind, geothermal, etc.). Based on the approach of Yuan and Shen (2011) and Engelken et al. (2016), the authors defined five categories of research methodology: literature review, modelling and simulation, case study, experimental, as well as theoretical and conceptual articles (see Table 1).

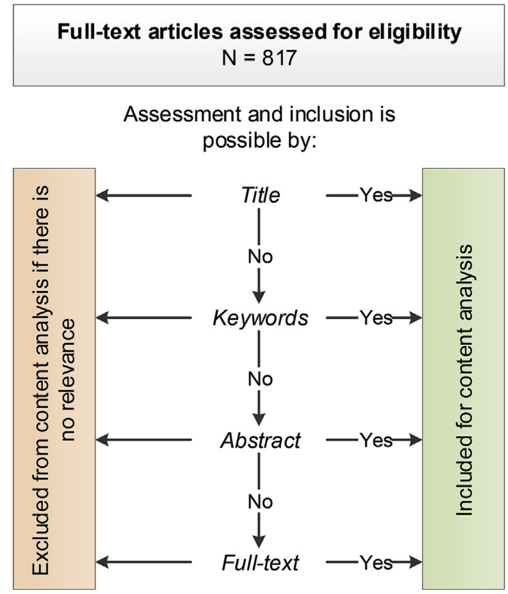

Fig. 4. A framework for inclusion or exclusion of articles.

2.4. Data synthesis

Data synthesis in this study involves summarising and combining the barriers, enablers, and drivers to EoL management of PV panels and BESS within the studied literature. This research followed a grounded theory (GT) approach by Strauss and Corbin (1990) to generate or discovery a theory that explains a process, action, or interaction of a topic. The developed theory from GT approach can take several forms including a narrative statement, hypotheses, propositions or a visual representation (Creswell, 1998). The approach started with *open coding* which refers to the identification, categorisation, and description of events found within the text, i.e. the researcher structure initial codes of barriers, enablers, and drivers found within the studied literature. Commonalities (e.g. based on similarity of meaning) among open codes can be categorised into several *axial codes* (concepts). The final step is *selective coding* where a core category is chosen if a group of concepts reflect to the respective core category.

The following example illustrates how open, axial, and selective coding strategies were applied in this study. Larsen (2009) mentioned “Currently, economic incentives may be inadequate to move the PV industry into voluntary recycling.” The researchers then coded this statement as “lack of economic incentives for recycling”. Anctil and Fthenakis (2013) stated “… as there will be no economic incentive for recycling.” The researchers coded this statement as “no economic incentives for recycling”. Both open codes from Larsen (2009) and Anctil and Fthenakis (2013) can be categorised into an axial code named “lack of economic incentives for recycling”. Meanwhile, Besiou and Van Wassenhove (2016) stated “… currently no global EPR regulation of the design,

Table 1
Category for research methodology classification.

Research Methodology	Description
Review	A study that reviews and analyses the progress of current research (Yuan and Shen, 2011)
Modelling and Simulation	A study that uses a model from mathematical functions for decision-making purposes (e.g. optimisation, simulation, system dynamics, life cycle assessment) (Yuan and Shen, 2011)
Case Study	A study that uses qualitative data (e.g. interview) to examine a problem or a case in one or some organisations. (Yuan and Shen, 2011)
Experimental	A study that uses a systematic and scientific procedure to manipulate one or more variables in order to achieve a result (Yuan and Shen, 2011)
Theoretical and Conceptual Articles	A study that discusses theories or conceptual framework (Engelken et al., 2016)

collection, or recovery of PV waste.” The researchers gave an open code “no regulation” for this statement and put this open code into axial code of “no regulation in place”. Since both of these axial codes are related to policy and economic barriers, they were categorised into a selective code named “policy and economic barriers”.

3. Analysis and results

3.1. Content analysis

Based on Table 2, the most widely studied research subject in the performed research is EoL PV panel, in which 152 articles (79.6%) have been published within the study period, with fewer studies addressing the EoL of BESS (29 articles; 15.2%). Studies addressing coupled EoL solar PV and BESS were few (5 articles; 2.6%); similarly, studies covering multiple renewable energy technologies EoL management were few (5 articles; 2.6%).

Experimental work was the most widely applied research methodology within EoL management of PV panels and BESS studies (81 articles; 42.4%). This was followed closely by *modelling and simulation* methods which accounted for 76 articles (39.8%). LCA (32) and mathematical modelling (14) were the most widely applied *modelling and simulation* approaches. 15 articles (7.8%) were dedicated to *theoretical and conceptual* framework, whilst 11 articles adopted a *case study* approach (5.8%). Review articles accounted for the least share of publications (8 articles; 4.2%).

The geographical location of the first author was mainly concentrated in European countries accounting for 81 articles (42.4%). Among this region, Italy had the largest share of publications (25), followed closely by Germany (20). Asia contributed to 55 articles (28.8%) where China (21), South Korea (12), and Japan (10) were the most research intensive countries in this topic. The third largest contributor was North America, accounting for 48 articles (25.1%). Within this region, United States contributed the largest number of publications (42). There were scant articles coming from other countries including those located in South America, Middle East, Oceania or Africa, which made up only seven articles (3.7%), collectively.

Table 2
Distribution of published articles.

Category	No of Articles	Percentage
Research Subject		
PV Panel	152	79.6%
BESS	29	15.2%
Both	5	2.6%
Multiple Renewable Energy Technologies	5	2.6%
Research Methodology		
Experimental	81	42.4%
Modelling and Simulation	76	39.8%
-LCA	*32*	
-Mathematical Modelling	*14*	
-Material Flow Analysis	*5*	
-Multi-Criteria Decision Making	*4*	
-Life Cycle Costing	*2*	
-Environmental Impact Assessment	*2*	
-Discounted Cash Flow	*2*	
-Multiple Modelling Methods	*5*	
-Other Modelling and Simulation Methods	*10*	
Theoretical and Conceptual Articles	15	7.8%
Case Study	11	5.8%
Review	8	4.2%
Geographical Context		
Europe	81	42.4%
-Italy	*25*	
-Germany	*20*	
-Spain	*7*	
-Belgium	*5*	
-Poland	*4*	
-Switzerland	*4*	
-United Kingdom	*4*	
-Austria	*3*	
-France	*3*	
-Other European Countries	*6*	
Asia	55	28.8%
-China	*21*	
-South Korea	*12*	
-Japan	*10*	
-Taiwan	*8*	
Other Asian Countries	*4*	
North America	48	25.1%
-United States	*42*	
-Canada	*6*	
Other	7	3.7%

3.1.1. General trends

The trend indicates a growing interest from the scientific community in managing EoL PV panels and BESS (see Fig. 5). The trend can be divided into two growth stages. In the first half of the study period (between 2000 and 2009), it can be argued that the research topic was undergoing an incubation period where a fluctuating trend can be observed as well as the absence of publications in 2002 and 2008. In the post-2009 period, the research begins to increase considerably. Overall, between 2009 and 2017, there has been at least a ten-fold increase in research activity. Readers should note that the 2018 value (21 articles) represents publications reported by the first half of year and should exceed the total number of articles reported in 2017 by year end.

