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D1.1

A systematic literature review of the photovoltaic and electric vehicle battery value chains for the development of a circular economy in the PV industry

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List of abbreviations

AC	Alternating current
Ag	Silver
Al	Aluminum
BESS	Battery energy storage systems
BEV	Battery electric vehicle
BMs	Business models
BMS	Battery management system
C	Carbon
Cd	Cadmium
CdTe	Cadmium telluride
CE	Circular economy
Co	Cobalt
CO_2	Carbon dioxide
Cr	Chromium
c-Si	Crystalline silicon
CSP	Concentrating solar power
Cu	Copper
DC	Direct current
EOL	End-of-life
EV	Electric vehicle
EVA	Ethylene Vinyl Acetate
Fe	Iron
FIT	Feed-in-tariff
GW	Gigawatts
GWh	Gigawatt hours
LbD	Learning by doing
Li	Lithium
LIB/Li-ion	Lithium-ion battery
mc-Si	Multicrystalline silicon
MG-Si	Metallurgical-grade silicon
Mn	Manganese
MW	Megawatt
N/A	Not available
Ni	Nickel
OEM	Original equipment manufacturer
Pb	Lead
PPA	Power purchase agreement
PV	Photovoltaic
R&D	Research and development
SLR	Systematic literature review
SOG-Si	Solar-grade silicon
TPO	Third-party owned
WEEE	Waste electrical and electronic equipment

1 EXECUTIVE SUMMARY

Solar photovoltaic deployment has grown at unprecedented rates since the early 2000s (IRENA and IEA-PVPS, 2016). As the solar power market booms, so will the volume of discarded products entering the waste stream. Simultaneously, recent advancements in energy storage solutions have fueled the growth of PV-connected battery system installations. When no longer suitable for automotive purposes, lithium-ion batteries from electric vehicles can be repurposed as stationary energy storage units for renewable energy sources, such as solar PV. The explosive growth in EV sales also poses the question of how decommissioned batteries will be handled after they have reached the end of their automotive life. It is within this context that this report aims to provide a holistic view (i.e., from product design to product end-of-life) of the different stages, processes, and stakeholder relationships present in the solar PV and the EV battery value chains. To achieve this goal, the authors undertake a systematic literature review of 112 peer-reviewed articles, published in English between the years 2000 and 2018.

Results showed that upstream, both industries allocated R&D funds for efficiency improvements in the asset's 1st life, disregarding design for reuse, disassembly, refurbishing, or recycling. Midstream in the PV value chain, business models were found to be adapted to the needs and circumstances of the country where they were the most prevalent (e.g., home-owned systems in Germany or third-party ownership models in the United States). Design and business model decisions proved to be crucial for achieving future product circularity in both industries. At the downstream end of the PV value chain, low volumes of waste, differences in PV panel architectures, and lack of design for disassembly and recycling, turned the recycling of PV into an unattractive and unprofitable activity for manufacturers and recyclers. Similarly, low waste volumes combined with different battery chemistries and configurations, as well as uncertainties surrounding the economic, technical, and environmental viability of repurposed EV batteries represented some of the main barriers to the end-of-life management of EV batteries. All in all, and as the analysis contained in this report shows, the challenges and barriers that both value chains exhibited can be taken as opportunities for the creation of innovative value formulas and policies.

2 INTRODUCTION

The harmful environmental and socioeconomic effects associated with the burning fossil fuels to generate electricity have prompted the development of various renewable energy sources, including solar, wind, geothermal and hydropower. Solar photovoltaic energy, or the capture of solar radiation through photovoltaic panels to produce electricity, is considered one of the most promising markets in the portfolio of renewable energies because of its potential to meet the CO2 reduction targets imposed by local authorities, national governments, and international agreements. Among the cited advantages of using PV energy are the ability to: reduce greenhouse gas and air pollution emissions, mitigate global warming caused by the burning of fossil fuels, transition towards a cleaner, more reliable, and more affordable source of electricity, reduce degraded land, and support energy security and independence (Shiue and Lin, 2012).

The PV industry has grown exponentially during the past few years as showcased by the increasing production volumes and the growing networks of solar installers and financing schemes worldwide. In 2017, cumulative global installed PV capacity reached almost 398 GW, representing about 5% of the global electricity output. By 2020, it is estimated that the global capacity could reach 700 GW, while by 2050, it could amount 4500 GW (IRENA and IEA-PVPS, 2016). The global rise of PV installations will inevitably lead to unparalleled streams of waste. Assuming the estimated lifetime of a PV panel fluctuates between 20 and 30 years, one can expect to deal with end-of-life materials from PV systems in the foreseeable future.

Supported by the belief that the issue of PV waste needs to be tackled from multiple angles, from product design to end-of-life (EOL), and with the aid of multiple stakeholders, including businesses, governments, customers, and academia, this article develops a systematic literature review (SLR) to understand the current configuration and functioning of the PV and the electric vehicle (EV) battery value chains. 2nd life EV batteries have been incorporated to this report because they represent suitable stationary storage units for photovoltaic energy. EV batteries promise to solve the intermittent and volatile profile of PV energy generation and to provide environmental, as well as economic, benefits to utilities, businesses, and homeowners.

The study of both value chains, both separately and in conjunction, is deemed necessary because of various reasons. First, extant literature is silent about the PV value chain and the stakeholders that play a role in its functioning (Besiou and Wassenhove, 2016; Jia et al., 2016). Research focusing on photovoltaic systems has been studied merely from a forward flow supply chain perspective (i.e., polysilicon production, cell and module manufacturing, and PV system installation), while ignoring other equally important stages such as R&D for product design, business models, reverse logistics at EOL, and strategies for circularity. Second, if one is to understand the dynamics guiding the behavior and evolution of PV systems, and to expect large-scale PV deployment in the future, a value chain view of the industry is necessary. Failing to account for the different networks that make the PV ecosystem function can prevent policymakers and new market entrants from recognizing that, for instance, changes in public policy, technology or market conditions, will affect the relative attractiveness and success of different PV technologies throughout the value network (Olson, 2014).

Third, to deal with PV and EV battery waste in an effective way, innovation from product design to product recovery is essential. In this realm, it has been argued that innovation in the renewable energy sector is increasingly distributed and interdependent, as it requires cooperation from incumbent and start-up firms, government institutions, service providers, and so on (Zobel et al., 2016). Because all of these actors often display their own value chain structures and interactions, knowledge about these structures can provide opportunities for joint value discovery and creation (e.g., regulations, business models, waste management systems, etc.) (Overholm, 2015; Sica et al., 2018). Fourth, the scarcity and supply disruptions of critical materials (e.g., tellurium, gallium, indium, and selenium in thin-film solar cell technologies or lithium, cobalt, nickel, and natural graphite in EV batteries also call for a value chain view. By identifying the risks along the PV and EV battery value chains, stakeholders can get prepared for imminent supply disruptions and price volatilities, and ensure the sustainability of their supply chains in the future (Bustamante and Gaustad, 2014; Gaustad et al., 2018). Finally, if the goal is to aim for high-value EOL recovery of PV panels and EV batteries, circular product design and business model strategies must be incorporated to industry practices. Among other pervasive problems in the EOL management of PV systems, the current configuration and design of PV panels do not allow, for instance, for the effective separation of materials before recycling, which provides incentives for low-value recycling and landfilling. Within this context, value chain cooperation promises to increase the security of raw materials and the safety of recycled materials through the design and acceptance of innovative waste management systems for PV panels.

The objectives this article proposes are: (1) to understand how the PV and EV battery value chains operate, including its main stages and processes, stakeholders, and the interactions among such stakeholders, and (2) to investigate which factors inhibit the incorporation of circular economy principles into existing PV and batteries value chains. We deem these questions to be of interest from both a policy and a firm perspective. First, a deeper understanding of the current arrangements in PV networks is necessary if policy makers are to ensure collaboration for innovation and the large-scale deployment of PV systems. Second, such a perspective is essential for managers and entrepreneurs looking for ways to participate or innovate within the ecosystem and for policymakers to offer the right incentives to the right players in the different value chain segments. Finally, and for the benefit of both policy makers and industry players, knowledge on the different value chains can support the development of accurate reporting and monitoring systems of PV panel waste systems. The resulting data could, for instance, pinpoint causes and frequencies of system failures along the chain, waste produced by PV technology, composition of this waste, and so on.