Articles researching on EoL management of PV panels are the fastest growing research subject, climbing from two articles in 2001 to 29 articles in 2017, although the number has fluctuated between 2000 and 2008. Researchers' interest on EoL BESS studies emerged from 2011 with only one published article and followed by a slow growth until the latter period. A peak of eight articles can be seen in 2017. There is only one published article on studies focused on both EoL PV panels and BESS in 2000, but no further studies had been conducted on this research subject until 2013. A further two articles were published in 2014, which was followed by only one article being published in 2017 and another in 2018. A similar unclear trend can be observed on EoL management of multiple renewable

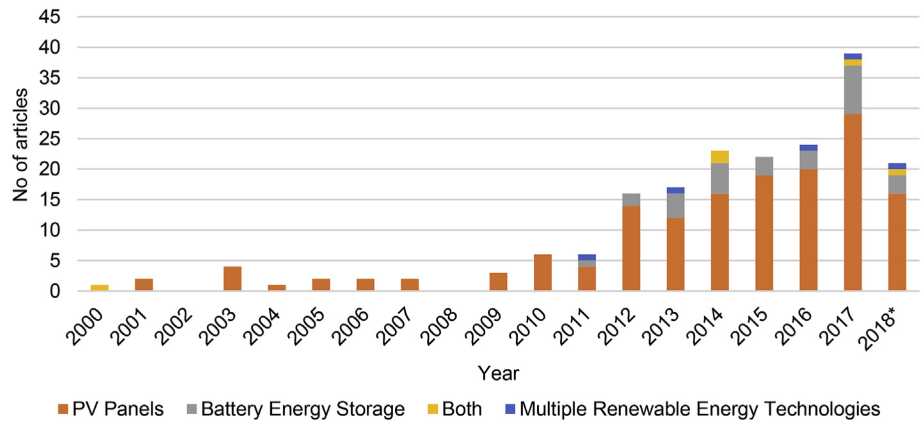

Fig. 5. Temporal distribution of published articles based on the research subject.

energy technologies studies, where there was only one article published in 2011, 2013 and from 2016 to 2018.

3.1.2. Methodological trends

As seen in Fig. 6, *experimental research* followed an upward trend from two articles in 2001 to 14 articles in 2017, despite some small decline in certain years, including the latter year (five articles). The use of *modelling and simulation* methods increased from one article in 2003 to 17 articles in 2017 despite some noteworthy absence during the first half of the study period. *Theoretical and conceptual* articles follow an uncertain trend with a peak of six articles in 2017. Research using a *case study* method follows a fluctuating trend during the study period with a peak of three articles in 2016. Similarly, no literature review articles have been produced until 2012.

3.1.3. Geographical trends

As seen in Fig. 7, Europe is at the forefront of countries leading the research on this topic with only one article published in 2004 and increasing to 17 articles in 2017. There are nine articles

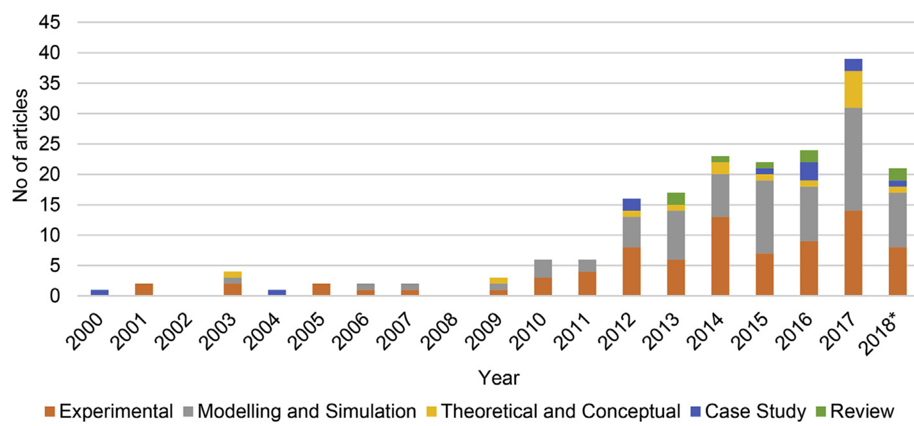

Fig. 6. Temporal distribution of research methodology.

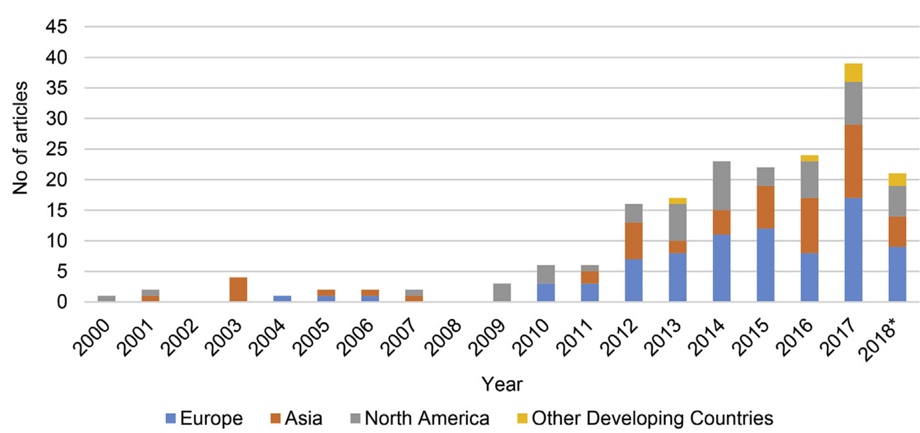

Fig. 7. Temporal distribution of geographical location of the first author.

published within the first half of 2018 which indicates an increase in the latter year. A fluctuating trend can be seen within the first half of the study period in Asia. However, there is an upward trend from one article in 2001 to 12 articles in 2017, whereas four articles published in 2018. Similarly, a fluctuating trend can be observed within North America between 2000 and 2008. An upward trend with a slight decline can be observed in the following period. Research in other regions contributed few publications to this research in the period.

3.2. Data synthesis

3.2.1. Drivers

Drivers are key opportunities which motivate stakeholders in promoting the uptake of EoL management of PV panels and BESS. The synthesis found a list of 10 drivers as seen in Table 3. Actors within the supply chain associated with each driver are described. The drivers were clustered under three categories:

- *Economic*: this cluster refers to economic opportunities that motivates stakeholders to implement EoL management of PV panels and BESS.
- *Social*: this cluster includes social benefits such as job creation, stakeholder expectations, and reducing human health risks.
- *Environmental*: this cluster includes driving factors associated with stakeholders' effort to mitigate environmental problems.

3.2.2. Barriers

Barriers refer to factors that hindered the implementation of EoL management of PV panels and BESS. Identifying these barriers will help policy makers to formulate a robust strategy to mitigate future challenges. This study identified 16 barriers from the collected literature as seen in Table 4. The involved actors within each barrier are described. These barriers have been classified into five clusters as described below:

- *Policy and economic*: this cluster refers to government policy and regulation, companies' policy, or economic factors that will hamper the implementation of EoL management of PV panels and BESS.
- *Social*: this cluster includes factors covering the lack of cooperation between actors involved in the entire solar energy system supply chain.
- *Market*: this cluster includes impediments originating within the broader consumer market or competition between manufacturers.
- *Environmental*: this cluster refers to the potential environmental impacts resulting from recovering EoL PV panels and BESS.
- *Recycling infrastructure*: this cluster represents the complexity of the system as well as the lack of adequate infrastructures needed to support collection and recycling programmes.

3.2.3. Enablers

A comprehensive understanding into the enablers to an effective EoL management of PV panels and BESS is the key to overcome the perceived barriers. Table 5 presents the aggregation of what scientific communities identified as the enablers, a description for each of them, and the involved actor(s). The authors synthesise the list of 15 enablers from the collected articles and structured them into five clusters:

- *Policy and economic*: this cluster refers to the factors, such as regulations, companies' policy on collection and recycling, as well as economic incentives to support EoL management of PV panels and BESS.
- *Social*: this cluster encompasses the interaction or cooperation between actors along the entire supply chain to promote refurbishment of recycling of PV panels and BESS.
- *Market*: this cluster refers to the optimal market condition to enable sufficient quantity of EoL products to be recycled and increasing demand of recycled products.
- *Behavioural*: this cluster refers to the level of environmental awareness among actors in the supply chain that will promote collection and recycling activities.
- *Recycling technology and infrastructure*: this cluster involves the potential development of new recycling technologies, infrastructure, and technical feasibility of recycling via eco-design.

4. Discussion

4.1. Current research trend

The small number of literature on EoL BESS reflects the massive share of on-grid photovoltaic system installations to date, which explains researchers' strong interest on managing EoL PV panels that are many times more prevalent than BESS. The trend is expected since widespread coupling of BESS with solar PV was cost-prohibitive until recently and there were not mass production and installation of such products (e.g. *Tesla Powerwall* system) for mainstream consumers. However, the coupling of PV with BESS will become more prevalent in the future as government, electricity providers and consumers become aware of the deficiencies of standalone solar PV, as well as the energy management benefits of these coupled systems (Katsanevakis et al., 2017a, b). It is expected that the uptake of coupled systems in the coming decade will display a similar growth trajectory to grid-connected small scale solar systems over the past decade (Katsanevakis et al., 2017a, b). Furthermore, there is less interest in studies investigating multiple renewable energy technologies since this subject can only be plausible within some methodological aspects such as case study or theoretical and conceptual papers, i.e. to compare barriers, enablers, and possible strategies to manage the EoL renewable energy technologies.

Experimental approach was the most widely applied method to EoL management of solar energy systems research and has considerably increased during the study period. This is largely due to the significant opportunity to improve recycling technologies of solar PV and BESS, particularly in regard to developing technical, economic, and environmental feasibility (Heelan et al., 2016; Xu et al., 2018). This trend was followed by *modelling/simulation method* which began when the scientific community started to look from the complex system perspective. This increasing trend is of interest to a wide audience as it will provide insights into optimal EoL management approaches for EoL solar PV and BESS (e.g. logistics costs, number of collection and recycling infrastructures, profitability, etc.). *Theoretical and conceptual articles* as well as *case study* remain poorly represented. Thus, further studies using these methods are necessary to reveal current challenges and potential enablers as these factors can vary across geographical locations. This will in return provide a basis for policy makers to formulate a systematic strategy to develop an effective EoL management for PV panels and BESS.

The predominance of publications in developed countries found in this study can be explained by two key factors. First, following the 2005 Kyoto Protocol, developed regions have increased their commitment to renewable energy implementation, including solar PV systems (Khoury et al., 2016). Thus, concerns have been put on the accumulation of EoL solar PV and batteries in the foreseeable

Table 3
Drivers to EoL management of PV panels and BESS.

Drivers	Description	Involved Actor(s)	References
Economic (ECD)			
Conserve and recirculate rare materials (ECD1)	Enabling responsible EoL management of PV panels and BESS in line with circular economy concepts will prevent shortage of rare materials and ensure resources are used to their fullest potentials	Producers, Governments	Anctil and Fthenakis (2013); Dominiguez and Geyer (2017); Fthenakis (2009); Giacchetta et al. (2013); Goe and Gaustad (2016); Hoang et al. (2014); Marwede and Reller (2012); Paiano (2015); Palitzsch et al. (2014); Sinha (2013); Xu et al. (2018)
Cost saving from reuse and recycle of materials (ECD2)	PV panels and BESS contain valuable materials that can save production costs via reuse and recycle of materials.	Producers, Recyclers	Choi and Fthenakis (2010b); Corcelli et al. (2017); Cucchiella et al. (2015a); D'Adamo et al. (2017); Hsueh and Lin (2015); Marwede and Reller (2012); Redlinger et al. (2015); Sinha (2013)
Enhancing competitiveness of producers and distributors (ECD3)	EoL management will increase company's green image and subsequently increase consumer and stakeholder trusts.	Producers, Installers	Larsen (2009); McDonald and Pearce (2010); Xu et al. (2018)
Reducing dependency of raw materials import (ECD4)	Materials embedded in PV panels and BESS are sourced from different locations, enabling reuse and recycling of these materials will reduce material import demand.	Producers, Governments	Dominiguez and Geyer (2017)
Social (SOD)			
Opportunities for job creation (SOD1)	EoL management of PV panels and BESS will create more job opportunities.	Governments, Producers, Recyclers	Dominiguez and Geyer (2017); McDonald and Pearce (2010); Yu and Halog (2015)
Reducing human health risks (SOD2)	Recovering and recycling EoL PV panels and BESS will prevent hazardous materials from entering landfill, thus minimising risks to human health.	Consumers, Producers, Recyclers	Cucchiella et al. (2015b); Dominiguez and Geyer (2017); Yu and Halog (2015)
Meeting stakeholder expectations (SOD3)	Governments, academics, consumers, etc. are increasingly aware of the impacts of improper disposal of EoL PV panels and BESS, thus expecting producers and recyclers of responsible disposal of EoL PV panels and BESS.	Consumers, Producers, Recyclers	Shiue and Lin (2012)
Environmental (END)			
Reducing greenhouse gas emissions (END1)	Enabling reuse and recycle of materials embedded in PV panels and BESS will prevent significant greenhouse gases generated during production stages.	Producers, Recyclers, Consumers	Alonso et al. (2017); Choi and Fthenakis (2010a); Dominiguez and Geyer (2017); Fthenakis (2009); Goe and Gaustad (2016)
Reducing energy payback time (END2)	EPBT is the amount of time for energy to be generated to equal the total energy required to manufacture the system. Less energy is required to refurbish and recycle PV panels and BESS than manufacturing from virgin materials.	Producers, Recyclers	Alonso et al. (2017); Dominiguez and Geyer (2017); Goe and Gaustad (2014); Raugei et al. (2012)
Ensuring appropriate EoL management strategies via evidence of product and material impacts (END3)	If evidence arises which demonstrates how a product or material has a negative impact on the environment or human health, consumers and/or governments may demand EoL management options which mitigate or address the impacts identified.	Governments, Academics, Consumers	Dominiguez and Geyer (2017); Paiano (2015)

Table 4
Barriers to EoL management of PV panel and BESS.