This remainder of this article is organized as follows: Section 3 introduces the value chain framework, Section 4 provides a detailed view of the methodological framework used to plan and execute this systematic literature review, Section 5 discusses the main findings of this review, including descriptive statistics from the article database and a description of the main stages of the value chain for PV systems and lithium-ion batteries, respectively. Finally, Section 6 presents the conclusions of this study and some questions for future analysis.

3 ANALYTICAL FRAMEWORK

3.1 VALUE CHAINS

Understanding how PV and EV batteries are developed, manufactured, sold, and managed throughout their lifetimes, demands a value chain view. The concept of value chain was coined by Michael Porter as a means of breaking down the activities of the firm into strategically relevant stages, processes, and relationships related to a product or service during the process of delivering value to a customer. Such activities involve product manufacturing, product delivery to consumers, and product disposal and/or reprocessing after use (Kaplinsky and Morris, 2001). Initially developed to help understand the value creation process at the firm level, the value chain concept is now used as a tool for understanding value creation in industries and countries (Porter, 2008; Yan and Wang, 2014). At the industry level, a value chain analysis allows for a comprehensive look at the industry, thereby supporting strategic and technology planning for incumbents and new entrants, as well as policy making at a higher level (Kim and Lee, 2018).

4 METHODOLOGY

To investigate the research question proposed in Section 2, we conducted a systematic literature review (SLR) by following the methodological framework proposed by Denyer and Tranfield (2009) and Tranfield et al. (2003). A systematic literature review is a self-contained research project that uses existing studies to provide answers to research questions, which are usually derived from policy or practice (Denyer and Tranfield, 2009). A systematic review differs from a traditional, more general literature review in that it proposes a replicable, scientific, and transparent process, thereby creating a foundation for advancing knowledge in a particular field and facilitating theory development (Cook et al., 1997; Webster and Watson, 2002). A summary of the employed methodology is displayed in Table 1.

4.1 PHASE 1 - PLANNING THE REVIEW

As a first step, and to ensure the validity, reliability, and replicability of the results, we developed a draft protocol for carrying out the literature review process. After agreeing on structured process flow for the review, we decided to embark on an informal preliminary literature scan to better delineate the scope of our research. The preliminary scan was instrumental in: (i) confirming that there was indeed a gap in the literature, (ii) delineating the thematic focus for the review and the exclusion criteria for the selection of articles, (iii) evaluating the selected time frame for the search, and finally (iv) defining the set of keywords to be employed in the systematic search.

Table 1 Summary of the methodology

SLR phase	Objective	Method	Tool	Article's section
Phase 1 Formulate the research question	To formulate the question(s) that will define the criteria for primary inclusion of studies in the review	• Formulate the research question(s)	• N/A	Section 2
Preliminary literature scan				
Phase 2 Locate studies	To locate relevant articles for the SLR	• Determine the search methods + search engines • Select types of data sources • Determine the relevant time-frame	• Web of Science and Scopus • Journal articles and conference papers published in English language • 2000-2018 (as of 30 August 2018)	Section 4.2
Phase 3 Select and evaluate studies	To select and analyze publications according to different criteria	• Define the specific search strings (i.e., Boolean keyword search) • Define criteria for inclusion/exclusion	• See Table 2 • Articles were excluded because they: mixed PV with other renewable energy sources; were too technical; discussed other types of solar energy different from PV; discussed small-scale PV applications such as mobile charging or water heating	Section 4.2
Phase 4 Analyze and synthesize	To synthesize and analyze the selected studies	• Define review protocol for selected studies • Code and extract data	• Excel • Atlas.ti	Supplementary file Supplementary file
Phase 5 Report the findings	To report on the findings	• Results: descriptive analysis of the article database • Results: value chain description for PV systems and EV batteries		Section 5

4.2 PHASES 2 AND 3 – LOCATION, SELECTION, AND EVALUATION OF STUDIES

Location

The literature search was undertaken using two of the largest abstract and citation databases of peer-reviewed literature, namely Web of Science and Scopus. A search in both databases ensured that the review results took into account all the available evidence and were based on quality contributions (Denyer and Tranfield, 2009). To identify the appropriate types of publications for the review, we adhered to the "fit-for-purpose" rationale proposed by Boaz and Ashby (2003). They suggested that rather than a hierarchy of evidence (i.e., ranking of the publication outlet), the criteria for the selection of articles must rely on the purpose and context of the research. Hence, we delimited our search to peer-reviewed articles and conference papers in English published in scientific journals and conference proceedings, respectively. The inclusion of conference papers ensured that results covered the most recent available knowledge, which is less likely to be found in journal publications, especially when it comes to the use of EV batteries for the stationary storage of PV energy.

Regarding the time frame, we set the keyword search to go from the year 2000 to the present (i.e., 2018). Timilsina et al. (2012) pointed out solar energy markets regained momentum only since the early 2000s, because during the 70s and 80s these markets collapsed due to low oil prices and weak institutional support. Similarly, sales of EVs, and in consequence of EV batteries, also started to peak since the beginning of the 21st century. Finally, we extended our search to the year 2018 after realizing a significant number of scholarly articles had been published just recently. The choice of time frame was confirmed during the preliminary scan, when the search results returned almost no publications before the year 2000 and a rising number of published articles within the past two years.

Selection

The articles that were scanned during the preliminary literature study also served as a basis to clearly define the exclusion criteria for the articles in the review. For instance, although some publications featured the words "supply" or "value chain," and "photovoltaic", "PV" or "solar" in their titles and abstracts, they did so by studying photovoltaic energy along with other renewable energy sources such as hydropower, wind power, biomass, biogas and biofuel. Because these articles addressed PV-related issues only marginally, and in conjunction with other renewable energy sources, we made the decision to exclude them from the search. Also, a great number of publications addressed PV panel manufacturing and deployment exclusively from an engineering, materials science, chemical or electrical perspective, and were therefore deemed as too technical and laying outside the scope of our review[1]. A third group of articles was removed from the analysis because they referred to alternative types of solar energy, such as solar thermal or concentrating solar power (CSP). Because the last two technologies are different from PV technology, they were not considered for this review. Finally, we excluded some publications because they referred to off-grid, small-scale PV applications used for water heating, lightening (i.e., solar lanterns) or mobile charging, primarily in remote areas in Africa, or because they referred to related, yet different, value chains such as refrigeration chains for food fueled by PV energy.

Evaluation

After conducting the actual search using the set of keywords displayed in Table 2, all information from the resulting articles (e.g., title, abstract, keywords, publication year, publication outlet, etc.) was exported to two Excel spread sheets (i.e., one for Web of Science results and another Scopus results). The two databases were then merged into one and the combined results analyzed to identify duplicate entries. Once identified, duplicates were tagged and removed from the merged database. The consolidated database therefore included the filtered list of articles, plus several others that were added later in the process as the result of cross-referencing.

To determine whether an article met the inclusion criteria and was to be included or excluded from the analysis, we read the article's title and abstract, and, when necessary, scanned the article's complete content. This filtering process resulted in the exclusion of 144 articles, with a final number of 93 articles being considered for further analysis. Furthermore, the articles' list of cited references served as a secondary and additional source of analysis. Cross-referencing resulted in 19 articles being added to the primary database, resulting in a total of 112 articles being considered for the present review (see Figure 1).