Barriers	Description	Involved Actor(s)	References
Policy and Economic (PEB)			
Lack of profitability to recycle (PEB1)	The cost of recovery is higher than the value of recovered materials as well as producing from virgin materials.	Producers, Recyclers	Al-Thyabat et al. (2013); Anctil and Fthenakis (2013); Arranz et al. (2014); Besiou and Van Wassenhove (2016); Bomgardner and Scott (2018); Brenner and Adamovic (2017); Collins and Anctil (2017); Fthenakis (2000); Giacchetta et al. (2013); Heelan et al. (2016); Kusch and Alsheyab (2017); Larsen (2009); Marwede and Reller (2012); McDonald and Pearce (2010)
No regulations in place (PEB2)	There are no specific regulations regarding collection and recycling target for PV panels and BESS as well as financial and non-financial responsibilities of actors along the supply chain.	Producers, Governments	Al-Thyabat et al. (2013); Besiou and Van Wassenhove (2016); Besiou et al. (2012); Collins and Anctil (2017); Dominiguez and Geyer (2017); Larsen (2009)
Lack of economic incentives for collection and recycling (PEB3)	There are no or few incentives offered to promote EoL collection and recycling activities.	Producers, Installers, Governments	Anctil and Fthenakis (2013); Duan et al. (2016); Fthenakis (2000); Kadro and Hagfeldt (2017)
Current collection scheme is not robust (PEB4)	Current business models or collection policies are not effective to attract producers to collect or consumers to return EoL PV panels and BESS and does not mandate participation from actors along the supply chain.	Governments, Producers, Installers, Recyclers	Heelan et al. (2016); Jung et al. (2016); Larsen (2009)
No incentives are given to design for recycling (PEB5)	There are no incentives (i.e. grants, awards) given to promote research and development (R&D) activities for developing easy-to-recycle PV panels and BESS.	Governments, Producers	Besiou and Van Wassenhove (2016); Besiou et al. (2012)
Social (SOB)			
Lack of consumers' willingness to return EoL products (SOB1)	Some consumers are reluctant to return the products because they feel it is manufacturers' or governments' responsibility.	Consumers	Besiou et al. (2012)
Lack of coordination among producers and recyclers (SOB2)	Producers are reluctant to share product information to recyclers due to market competition. Thus, recyclers cannot determine the best method to recycle them.	Producers, Recyclers	Besiou and Van Wassenhove (2016)
Market (MAB)			
Insufficient quantity of EoL products (MAB1)	Countries with less developed PV and BESS markets will see only a small quantity of EoL PV panels and BESS become available for recovery, thus making the recycling process unprofitable.	Consumers, Producers, Recyclers	Al-Thyabat et al. (2013); Besiou and Van Wassenhove (2016); Choi and Fthenakis (2014); Fthenakis (2000); Gómez et al. (2012); Kadro and Hagfeldt (2017); Kusch and Alsheyab (2017); Latunussa et al. (2016); Marwede et al. (2013); Yi et al. (2014)
Poor market confidence in refurbished and recycled products (MAB2)	There is a low level of confidence in refurbished and recycled PV panels and BESS especially in terms of perception around decreased efficiency and durability.	Producers, Recyclers, Governments	Arranz et al. (2014); Besiou and Van Wassenhove (2016); Besiou et al. (2012); Bomgardner and Scott (2018)
Various typical life-cycle across PV panels and BESS (MAB3)	PV panels and BESS have varied typical lifespans (approximately an average of 20 years for PV panels and 7–20 years for BESS) which presents issues for consolidated EoL management and regulatory approaches.	Producers, Consumers, Installers, Recyclers, Governments	Arranz et al. (2014); Uppal et al. (2017)
New manufacturers introducing price competitive products (MAB4)	New manufacturers of price competitive PV panels and BESS lack maturity in environmental responsibility.	Producers	Besiou and Van Wassenhove (2016)
PV panels and BESS are emerging technologies with a potential of material changes (MAB5)	New product technologies and materials embedded in PV and BESS will continue to add complexity to EoL management options and regulatory approaches.	Producers, Recyclers, Governments	Larsen (2009)
Environment (ENB)			
Emissions and pollution generated during recycling (ENB1)	Intensive chemical usage, thermal treatments, and machineries during the PV panels and BESS′ recycling process.	Producers, Recyclers	Marwede et al. (2013); Strachala et al. (2017); Tao and Yu (2015); Tian et al. (2017)
Energy intensive recycling process (ENB2)	High energy demand for recycling EoL PV panels and BESS.	Producers, Recyclers	Alonso et al. (2017); Marwede and Reller (2012); Tao and Yu (2015)
Recycling Infrastructure (RIB)			
EoL recycling process complexity (RIB1)	Recycling process complexity includes: uncertain quality of EoL products, products dispersed in various geographical location, various technologies are required since there are various types of PV panels and BESS, etc.	Governments, Producers, Recyclers, Consumers	Al-Thyabat et al. (2013); Bogacka et al. (2017); Brenner and Adamovic (2017); Choi and Fthenakis (2010b); Fthenakis (2000); Goe and Gaustad (2016); Latunussa et al. (2016); Marwede et al. (2013); Masoumian and Kopacek (2015); Tao and Yu (2015)
Lack of adequate collection centres and recycling plants (RIB2)	PV panels and BESS′ installation is dispersed in various geographical locations. Adequate collection centres and recycling plants are required to ensure high collection and recycling rates.	Producers, Recyclers	Choi and Fthenakis (2014); Goe and Gaustad (2016); Jung et al. (2016); Lapko et al. (2018); Vellini et al. (2017)

future. Secondly, countries in developed economies play a leading role in driving policy discourse on product stewardship for managing EoL products (Weckend et al., 2016). Europe, in particular, has been the leading voice of regulatory initiatives managing EoL PV panels and BESS via WEEE and Waste Batteries and Accumulators directives. It is reported that the United Kingdom has successfully recovered 84.7% of waste PV panels, whilst France has successfully recovered 96.1% of their PV panel waste in 2015 (Eurostat, 2017).

Table 5
Enablers to EoL management of PV panel and BESS.