Table 2 Database search summary

Keywords	Database	Type of document	Language	Quantity
TITLE-ABS-KEY (("supply chain*" OR "value chain*") AND ("photovoltaic*" OR "solar" OR "pv") AND NOT ("wind*" OR "biomass" OR "biofuel" OR "biogas" OR "hydro")) AND PUBYEAR > 1999 AND LANGUAGE ("English")	Scopus	Journal articles and conference papers	English	141

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[1] The following subject areas were filtered from the Scopus search: engineering, materials science, computer science, physics and astronomy, chemical engineering, mathematics, chemistry, medicine, biochemistry, genetics, and molecular biology, immunology and microbiology, veterinary, and dentistry.

AND (EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "COMP") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "VETE") OR EXCLUDE (SUBJAREA , "DENT"))				
(TS=(("supply chain"* OR "value chain*") AND (photovoltaic* OR solar OR pv) NOT (wind* OR biomass OR biofuel OR biogas OR hydro*))) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article) Timespan: 2000-2018. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.	Web of Science	Journal articles and conference papers	English	141

4.3 PHASE 4 - DATA ANALYSIS AND CODING SCHEME

In this final stage, we imported all the articles that met the inclusion criteria (N=112) to the coding software Atlas.ti and read them all in detail to perform an open coding content analysis. Using this technique, we coded the article's content inductively and structured the incoming data according to its relationship to the PV and EV battery value chains. The established coding system, therefore, included labels such as: UPSTREAM PV cell raw material, UPSTREAM PV cell manufacturing, DOWNSTREAM PV module recycling, STAKEHOLDER Equipment manufacturers, and so on. Throughout the coding process, we also kept a diary to help structure our analysis. At the end of the coding stage, we reviewed each code and merged or deleted some of them for clarity. This process resulted in 214 codes that served as the basis for the content of this report.

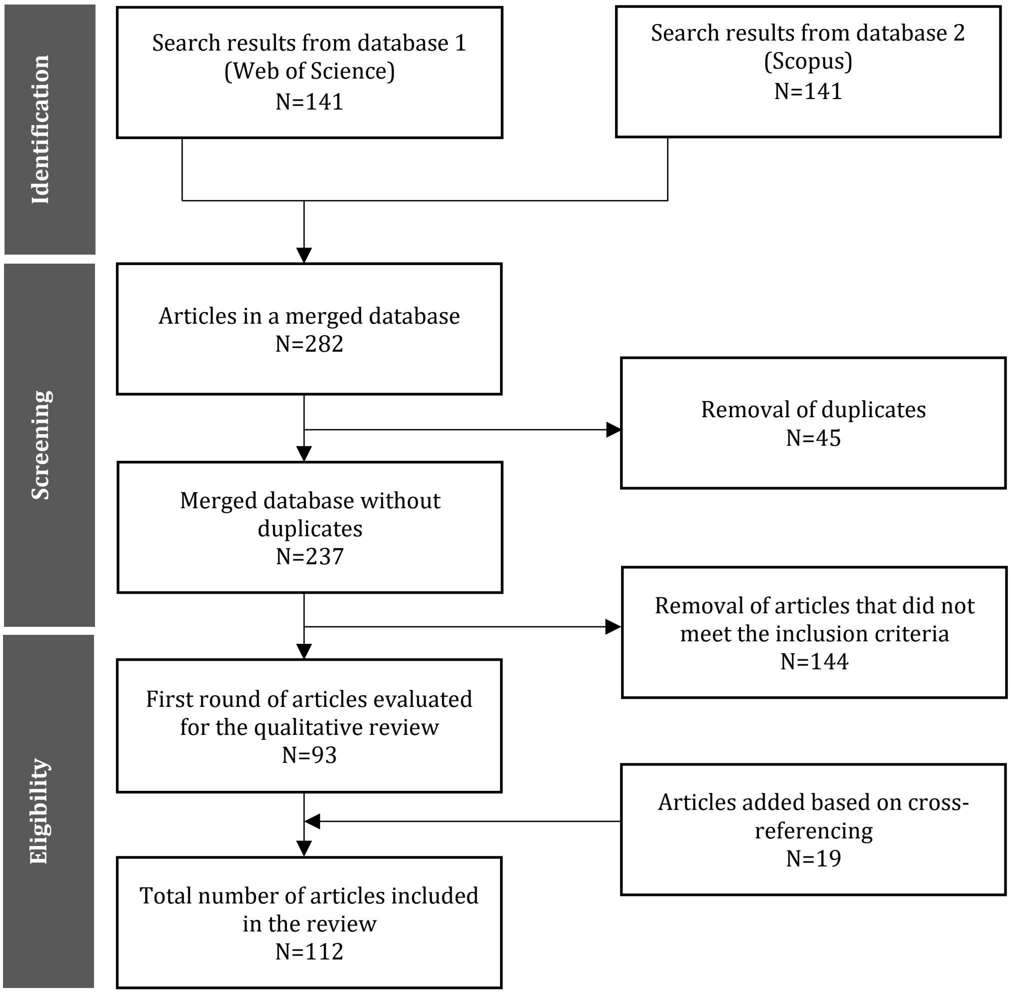

Figure 1 Flow diagram of the systematic review

5 ANALYSIS AND RESULTS

5.1 GENERAL TRENDS

The trend indicates a growing interest in solar photovoltaic-related research from the year 2012 onwards (see Figure 3). A peak in publications was achieved in the present year, with a total number of 28 published articles until August 2018, exhibiting a 100% increase from 2017 to the first half of 2018. Overall, between 2012 and 2017, published articles increased by an average of 13% per year. Before the year 2012, academic research was undergoing an incubation period, especially in relation to the analysis of value chain actors and dynamics. Also, articles describing the evolution of the PV industry in certain regions or countries outnumbered the articles published in the rest of the value chain categories (see Table 6). Finally, the academic journals where more than one or two articles were published, were the Journal of Cleaner Production (N=12), Energy Policy (N=8), Renewable and Sustainable Energy Reviews (N=6), Applied Energy (N=5), and Renewable Energy and Sustainability with 4 publications each (see Table 3).

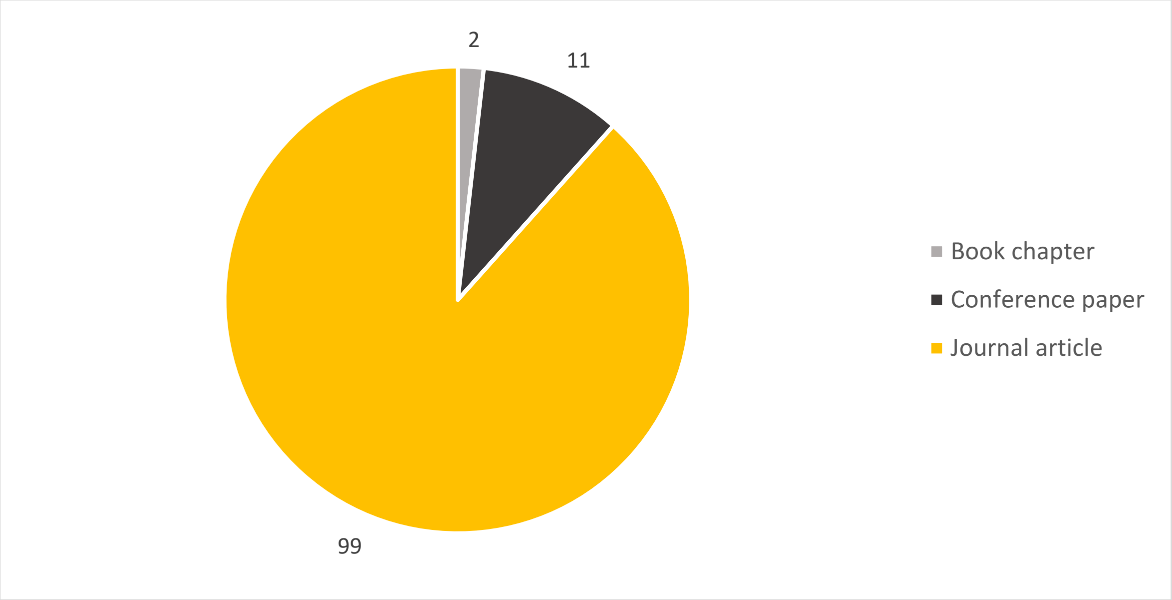

Figure 2 Proportion of journal and conference publications (N=112)