Enablers	Description	Involved Actor(s)	References
Policy and Economic (PEE)			
Introduce strict regulations and policies such as product stewardship (PEE1)	Regulations can force consumers, producers, and recyclers to return/collect the products at the end of their life-cycle as well as by urge producers or recyclers to meet a certain standard of recovery rate.	Governments	Besiou and Van Wassenhove (2016); Brenner and Adamovic (2017); Giacchetta et al. (2013); Gottesfeld and Cherry (2011); Hsueh and Lin (2015); Larsen (2009); Malandrino et al. (2017); Marwede et al. (2013); Marwede and Reller (2012); Sica et al. (2018); Xu et al. (2018)
Implementing business model for take-back/ collection scheme (PEE2)	The availability of take-back/collection scheme allows consumers to return their products at the end of life-cycle for recovery process through various business models (buy-back, lease, etc.).	Producers, Recyclers	(Arranz et al., 2014); Choi and Fthenakis (2010b); Collins and Anctil (2017); Fthenakis (2000); Gottesfeld and Cherry (2011); Kadro and Hagfeldt (2017); Kusch and Alsheyab (2017); Marwede et al. (2013); Peeters et al. (2017); Raugei et al. (2012); Sica et al. (2018); Sinha (2013); Yu and Halog (2015)
Provide economic incentives to increase collection and recycling (PEE3)	The economic incentives to promote effective EoL management of PV panel and BESS: subsidies to recovery technologies, tax relief, penalty for non-compliance, and increasing virgin materials' price.	Governments	Anctil and Fthenakis (2013); Arranz et al. (2014); Jia and Fang (2016); Lapko et al. (2018); Larsen (2009); Marwede et al. (2013); Marwede and Reller (2012); McDonald and Pearce (2010); Xu et al. (2018)
Stimulate design for recycling by providing various incentives (PEE4)	Enabling incentives will stimulate research and development (R&D) to increase recyclability of PV panel and BESS (i.e. easy to disassemble).	Governments	Besiou and Van Wassenhove (2016); Espinosa et al. (2015); Marwede et al. (2013); Tran and Khambadkone (2013); Xu et al. (2003)
Increasing landfill cost of hazardous materials (PEE5)	A higher cost of disposal will make recycling a more affordable alternative.	Governments	Besiou and Van Wassenhove (2016); Xu et al. (2018)
Market (MAE)			
Standardisation and warranties for recycled products (MAE1)	Standardisation and warranties for recycled products will help to develop market on recycled products by providing guarantee on quality and reliability.	Producers	Arranz et al. (2014); Besiou and Van Wassenhove (2016); Xu et al. (2018)
Developing end market for PV and BESS (MAE2)	A developed market of PV and BESS will enable sufficient quantity of EoL PV panels and BESS for recycling, thus making recycling more affordable.	Consumers, Producers, Recyclers, Governments	Besiou and Van Wassenhove (2016); Gottesfeld and Cherry (2011); Lapko et al. (2018)
Social (SOE)			
Promoting cooperation among stakeholders (SOE1)	Cooperation among stakeholders is required to enable constructive and collaborative discussions on policy or recycling solutions.	Governments, Recyclers, Producers, Consumers, Research Institutions	Brenner and Adamovic (2017); Lapko et al. (2018); Marwede et al. (2013); Sica et al. (2018); Xu et al. (2018)
Developing industrial symbiosis network (SOE2)	Industrial symbiosis network is an association of two or more industries which enables an exchange of recovered materials from waste or by-products.	Producers, Recyclers	Arranz et al. (2014); Arranz et al. (2012); Brenner and Adamovic (2017); Nosrat et al. (2009)
Information transparency across the supply chain (SOE3)	Manufacturers should label their products clearly to provide information to recyclers the best method to recycle the products and provide a guide to consumers for proper disposal in a collection facility.	Producers, Recyclers, Consumers	Besiou and Van Wassenhove (2016); Xu et al. (2018)
Behavioural (BEE)			
Improving consumers' environmental awareness (BEE1)	Consumers' environmental awareness is important to promote high collection rate of EoL PV panel and BESS as well as to develop market of recycled PV and BESS.	Consumers	Hsueh and Lin (2015); Xu et al. (2018)
Promoting corporate social responsibility (BEE2)	Some producers recycle PV and BESS wants to demonstrate social and environmental responsibility (increase their green reputation) although it is not profitable to recycle.	Producers, Recyclers	Alonso et al. (2017); Besiou et al. (2012); Hsueh and Lin (2015); McDonald and Pearce (2010)
Promoting shared value business strategies (BEE3)	Shared value business strategies aim to create measurable economic benefits by identifying and addressing social and environmental issues associated with their business	Producers	Sica et al. (2018)
Recycling Technology and Infrastructure (TIE)			
Research and development on new efficient recycling technologies (TIE1)	R&D is required in order to achieve more cost-effective technologies for recycling waste PV panels and BESS as well as to increase the recovery rate of the materials.	Government, Producers, Recyclers	Al-Thyabat et al. (2013); Arranz et al. (2014); Cucchiella et al. (2015a); Fthenakis (2000); Gómez et al. (2012); Heelan et al. (2016); Lapko et al. (2018); Uppal et al. (2017)
Optimal number of collection centres and recycling plants (TIE2)	The optimal strategy for the number and type of (e.g. centralised or decentralised) collection centres and recycling plants ensures optimal balance between the collection rate as well as economic and environmental feasibilities.	Producers, Recyclers	Arranz et al. (2014); Bogacka et al. (2017); Choi (2017); Choi and Fthenakis (2010a); Fthenakis (2000); Gómez et al. (2012); Kusch and Alsheyab (2017); Marwede et al. (2013)

The circular economy package introduced by European Commission in 2016 enables higher recycling targets and stricter enforcement for waste prevention and reuse (Bourguignon, 2016). In addition, some states (e.g. Washington, Maine, Texas, Minnesota, etc.) in the United States have a strong implementation of EPR schemes for various EoL electronic products (Nash and Bosso, 2013).

In developing countries where government strategies for renewable energy transition are less robust or even non-existent (Khoury et al., 2016), there are no inherent pressures or incentives for the scientific community and industry to address the issue of EoL management of PV panels and BESS. The subsidised nature of electricity from fossil fuels in many developing countries (Sovacool, 2017), has meant that solar PV systems and other renewable energy technologies are less favourable. China is an exception, where it has led PV installation capacity in less than a decade (Xu et al., 2018) and a large number of PV and BESS manufacturing companies are based in China. Many researchers in China have started research focused on mitigating the impending waste solar PV and BESS problems, although most Chinese PV systems have not yet reached the end of their life-cycle. A more balanced research between technological and policy aspects can be used as a basis to influence the Chinese government to regulate the EoL management of PV panels and BESS in the foreseeable future.

4.2. Critique of drivers, barriers and enablers

4.2.1. Drivers

The reasons for implementing EoL management of PV panels and BESS span across the entire sustainability spectrum i.e. economic, social, and environmental aspects. Conserving and recirculating rare materials (ECD1) in line with circular economy concepts was regarded as a key opportunity driving governments, producers, and other stakeholders towards EoL management of PV panels and BESS. This issue is more prevalent within EoL PV panels since rare materials e.g. ruthenium, gallium, indium, and tellurium are embedded within the modules (Cucchiella et al., 2015a). EoL PV panels and BESS contain valuable materials that can potentially save production costs (ECD-2) via reuse and recycling. Although some recycling methods can be unprofitable, some companies go beyond legal requirement by enabling internal recycling infrastructure of PV panels such as *First Solar* and *SolarWorld*. This type of companies tend to focus in obtaining market competitiveness (ECD3) via increased green image (McDonald and Pearce, 2010). In some countries, materials to manufacture PV panels and BESS are sourced throughout different geographical regions (Dominiguez and Geyer, 2017). In this sense, the uptake may be driven by government's effort to reduce dependency of virgin material imports (ECD4).

Enabling EoL management of PV panels and BESS presents a significant opportunity for employment growth (SOD1). Thus, the uptake maybe driven by government's aim to increase number of jobs and enhance skilled labour in local resource recovery sectors (Dominiguez and Geyer, 2017). Exposure of heavy metals embedded in both of these technologies will cause various negative health effects. For example, cadmium is associated with its impact on lung, kidney, and bone damages once absorbed in the body (Bernard, 2008), whilst exposure to lead will cause damages to nervous system (Kampa and Castanas, 2008). Environmentalists and academics have called for voluntary or mandatory measures to promote EoL management of PV panels and BESS in an attempt to prevent human health related impacts (SOD2). PV panels and BESS producers are typically engaged with environmentally-conscious stakeholders who are likely to seek and expect EoL management options (Shiue and Lin, 2012), which may drive producers and recyclers to promote reuse and recycling of EoL PV panels and BESS.

Studies revealed not only a significant upstream greenhouse gas emissions generated during mining of raw materials, transportation, and electricity required to produce PV panels and BESS (Fthenakis and Kim, 2011), but also emissions to landfills at the end of life-cycle (Celik et al., 2018). In this sense, stakeholders may be driven by the effort to avoid or reduce emissions (END1) generated during the production stage as well as from landfill diversion. Furthermore, some studies claim that recycling PV panels will reduce the energy payback time (EPBT) (END2). EPBT refers to the amount of time required for energy to be generated from PV system to equal the total of energy required to produce PV panels from virgin materials (Goe and Gaustad, 2014). A study by Goe and Gaustad (2014) found that exhaustive recovery of materials embedded in EoL PV panels has a potential to halved EPBT of mature silicon-based and thin-film technologies. Finally, presenting the evidence of environmental and social impacts from stockpiling EoL PV panels and BESS (END3) will incentivise governments to demand producers and recyclers to adopt EoL management to mitigate the impacts via regulatory framework (Paiano, 2015).

4.2.2. Barriers

The first cluster of policy and economic barriers is predominately concerned with the lack of profitability to recycle (PEB1) EoL PV panels and BESS. This includes the high price of chemicals required during the recycling process (Marwede et al., 2013), transportation costs for collecting EoL PV panels and BESS (Collins and Anctil, 2017), as well as capital costs for establishing collection centres, recycling plants and purchasing the necessary recycling machinery (Choi, 2017). D'Adamo et al. (2017) studied the economic feasibility of recycling waste crystalline silicone PV panels and reported a lack of profitability in recycling PV panels (i.e. NPV per kg ranging from −1.19 €/kg to −0.50 €/kg). Similarly, a review by Heelan et al. (2016) suggest that the recycling process of BESS is also unprofitable due to the low recovered materials for some BESS and high cost of recovery from transport and manual labour.

The second most common barrier to EoL management of PV panels and BESS is the lack of appropriate government regulation (PEB2). Without regulatory mechanisms for managing EoL PV and BESS, there are no legal protocols to guide consumers and industry on how these products should be collected and recovered to avoid unintended environmental impacts and human health related impacts from improper disposal method. Regulations will exert necessary pressure on producers, importers, retailers, and resellers to achieve recovery targets and assign responsibilities on each actor along PV system supply chain (Malandrino et al., 2017). Another core barrier is the lack of economic incentives to promote collection and recycling activities (PEB3) since the current recycling process can be unprofitable for some products. In addition, the absence of awards or grants to promote better design for refurbishment and recycling (PEB5) is also reported as an important barrier that will hinder producers to invest in R&D for easy-to-disassemble PV panels and BESS.

There is clearly no standard or coherent business model (PEB4) for collecting and recovering EoL PV panels and BESS. Current business models do not offer enough incentive for consumers to refurbish or recycle EoL PV panels and BESS, particularly in light of the current lack of coercive pressures from governments (Xu et al., 2018). Voluntary schemes are often firstly introduced by government for impending complex e-waste problems but rarely achieve the objectives of reverse logistics since the majority of consumers are not willing to pay an environmental premium (Larsen, 2009).

Two barriers are reported under the social barriers cluster. The first is the lack of consumers' willingness to return EoL products (SOB1). A study by URS Australia Pty Ltd (URS, 2009) on recycling televisions and computers concluded that consumers prefer kerbside collection rather than dropping e-waste off at specific recycling facilities. This report also found that most consumers do not believe they should have to pay for collection and recycling. This reinforces the requirement for an appropriate business model or incentives for developing an effective collection scheme of EoL PV panels and BESS. The second social barrier is the lack of coordination between producers and recyclers (SOB2). Recyclers are facing difficulties to determine the best method to recycle PV panels because producers are reluctant to share proprietary product information and/or do not have sophisticated processing equipment capable of decommissioning various components or recovering valuable resources (Besiou and Van Wassenhove, 2016).

There are three underlying factors within the market barriers cluster. Firstly, the undeveloped market of PV panels and BESS (MAB1) means that there are few available EoL products to recycle which will make recycling process unprofitable. The second market barrier is the poor market confidence in refurbished and recycled PV and BESS (MAB2). It is reported that one of the challenges of refurbished and recycled PV panels is consumer perception on diminishing efficiency of refurbished or recycled modules (Besiou and Van Wassenhove, 2016). Finally, many entrant manufacturers of PV panels and BESS from newly industrialised countries will produce low-cost products with little concern for the same environmental requirements expected from established global manufacturers (Besiou and Van Wassenhove, 2016). A mandatory requirement to be registered to a collective recycling scheme maybe one option to promote collection and recycling activities for EoL PV panels and BESS, and sustainable product design.

This study highlighted two environmental barriers to EoL management of PV panels and BESS. Many literature suggests that emissions and pollution generated during the recycling process (ENB1) of PV panels and BESS is a salient environmental barrier. This is because the recycling process may involve an extensive use of chemicals, thermal treatment, or machineries during the module separation stage, depending on the recycling method used (Xu et al., 2018). Although recent developments on BESS recycling methods have substantially decreased emissions and pollution, high energy consumption remains a critical challenge in recycling a certain type of BESS i.e. lead-acid (Alonso et al., 2017). Likewise, some recycling methods for PV modules also requires high energy e.g. thermal decomposition process used in *SolarWorld* recycling process and generate air emissions (Tao and Yu, 2015).

Within the recycling infrastructure barriers cluster, studies reported the complexity of the EoL management process (RIB1) as the most significant barrier for managing EoL PV panels and BESS. This complexity ranges from uncertain quality of the returned EoL PV panels and BESS (Besiou and Van Wassenhove, 2016), products dispersed in various geographical locations (Fthenakis, 2000), technical challenges to recycle due to the various materials inside the PV panels and BESS (Bogacka et al., 2017), to various recycling technologies required due to the different type of PV panels (Tao and Yu, 2015) and BESS technologies (Das et al., 2016). Lack of adequate collection centres and recycling plants (RIB2) was the second barrier under this category. Since PV systems have been distributed across various geographical locations, it is necessary to establish an optimal collection and recycling network.

4.2.3. Enablers

Strict regulations and policies (PEE1) was the most reported policy and economic enabler. Government regulations need to prescribe clear guidelines, targets, and objectives for businesses operating within each step of the supply chain and enforce penalties for non-compliance. Such regulations could include product stewardship schemes, industry-led codes of conduct, mandatory recovery targets, as well as product design standards incorporating easy-to-disassemble criteria, to name a few. These regulations will place responsibility on all actors in the supply chain for implementing the necessary measures for collecting and recycling the EoL PV panels and BESS from consumers. EPR is the most common type of product stewardship regulation applied for managing post-consumer electronic waste (Weckend et al., 2016). It holds producers and importers of the products liable for collecting and recycling activities. Within the WEEE and Waste Batteries and Accumulators Directives, European countries adopted an EPR principle. This scheme is an effective approach to enable recycling EoL PV panels and BESS by internalising recycling costs within the products upfront price, although it will affect the affordability of PV systems unless cost-effective recycling technologies are discovered. This cost should be internalised to incentivise producers in innovating for easy-to-recycle products and mitigating environmental problems throughout the supply chain (Manomaivibool, 2008).

Consumers and/or installers tend to be reluctant to return their EoL PV panels and BESS unless there is an incentive or formal and funded product take-back scheme in place (PEE3). In response to the regulation, producers may alter their business model to enable an effective collection of EoL PV panels and BESS. Business models can be aligned with the circular economy paradigm which focuses on access rather than ownership, such as lease and sharing platforms (Kalmykova et al., 2018), but also conventional approaches such as buy-back (Fthenakis, 2000) and third-party collection services (Peeters et al., 2017). Additionally, enabling collection services will minimise the role of informal recyclers that are likely to achieve low recovery rates (Yu et al., 2010).

Literature suggests economic incentives (PEE4) are an important enabler to promote higher recovery and recycling rates. It is argued that in order to achieve substantial recovery of EoL PV modules and BESS, waste regulations should be coupled with subsidies for recovery technology (Goe et al., 2015) or shared costs and responsibilities among stakeholders (Lapko et al., 2018). Financial incentives can also be offered to producers which have designed easy-to-recycle PV panels and BESS (Besiou and Van Wassenhove, 2016). In addition, it is suggested that increasing landfill cost (PEE5) will make recycling more economically favourable to producers than disposing EoL PV panels and batteries as well as manufacturing from virgin materials (Xu et al., 2018).