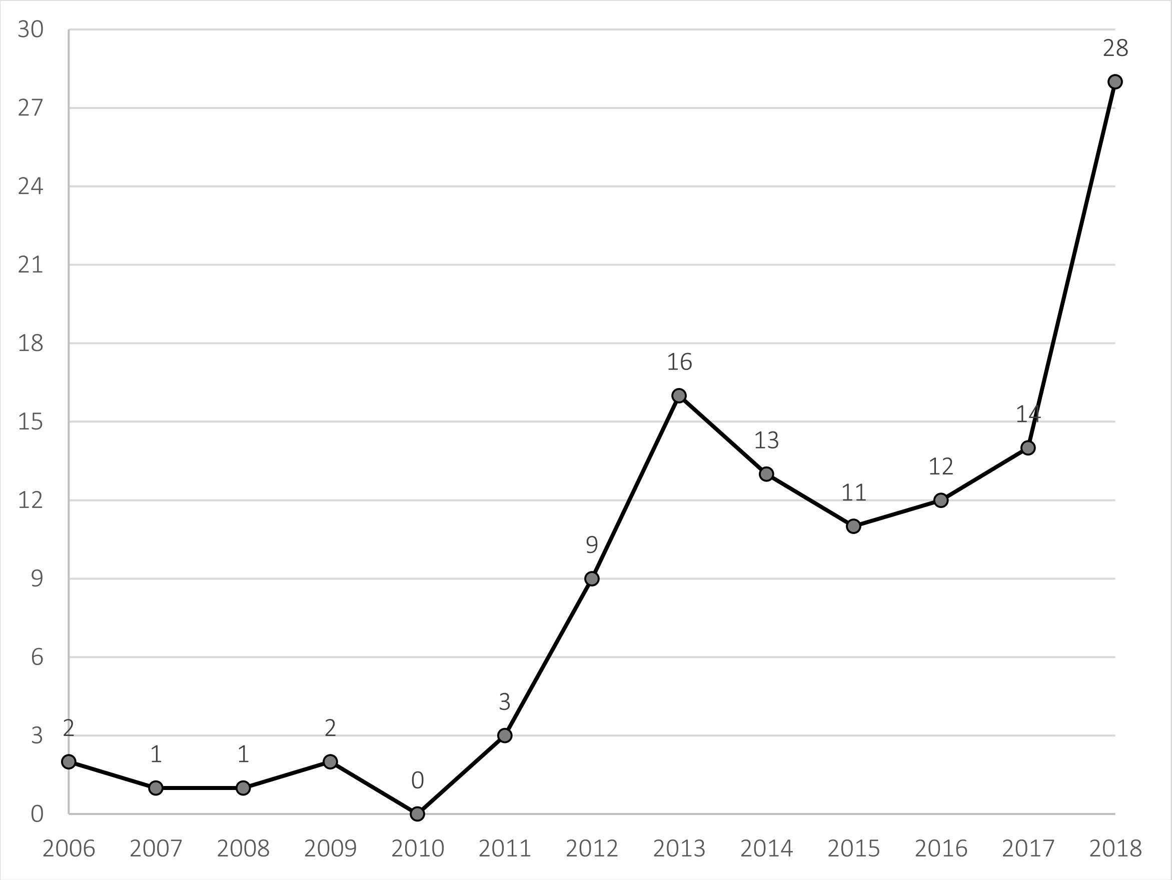

Figure 3 Distribution of reviewed publications over time (N=112)

Table 3 Number of publications per journal

Journal	Articles
Journal of Cleaner Production	12
Energy Policy	8
Renewable and Sustainable Energy Reviews	6

Applied Energy	5
Renewable Energy	4
Sustainability	4
Progress in Photovoltaics	3
Solar Energy Materials and Solar Cells	3
Journal of Energy Storage	2
International Journal of Photoenergy	2
Industrial and Corporate Change	2
Clean Technologies and Environmental Policy	2
Energy Conversion and Management	2
Energy Research and Social Science	2
Renewable Energy Focus	2
IEEE Journal of Photovoltaics	2
Energy and Buildings	2
Perspectives on Global Development and Technology	1
IEEE Transactions on Engineering Management	1
Computers & Chemical Engineering	1
Energy Sources Part B-Economics Planning and Policy	1
Metallurgical Research & Technology	1
International Journal of Construction Management	1
Production and Operations Management	1
International Journal of Environmental Research and Public Health	1
Energy for Sustainable Development	1
Environmental Innovation and Societal Transitions	1
Journal of Industrial Ecology	1
Resources Policy	1
Ore Geology Reviews	1
Environmental Research Letters	1
Physica Status Solidi A-Applications and Materials Science	1
Engineering	1
Energy and Environmental Science	1
Batteries	1
Electricity Journal	1
Sustainable Materials and Technologies	1
Resources Conservation and Recycling	1
Energy Sources	1
European Planning Studies	1
Technovation	1
International Journal of Production Economics	1
Waste Management	1
International Journal of Sustainable Energy	1
SAE International Journal of Manufacturing	1
International Journal of Technology Management and Sustainable Development	1
Journal of Industrial Engineering and Management	1
International Studies Quarterly	1
Journal of Power Sources	1
Journal of Energy in Southern Africa	1
Ecological Indicators	1
Journal of East Asian Studies	1

Table 4 Number of publications per conference

Conference	Articles
ASES National Solar Conference	4
PICMET Portland International Center for Management of Engineering and Technology	2
IEEE India Conference	1
Global Conference on Sustainable Manufacturing	1
ICDRET International Conference on The Developments in Renewable Energy Technology	1
Energy Procedia	1
IFIP Advances in Information and Communication Technology	1

5.2 METHODOLOGICAL TRENDS

Figure 4 displays the different methodologies used in the reviewed publications from 2006 onwards. Upon examination of the article database, it can be observed that four types of research methods were the most popular, namely: (i) literature review (i.e., a study that collects, reviews, and analyses the progress of current research), (ii) modelling and simulation (i.e., a study that uses mathematical functions for decision-making), (iii) case study (i.e., a study that uses qualitative data to build a case about a problem), and (iv) theoretical and conceptual (i.e., a study that proposes a theory or a conceptual framework) (Salim et al., 2019; Yuan and Shen, 2011).

By far, modelling and simulation was the preferred method among the researchers in the database. Some of the most popular techniques included optimisation, life cycle assessment, financial modelling, and techno-economic modelling. These methods were used to study a broad range of problems, such as foreign trade, environmental sustainability, competing supply chains, R&D cooperation among actors in the value chain, growth of the PV industry in a specific location, among others. Theoretical and conceptual papers ranked second in the list of the most preferred methods (33%), followed by case studies (17%), and literature reviews (5%) (see Table 5). As expected, the share of case study and literature review articles has been increasing only recently.