There are two market enablers presented in this study. Firstly, developed end market of PV and BESS will enable a sizeable quantity of collected EoL PV panels and BESS (MAE1). This is because each processing batch will need to meet a minimum quantity to warrant recycling activities and outweigh processing costs. Given that PV system will be one of the primary sources of energy in the future, the amount of waste would likely be sufficient in the foreseeable future (Weckend et al., 2016) to make the recycling process profitable. Secondly, a quality standard needs to be established for refurbished and recycled products (MAE2). Standardisation through certification will inform consumers that the refurbished and recycled products have met a strict quality standard and inspection. In addition, offering user warranties to consumers who buy refurbished and recycled PV panels and BESS will ensure greater consumers' interest in purchasing recycled products. This will incentivise producers and other actors along the value chain to perform collection and recycling activities of EoL PV panels and BESS due to the growing consumers' demand on refurbished PV panels and BESS (Arranz et al., 2014) which can also be significantly more affordable than purchasing new products.

Collection and recycling activities can be a complex process which requires mutual understanding among stakeholders to align interests and exchange knowledge to work towards a common goal. Cooperation among stakeholders (consumers, producers, recyclers, governments, and non-governmental organisations) (SOE1) is one way to enable constructive and collaborative discussion on policy or recycling solutions (Joseph, 2006). For example, governments can increase public awareness through social marketing campaigns and ensure producer and installer engagement through formal EoL education programs (Joseph, 2006). Furthermore, promoting information exchange and supply chain transparency (SOE3) is required to facilitate an effective EoL management of PV panels and BESS (Xu et al., 2018). Producers should clearly label their products, e.g. product specifications and materials composition with recyclers (Besiou et al., 2012) in order to help recyclers to determine the best method to recycle PV modules and BESS.

Studies suggest that the development of an industrial symbiosis network (SOE2) is an important enabler to facilitate waste exchange between two or more industries. PV panels and BESS partially share the same materials with other electronic products (Busch et al., 2017). Companies or recyclers can decide when the recovered components can be cascaded for reuse or recycling in different infrastructures or products through the industrial symbiosis network (Arranz et al., 2014). In particular, cascaded reuse of recovered BESS can be more practicable since its application is overlapped with other products such as electric vehicles and marine motors.

In regards to behavioural enablers, consumers' environmental awareness (BEE1) plays an important role in managing EoL PV and BESS. Consumers with high environmental awareness tend to display recycling behaviour. In a study of mobile phone recycling behaviour by Yin et al. (2014), consumers with greater environmental awareness tend to display willingness to pay for recycling. Furthermore, consumers with high environmental awareness tend to display willingness to purchase remanufactured products (Jiménez-Parra et al., 2014). This will incentivise companies to promote collection and recycling activities in order to achieve market competitiveness. Thus, it is important for government and non-governmental organisations to educate public regarding whole systems' environmental and human health impacts.

Corporate social responsibility (CSR) (BEE2) refers to companies' proactive and self-regulated approach to mitigate environmental and human health related impacts throughout the value chain (Kovács, 2008). Companies with corporate environmental responsibility tend to be driven by the efforts to achieve market competitiveness and increase their green image among consumers rather than driven by the economic benefits to recycle EoL PV panels and BESS (McDonald and Pearce, 2010). For example, *First Solar* operates an internal collection and recycling program for their own PV panels and have the capability to recover more than 90% of the materials (First Solar, 2018). In 2016, this company appeared in the top ten companies in terms of its production volume (International Solar Energy Agency, 2016). Furthermore, Sica et al. (2018) argue that creating shared value (BEE3) is necessary to promote an effective EoL management of PV panels and BESS. While the CSR concept heavily focuses on social and environmental aspects, shared value strategies focus on creating business opportunities, new markets, and improving profitability whilst considering social and environmental objectives.

In regards to the current high recovery and recycling costs, the introduction of new recycling technologies (TIE1) that offer technical practicality and economic feasibility will incentivise producers and recyclers to recycle EoL PV panels and BESS (Lapko et al., 2018). Furthermore, design for recycling (TIE2) is a salient enabler in order to promote a more cost-effective and technically feasible recycling process as well as preventing further waste from damaged materials during the decommissioning process via the development of easy-to-disassemble products (Besiou and Van Wassenhove, 2016).

There is a need to establish collection and recycling plants in order to promote EoL management activities of EoL PV panels and BESS (TIE3). The strategy for both centralised and decentralised collection centres and recycling plants is also an important enabler to minimise the EoL management system costs (Choi and Fthenakis, 2010b), particularly in regional and remote areas where transport costs can be substantially higher than metropolitan regions. This issue includes capital costs to open collection centres, transportation costs for reverse logistics, distance between collection centres to recycling plants, distance between PV installations to collection centres, etc. (Choi, 2017). Finally, both adequate collection centres as well as robust business models to collect or take-back the EoL PV panels and BESS is essential for appropriate EoL management (Besiou and Van Wassenhove, 2016).

4.3. Solar photovoltaic system circular supply chain

Fig. 8 presents a conceptual framework that will facilitate the development of a circular supply chain for PV panels and BESS. The current implementation of EoL management of waste PV panels and BESS is being hampered by five interconnected barrier categories: policy and economic, market, social, environmental, as well as recycling infrastructure. The conceptual framework demonstrates how five interconnected enabling factors will consequently overcome the identified barriers by achieving the key opportunities i.e. economic, social, and environmental aspects as driving factors. This is because the success of EoL management activities must depend on the involvement, participation, and commitment of all stakeholders along the supply chain. Collaborative dialogues on policy solutions, market development, and alignment of interests can be a way to promote the development of effective enabling factors that consider the balance of objectives between stakeholders (e.g. total government investment, company profit, recycler profit, number of recycled products, job creation, etc.).

In this regard, governments are responsible to explore and progress both regulatory and non-regulatory approaches which increase compliance for collection and recycling activities but also promote R&D of new effective recycling technologies and design for recycling via economic incentives. Research institutions can derive the evidence that underpins governments' decision on regulations and incentives via collaborative and consultancy research. Furthermore, governments need to raise public environmental awareness around better practice recycling options through awareness campaigns and trade or professional education, which will subsequently increase the rate of voluntary participation for returning EoL products. Likewise, producers will need to establish a take-back programs or business models that will influence consumers' willingness to return EoL products, either internally or via joint collection and recycling programs managed by third-party providers. Producers will also need to ensure adequate collection points or recycling plants are available and recycling plants are capable to effectively treating recovered products to promote and ensure best possible environmental and resource recovery outcomes. Cooperation among stakeholders in the supply chain will also facilitate information exchange that will overcome technical challenges of recycling EoL PV panels and BESS, whilst industrial symbiosis networks facilitate the need for material exchange among producers.