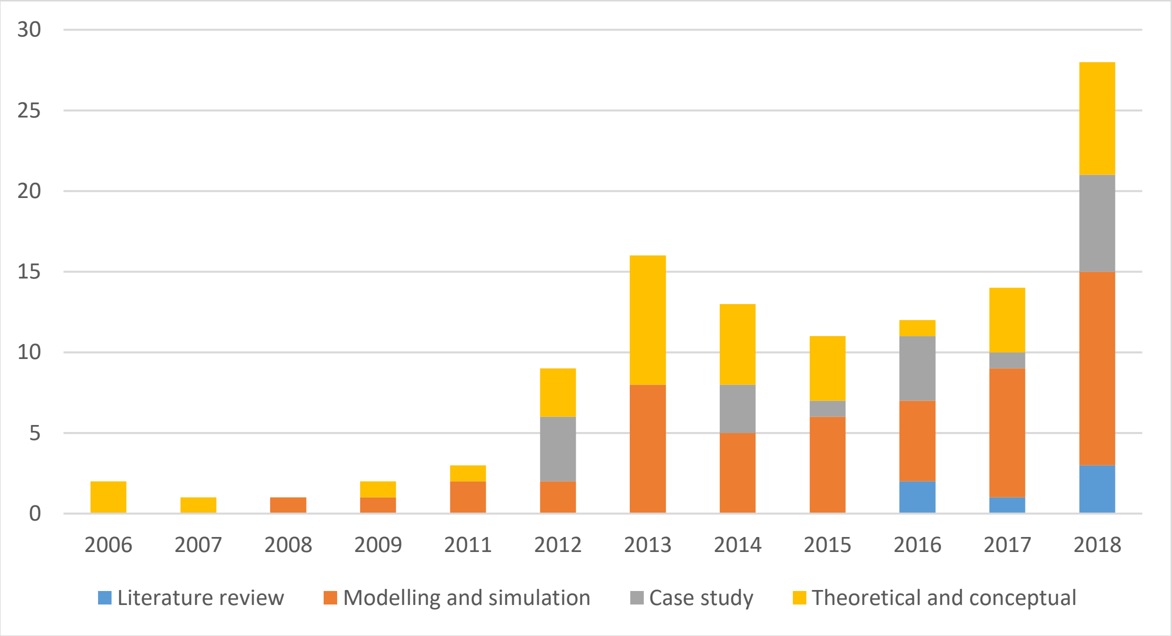

Figure 4 Temporal distribution of research methodologies

5.3 GEOGRAPHICAL TRENDS

As exhibited in Table 5, European countries were at the forefront of academic publishing in relation to PV systems. 41% of all articles reviewed for this study had their first authors coming from a European institution. Germany, the United Kingdom, and Italy were the most active players in the publishing field. Asia and North America are also worth highlighting, with 31% and 21% of the publications originating in these regions, respectively. Conversely, in developing countries, where government policies for PV deployment are less robust or inexistent, there is no motivation for academic research to be undertaken. Therefore, we reviewed only one article coming from this region.

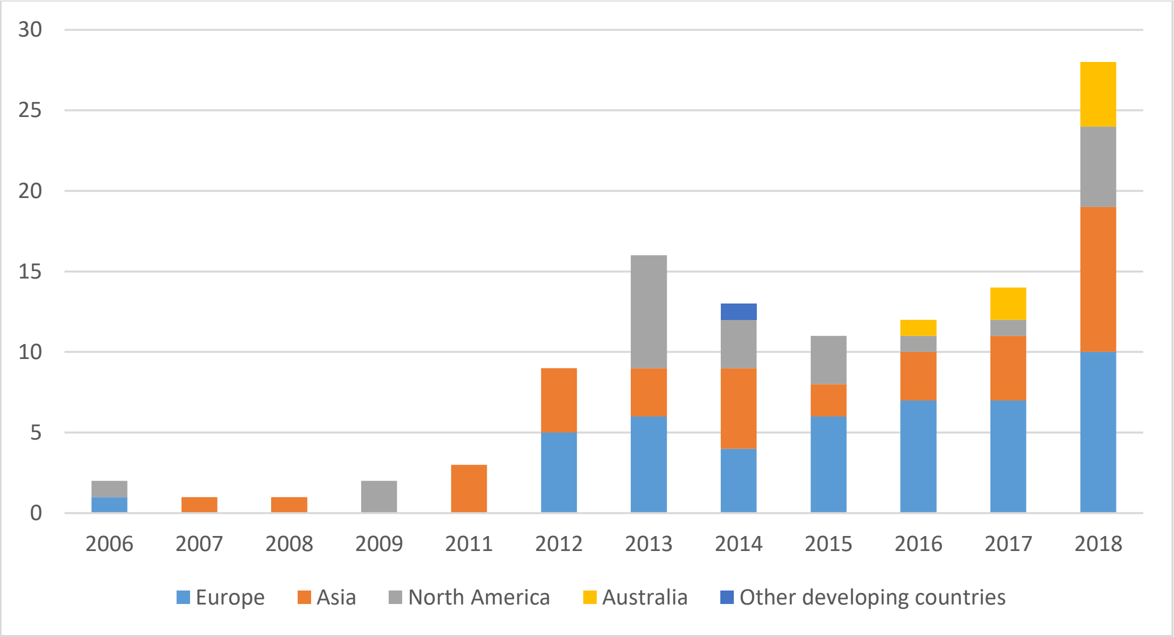

Figure 5 Temporal distribution of the geographical location of the first author

Table 5 Distribution of published articles

Category	No. of articles	Percentage
Research subject	112	100%
PV panels	95	85%
Batteries	13	12%
Both	4	4%
Research methodology		
Literature review	6	5%
Modelling and simulation	50	45%
Case study	19	17%
Theoretical and conceptual	37	33%
Geographical context		
Europe	46	41%
Germany	11	
United Kingdom	9	
Italy	7	
Spain	4	
Netherlands	4	
Norway	4	
Sweden	2	
Switzerland	2	
France	1	
Denmark	1	
Hungary	1	
Asia	35	31%
China	17	
Taiwan	5	
South Korea	4	
Japan	3	
India	2	
Singapore	2	
Iran	1	
Bangladesh	1	
North America	23	21%
United States	22	
Canada	1	

Australia	7	6%
Other developing countries	1	1%

Table 6 Publications per thematic group

Stage of the PV value chain	Category	Description	Reference
Upstream	Raw material	Issues related to the raw materials used in the manufacturing of silicon and thin-film PV cells	Bustamante and Gaustad (2014) Cowern (2012) Fthenakis and Anctil (2012) Gaustad et al. (2018) Hancock et al. (2018) Kaja and Barki (2011) Werner et al. (2017) Woodhouse et al. (2012)
	Technologies	Engineering processes in wafer, cell, and module manufacturing	Di Sabatino and Stokkan (2013) Goodrich et al. (2013a) Long and Geng (2015) Luo et al. (2018) Moser et al. (2017) Sheikh et al. (2014) Steeman et al. (2012)
	Supply chain collaboration	Collaboration among supply chain partners for innovation in PV manufacturing	Chen et al. (2014) Davies and Joglekar (2013) Dominguez Lacasa and Shubbak (2018) Jayanthi et al. (2009) Overholm (2015) * Zobel et al. (2016)
	Human resources	Job markets and job creation in the PV industry	Aziz and Chowdhury (2012) Llera et al. (2013)
	PV energy diffusion	Enablers and barriers for the diffusion of PV energy in a country, region, or industry	Curtius (2018) Grau et al. (2012) Hanson (2018) Hoffmann (2006) Hu and Yeh (2013) Huo and Zhang (2012) Jia et al. (2016) Kebede and Mitsufuji (2014) Kemeny et al. (2014) Kim and Lee (2018) Klitkou and Coenen (2013) Lam et al. (2018) Li et al. (2013) Newman et al. (2009) Nygaard et al. (2017) Pinkse and van den Buuse (2012) Sekhar et al. (2011) Shum and Watanabe (2007) Su (2013) Votteler et al. (2014) Xiaohua (2014) Yu (2018) Zeng (2015) Zhang and Gallagher (2016)
	PV BOS and system installation	Issues related to BOS components and the	Hanna et al. (2018) Shum and Watanabe (2007)