4.4. Future research agenda

Based on this systematic quantitative literature assessment, it was clear that the current research to date has predominantly covered the technological aspects of recycling EoL PV panels and BESS. Although technological research for recycling EoL PV panels and BESS are still relevant issues, there still a need to increase research intensity on the socio-economic and policy aspects of the problems mentioned herein. Covering these aspects is particularly important as the success of any EoL e-waste strategy is highly dependent on an effective voluntary or mandatory approaches, incentives as well as consumers' willingness to pay for collection and recycling either upfront or at the end of life-cycle. While conducting this socio-political research is imperative for proactive interventions, it is difficult to gauge consumer perceptions on this issue at the present time since there are not many EoL PV panels and BESS generated to date, meaning that this issue is not at the forefront of society (Xu et al., 2018). However, within a decade there will be a massive increase in EoL PV system that will stir up vigorous societal debate on how to best tackle this e-waste

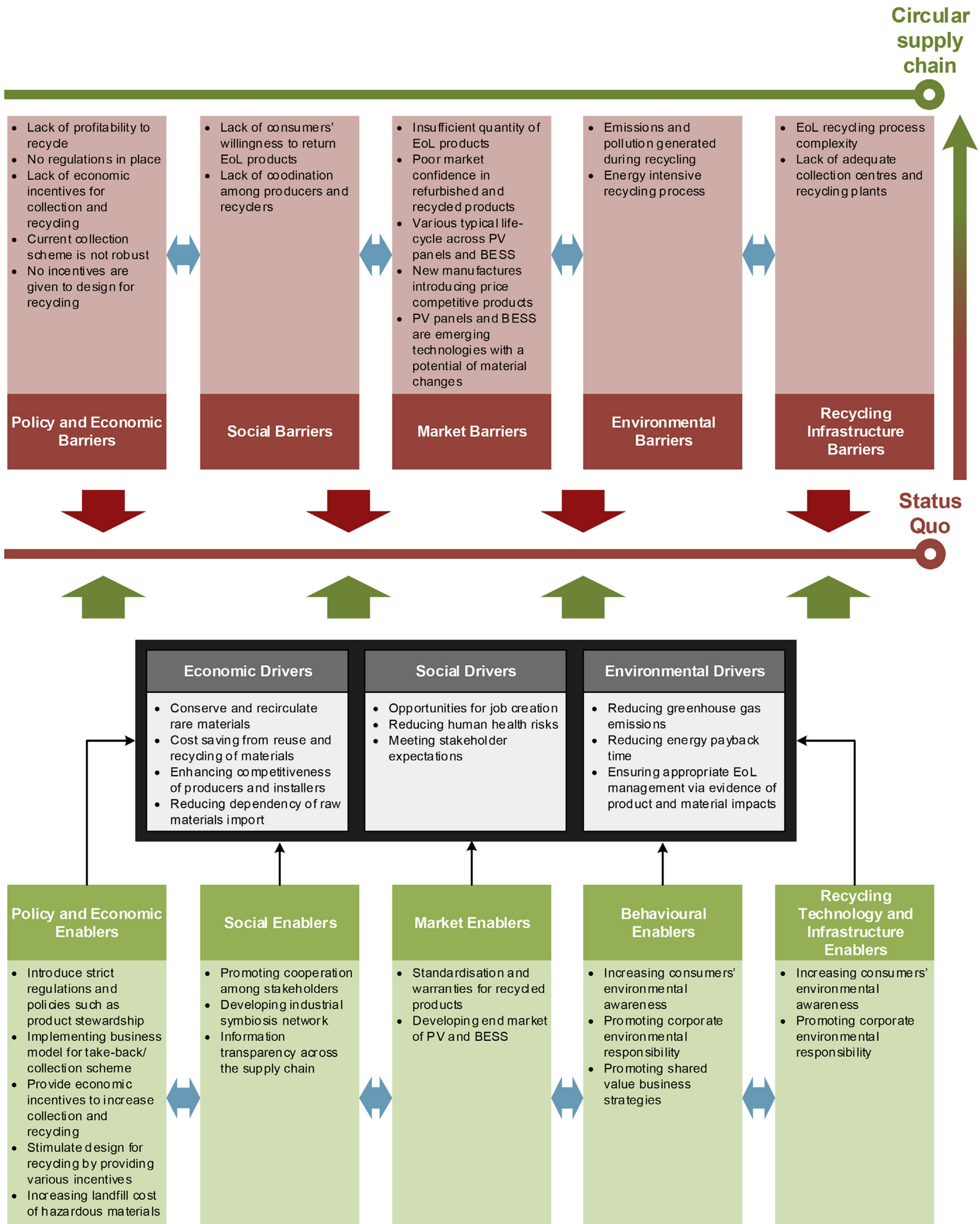

Fig. 8. Conceptual framework for solar energy system circular supply chain.

problem; pre-empting this challenge by conducting evidence-based research on the socio-economic and policy aspects is essential.

Furthermore, current modelling and simulation efforts strongly biased towards LCA and mathematical modelling methods. However, these traditional modelling approaches are not capable of capturing the dynamic and interdependent nature of the collection and recycling system. As pointed out by Besiou and Van Wassenhove (2016), that EoL management of PV panels and BESS systems are complex and involves multiple stakeholders working together to be effective. Thus, it is essential to examine the feedback mechanisms between the critical factors stemming from each stakeholder. Systems modelling approaches such as agent-based modelling, Bayesian network, discrete event simulation, and system dynamics modelling have the power to capture the interrelationship between these factors.

Arguably, EoL management options for solar PV systems should be examined systematically covering all of the drivers, barriers, and enablers described in this paper as well as their interdependencies. Firmly embedding socio-economic and political factors within such a systems model is distinctly lacking in the current literature. Completing sufficient research on the technological, socio-economic, and policy aspects will facilitate the development of an effective EoL management process for PV panels and BESS in respect to the technical and economic feasibility of recycling processes and methods, environmental improvement, as well as social welfare (i.e. job creation). Engagement with stakeholders is an essential step within the systems modelling approach to ensure correct representation of system structure so that the models would truly reveal real-world system behaviour (Bertone et al., 2018; Sahin et al., 2016). Addressing micro-level problems such as appropriate business models for take-back (i.e. lease, buy-back, etc.) and willingness to pay for collection and recycling are also necessary to proffer a systematic strategy and best practices within firm-level.

5. Conclusion

This study performed a systematic quantitative literature review of 191 articles in EoL management of PV panels and BESS from the Web of Science and Scopus databases between 2000 and 2018 (by 30 June 2018). In general, there is an increasing interest among academic community to address the issue of EoL PV panels and BESS indicated by a strong upward trend in the past few years. It was reported that research on EoL PV panels shared the largest number of publications and experienced an increasing trend during the study period. This study identified the lack of studies focused on EoL BESS which reflect the current low interest of off-grid system. However, due the predicted exponential increase of BESS installation (Katsanevakis et al., 2017a, b), there is a critical need to address this issue in the near future. Despite the importance of technological research, the lack of socio-economic research will hamper an effective policy implementation to manage EoL PV panels and BESS. It is further argued by the authors that the current modelling and simulation efforts have not captured the inter-connectedness and feedback mechanisms within the system. Systems modelling approach will enable to capture the dynamics and complexity since PV panels and BESS supply chain is governed by multiple stakeholders (Besiou and Van Wassenhove, 2016).

Furthermore, this paper synthesised the drivers, barriers, and enablers to EoL management of PV and BESS from the collected literature to provide a basis for future studies with a systemic perspective on current key issues and influential factors. This study retrieved a list of 10 drivers which was clustered under three categories: (1) economic, (2) social, and (3) environmental. A list of 16 barriers was retrieved and categorised into five clusters: (1) policy and economic; (2) social; (3) market; (4) environmental; and (5) recycling infrastructure. Similarly, a list of 15 enablers was retrieved and classified into five clusters: (1) policy and economic; (2) social; (3) market; (4) behavioural; and (5) recycling technology and infrastructure. A conceptual solar energy system circular supply chain framework was proposed based on the list of drivers, barriers, and enablers. The framework illustrates how the five enabler categories can function as an inter-connected system that will overcome the underlying barriers to achieve the economic, social, and environmental objectives.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.11.229.

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