		installation of PV systems	
Midstream	Business models	Business models used in the PV industry	Horváth and Szabó (2018) * Huijben and Verbong (2013) * Overholm (2015) * Strupeit and Palm (2016) *
Downstream	Closed-loop supply chain	Describes issues and the modeling of PV panels at end-of-life (for reuse or recycling)	Adamo et al. (2017)* Besiou and Wassenhove (2016) Corcelli et al. (2018) Gaustad et al. (2018) Hsueh and Lin (2015) Kim and Jeong (2016) Shiue and Lin (2012) Xu et al. (2018)
Other categories	Electricity networks	Interactions between distributed PV providers and utilities	Cliburn and Robertson (2006) Corsatea et al. (2016) Fridgen et al. (2018) Mills and Wiser (2013) Munson (2015) Tayal (2017)
	Government and other institutions	Role of governments and other institutions in supporting PV deployment	Funcke (2012) Grau et al. (2012) Martin and Rice (2018) Migendt et al. (2017) Shum and Watanabe (2007)
	PV systems and EV batteries	Studies combining the use of LIBs for stationary PV energy storage and issues at battery EOL	Agnew et al. (2018) Bulman (2015) Canals Casals et al. (2017)* Gaines (2018)* Golembiewski et al. (2015)* Jiao and Evans (2016)* Martinez-Laserna et al. (2018)* Neubauer et al. (2015)* Olsson et al. (2018)* Ordoñez et al. (2016)* Ramoni and Zhang (2013)* Schneider et al. (2016) Sick et al. (2018)* Stenzel et al. (2014) Sun et al. (2018)* Zheng et al. (2018)*
	Economic modelling	Various types of economic analyses, including: cost-benefit analysis, foreign trade, competing PV supply chains, manufacturing plant locations, and energy payback time calculations	Abdallah et al. (2013) Basore and Cole (2018) Castellanos et al. (2018) Chen and Su (2014) Chen and Su (2017) Chen and Su (2018) Chiaroni et al. (2014) Cucchiella et al. (2012) Cucchiella et al. (2015) Dehghani et al. (2018) Goodrich et al. (2013b) Koppelaar (2017) Lee and Klassen (2008) Liu et al. (2017) Loomis et al. (2016) Meckling and Hughes (2017) Sawhney et al. (2014) Tanaka et al. (2018) Yang and Zou (2016)

Zhang and Wang (2017)

* Cross-reference

6 PV VALUE CHAIN

The solar PV value chain can be regarded as complex, not only technology wise, but also because of the various supply chains and stakeholders it displays, the different installation sizes it supports, the different business models it operates, and the different customer segments it is targeted to. Despite its inherent complexity, there is no comprehensive study that describes the interdependencies between the different value networks that play a role in the PV value networks (Jia et al., 2016). Some of the main players in these networks include governments, financiers (financing value chain), manufacturers (manufacturing value chain), customers (business models), and utilities (electricity provision value chain).

The upstream side of the PV value chain begins with polysilicon, ingot, wafer and cell production, and ends with the production and installation of modules. In this article, and different to the way the PV value chain has been traditionally described in the literature[2], *the authors will treat all the activities ranging from raw material production up to PV system installation as being only upstream activities*, since that is the place they occupy from a value chain perspective. Operations comprising solar grade silicon feedstock and wafer production are therefore in the upper-end of the upstream value chain. The main stakeholders in this section are the firms engaged in research and development, silicon supply (i.e., raw material suppliers), thin-film technology, ingots and wafers producers, as well as capital equipment manufacturers. Capital equipment is used to refine the silicon, produce the cells, as well as to manufacture complementary system components such as inverters and balance of systems (BOS) components (Zhang and Gallagher, 2016).

The middle part of the upstream value chain is concerned with solar cell and PV module production. These stages are carried out by the manufacturers of solar cells and the manufacturers of modules, respectively. At the lower-end of the upstream value chain, operations related to the installation of the PV system take place. Downstream actors include “BOS manufacturers” or system component manufacturers (e.g., inverters, energy management systems, tracking technology, structures, arrays, mounting, etc.) and “solar system integrators” (i.e., designers, distributors, installers, and managers of residential and commercial solar systems) (Hsueh and Lin, 2015; Luo et al., 2018; Zhang and Gallagher, 2016; Zobel et al., 2016). Because components are not necessarily sold in the same place where they are produced, this stage relies heavily on complex local networks of dealers and installers, who commercialize and handle the PV system. Finally, the midstream section covers all business model configurations for the commercialization and use of the PV system, whereas the downstream portion is concerned with strategies at EOL including refurbishing, reuse, and recycle.

6.1 INTRODUCTION TO PV SYSTEMS

PV systems report many advantages. From a market and end-use perspective, PV modules can be manufactured in massive production lines, thus allowing for economies of scale. Besides, PV is also a very modular technology, which facilitates an extremely wide range of applications: from small appliances to MW-scale PV power plants. From an installation perspective, PV energy systems are visually unobtrusive, and their operation is silent, rendering PV more advantageous than other renewable energies, particularly for deployment in the urban fabric (i.e., for residential or commercial building applications). Moreover, operation and maintenance costs for PV modules are considered relatively low, requiring infrequent interventions throughout the course of their (typical) 25-year lifetime. As such, PV systems are also ideal for abundant, clean energy generation in remote areas, such as islands.

Before presenting a detailed description of each stage of the PV value chain, though, it is important to list the various PV technologies that compete today in the marketplace. Based on the semiconductor materials

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[2] Most of the papers that were analyzed for this systematic literature review describe the PV value chain as starting with raw material procurement (upstream), continuing with cell and module manufacturing (midstream), and ending with the installation of PV systems (downstream). What these publications treat as up-, mid-, and downstream, the authors of this paper treat only as upstream. Business models and strategies at EOL were part of other, more specific publications.

and the manufacturing processes they employ, PV technologies can be classified as follows: (i) 1st generation technologies of crystalline silicon cells (c-Si) (i.e., mono-, and multicrystalline), (ii) 2nd generation technologies of thin-film technologies, and (iii) newer, 3rd generation technologies of multi-junction, organic PV cells, and concentrating photovoltaics (CPV) (Dominguez Lacasa and Shubbak, 2018; Zhang and Gallagher, 2016). Each PV technology has its own cell and module efficiency and different area requirements for its installation. First generation technologies (i.e., crystalline silicon PV) will be the focus of this paper since they are the most prevalent in the global market today, accounting for around 90% of PV production (Xu et al., 2018).

6.2 UPSTREAM PV VALUE CHAIN

6.2.1 RESEARCH AND DEVELOPMENT (R&D) FOR C-SI PV SYSTEMS

Research and development efforts in the PV industry are mostly concentrated on new material development, crystalline silicon and thin-film cell efficiency improvements, concentrated photovoltaics, balance of systems (BOS) components, production equipment, and process manufacturing. As an example of the expected efficiency gains in PV technologies, Woodhouse et al. (2012) suggest that the layer thickness in a CdTe (cadmium telluride) module could be reduced to around 1.0-µm, resulting in an efficiency gain of around 18%. The same can be forecasted for polycrystalline single-junction modules that could see their material intensity lowered and their weight be reduced through basic research.

Nowadays, almost all leading countries in PV production (i.e., China, Japan, Germany, and the United States) have devoted government funds to develop basic research related to PV technologies. In Germany, for instance, it is reported that more than half of the R&D support in 2010 was directed towards silicon technology, with the remaining funding being distributed for thin-film cells, and alternative concepts such as concentrated photovoltaics (Grau et al., 2012).

6.2.2 SOLAR GRADE SILICON PRODUCTION

Pure silicon is the dominant semiconductor material used in the production of solar cells (Lam et al., 2018). Silicon remains the material of choice for solar PV because of its abundance, non-toxicity, high and stable cell efficiency, and the maturity of its production infrastructure. Today, more than 90% of all solar cells are manufactured with silicon as the main semiconductor material. Furthermore, silicon is reportedly the only element that can help the PV industry achieve the number of terawatts needed for renewables to make a substantial contribution to global energy use (Cowern, 2012).

Although silicon is the second most abundant element in the crust of the earth, it is not pure in its natural state and must be refined before it is used in the production of solar cells. This is because solar panels require at least 99.999999% (6N) pure silicon. The first step in the overall silicon PV production process therefore involves the conversion of high-purity silica sand into silicon. The resulting metallurgical grade silicon (MG-Si), of about 98.5% purity, is obtained by the carbothermic reduction of silicates in electrode arc furnaces at temperatures above 1900°C. Most of the MG silicon at this point is used for aluminum casting or in the chemical industry. The remainder MG-Si is further refined and converted into semiconductor or solar grade silicon (SOG-Si) of 99.999999% purity by using, among others, the modified Siemens process or the fluid bed reactor process (FBR) (Goodrich et al., 2013a; Yu, 2018).

6.2.3 CRYSTALLIZATION, INGOT MOLDING, AND WAFERING

Before solar cells are manufactured, a silicon ingot is grown by different crystallization methods. Crystallization is actually one of the first steps in the silicon solar-cell value chain and can be differentiated by monocrystalline and poli- or multi- crystalline processes (Di Sabatino and Stokkan, 2013; Goodrich et al., 2013a; Jia et al., 2016). Monocrystalline silicon (mono-Si) is both more expensive and more efficient than polycrystalline silicon because it has gone through an additional recrystallization process known as the Czochralski process. Monocrystalline silicon panels have a conversion efficiency of 15-20% compared to the 13-16% conversion efficiency of polycrystalline panels [3]. However, around 56% of the world's solar

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[3] Conversion efficiencies depend on the manufacturing company

cells today are produced by multicrystalline processes because they are cheaper to manufacture and thus more preferred in the market.

Once either type of silicon ingot is manufactured, it is sliced into thin disks or wafers, and then chemically treated, doped, coated, and provided with electrical contacts in order to produce solar cells (Yadav et al., 2017). Most of the published research at this early stage of the value chain deals with examining the effect of defects and impurities on material property and ultimately on device performance. It has been demonstrated that defects and impurities arising throughout the silicon solar-cell value chain (e.g. silicon feedstock, crucible and coating, furnace atmosphere and crystallization) have a detrimental effect on solar cell performance (Cowern, 2012; Di Sabatino and Stokkan, 2013).

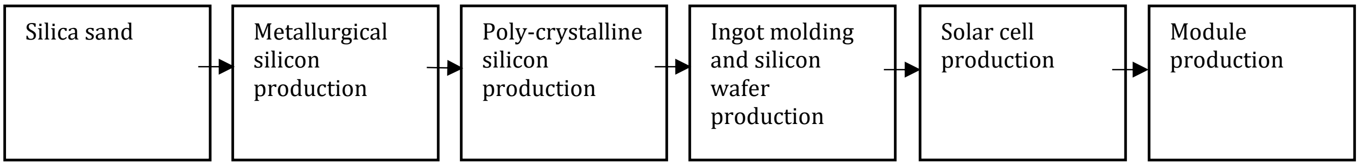

Figure 6 Manufacturing process for silicon PV modules

6.2.4 SOLAR CELL MANUFACTURING

Silicon based

To turn wafers into c-Si solar cells that can convert solar power into electric power, wafers are first cleaned and placed in a phosphorous diffusion furnace, resulting in a P-N junction for the photovoltaic effect. Next, the top surface of the wafer is covered with an anti-reflective coating to reduce the reflectivity of light and raise efficiency. Afterwards, electrical contacts are imprinted on the entire front surface of the wafer, while aluminum-based conductive material is deposited on the back surface of the wafer. To finish, each cell is electrically connected to other cells to form cell circuits for assembly in PV modules (Goodrich et al., 2013a; Jayanthi et al., 2009; Jia et al., 2016). Sets of cells or “strings” usually connect 10-12 cells in a silicon-based module and 60-100 cells in a thin-film module.

Thin-film

Thin-film is an alternative PV technology aimed at reducing the cost and the price of active materials in solar cells by using little or no silicon in the manufacturing process. Originally introduced in the 1970s, thin-film cells are still not mainstream technologies when compared to silicon-based cells. Although they exhibit an easier manufacturing process and lower costs, they also present lower light-to-voltage conversion rates than c-Si cells (i.e., 10-11%). Among the several types of thin-film cells that exist nowadays (e.g., cadmium telluride (CdTe), copper indium gallium selenide (CIGS), gallium arsenide (GaAs), and amorphous silicon (a-Si)), CdTe cells are the most prevalent. Otherwise identical in structure and function, the difference between c-Si and thin-film solar cells resides in their thin and flexible layers and the semiconductor material they use: CdTe, CIGS or GaAs instead of silicon. Also, whereas c-Si solar cells are made from wafers that are cut from a silicon ingot, thin-film cells are deposited directly on a substrate like glass, plastic or steel. Finally, because of their lower efficiency, thin-film energy cells require more physical space than crystalline silicon PV cells to generate the same amount of power.

Concerns exist regarding the scarcity of the base metals that make up CdTe thin-film cells (i.e., tellurium, indium, and gallium) and therefore, of the suitability of this technology for large-scale PV deployment (Bustamante and Gaustad, 2014; Woodhouse et al., 2012). For instance, the scarce material in CdTe solar PV is tellurium, which is found in low concentration and as the by-product of other more abundant metals like copper. The copper/tellurium nexus is not the only critical parent metal/byproduct nexus in clean energy systems, however. Others, such as aluminum/gallium and zinc/germanium also stand out. Some authors have also suggested that the current base of critical elements in thin-film cells (i.e., tellurium, indium and gallium) is not large enough to support large-scale PV deployment even if the industry were to somehow monopolize the reserves over each element (Woodhouse et al., 2012). Technological improvements that involve material reduction or cheaper byproduct recovery processes could, however, offset the potential supply limitations and imminent price increases associated with these materials.

Emerging PV cell technologies

Both crystalline silicon and thin-film technologies are single-junction. Multi-junction solar cells, or cells with multiple P-N junctions, promise to drastically increase solar cell efficiency because of their ability to absorb different multiple light wavelengths. Grau et al. (2012) report, for instance, that for two- (tandem), three- and four-junction devices, maximum efficiencies of 55.9%, 63.8%, and 68.8% are predicted. Besides multi-junction cells, organic materials also offer the potential for low cost and high energy absorption. These cells can be of various natures, namely: petrochemical cells, dye sensitized solar cells, organic and polymer solar cells, and other emerging technologies like quantum dot solar cells. These technologies are still under demonstration and have not been yet widely commercialized.

Table 7 PV technologies and configurations

Crystalline Si (Single-junction)	Thin-film (Single-junction)	Cell technology	Module construction	Frame
Mono-Si (c-Si)	CdTe	Al-BSF (aluminum back surface field)	Glass/back sheet	Yes
Multi-Si (mc-Si)	CIGS	PERC (passivated emitter and rear cell)	Glass/glass	No
	GaAs			
	a-Si			

Sources: Lam et al. (2018) and Luo et al. (2018)

6.2.5 MODULE MANUFACTURING

In the PV supply chain, solar modules are the core components of PV systems and account for a significant proportion of the PV system price (50%-60% for grid-connected systems) (Shum and Watanabe, 2007). After silicon has been casted into ingots, and wafers have been sliced from the ingot blocks and turned into solar cells through etching and polishing (plus cleaning, coating and screen printing), cells are put together into modules (Zhang and Gallagher, 2016). PV modules are assemblies of typically 6x10 or 6x12 series-connected solar cells, which are packaged into a protective multilayered structure of 5 main components: the front cover (tempered glass), the interconnected solar cells matrix in an envelope of two encapsulant layers (front/back) and a back cover (back sheet or tempered glass). Such structure provides electrical insulation and long-term protection of the solar cells against external environmental stresses. Externally, metal frames consisting of racking components and brackets are used to better support the panel structure. Electrical cables (i.e., positive and negative terminals) are linked to a so-called junction box, which is adhered on the back side of each PV module, and used to connect multiple modules at a PV system level.

From an engineering perspective, the quality and performance of a photovoltaic module can be determined by factors such as: (i) the photo-electric conversion efficiency (it is estimated that throughout the lifetime of a photovoltaic panel, its power conversion efficiency might decrease by around 20%), (ii) the degradation rate (i.e., the performance decay of the module), (iii) the environmental suitability (e.g., wind and dirt resistance), (iv) the repair peak time (i.e., the time after which the modules need to be repaired after installation), and (v) the technological risk (i.e., how outdated the technology of modules is) (Long and Geng, 2015). According to a 2014 report from the International Energy Agency, some of the most common failures found in silicon wafer-based PV modules included: (i) glass breakage and loose frame, (ii) back sheet adhesion loss, (iii) delamination and discoloration, (iv) potential induced degradation or PIT, (v) disconnected cell and string interconnection ribbons, (vi) defective bypass diode, and (vii) junction box failure (International Energy Agency, 2014). These failures occur in greater or lesser proportion depending on stage in the lifetime of the module (i.e., infant failures at the beginning of the working life of a PV module, midlife failures occurring to modules that have been in the field for an average of 8 years, or wear-out failures occurring after 15 years of operation of the PV module). Finally, as the amount of decommissioned PV panels gradually increases, so will the availability of more accurate data on failure types and rates.

6.2.6 BALANCE OF SYSTEMS (BOS)

All the components in a PV system, except for the modules, are referred to as balance of systems or BOS components (Shum and Watanabe, 2007). These components are intended to regulate and monitor the energy produced by the PV panels. The balance of system's most relevant components include cables and wiring, power electronics (e.g., charge controllers, over-current protection, PV current monitoring devices, combiner box, lightening protection systems, inverter) and the mounting support frames (Jayanthi et al., 2009; Zhang and Gallagher, 2016). From all these elements the inverter is the most important, as well as the most expensive, and the most technically complicated. An inverter transforms direct current (DC) from the PV array into a form of alternating current (AC) electricity that can be connected to the electric utility grid. Moser et al. (2017) report that most PV system failures are inverter related and that most of these failures are electric ones (e.g., failures in bus capacitors, electronic switches and printed circuit boards). Inverters are, therefore, usually replaced one or more times throughout the PV system's service life.

6.2.7 DEPLOYMENT OR INSTALLATION

This stage is concerned with the integration of the PV system and the delivery of electricity to the consumer. The deployment or installation process consists of various activities, including: system design and installation, permit and license acquisition, construction, operation, maintenance services, and insurance (Zhang and Gallagher, 2016). According to Funcke (2012), small PV systems in rooftops are typically planned by the installer, whereas larger rooftop and open space installations are handled by a planner who takes care of various aspects such as financing, administrative authorizations and so on. Installation of a PV system is a labor-intensive activity because qualified personnel is needed to install and connect the solar panels and to provide after-sale services to customers (Newman et al., 2009; Votteler et al., 2014). The personnel needed for a PV installation will depend on the project size, namely whether the PV project is residential (i.e., 1-10 kW), commercial (i.e., 11-500 kW), or industrial (i.e., > 500 kW).

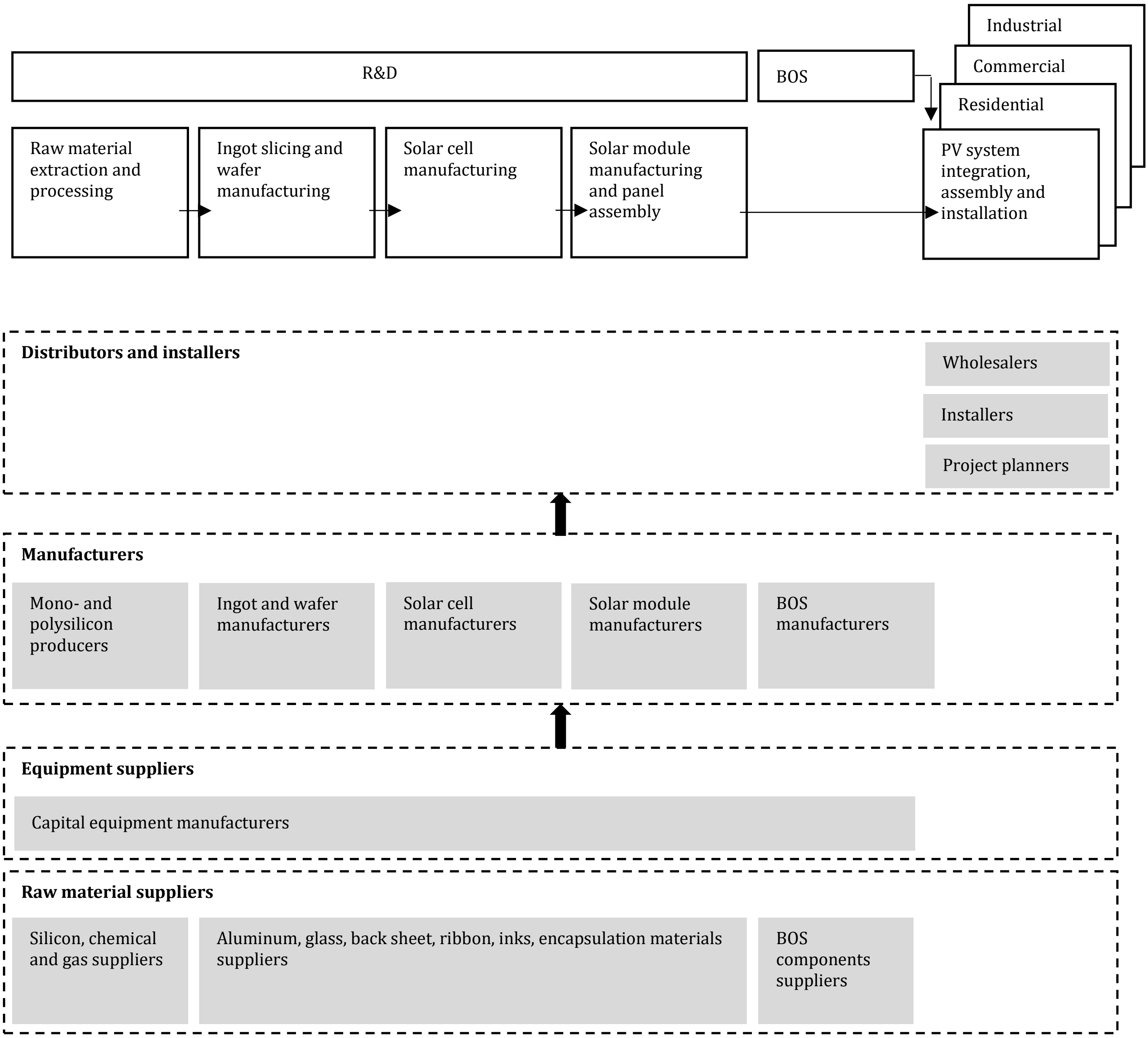

Figure 7 View of the upstream or supply side of the PV value chain

Solar modules are installed as panels with cables and inverters either on rooftops or on the ground and can be either connected to the grid or not (Jia et al., 2016). On-grid customers are connected to the utility or electrical service provider and can use not only the solar energy they produce, but also the energy from the grid. Off-grid installations, on the other hand, are not connected to the grid, and thus function independently from the utility. Off-grid customers produce their own energy by means of their PV installations.

Finally, authors like Hanna et al. (2018) report the extent to which installers of PV systems are dependent on government incentives for small-scale installations. Changes or lack of financial incentives triggered uncertainty among consumers, who had unclear or conflicting information about their financial incentives to begin, change or remain with a PV system.

Geography of stakeholders in the global PV supply chain

Knowledge- and technology-intensive R&D and capital equipment segments have been traditionally located in Europe, the United States, and Japan. This scenario, however, has slightly changed as many segments of the PV value chain have become part of a global value network with the participation of new market players such as China and Taiwan (Zhang and Gallagher, 2016). Despite the new competitive landscape, Xiaohua (2014) suggests low-labor, high-value added activities, such as polysilicon production and capital equipment manufacturing, are still led by European and American players.

Overall, it is undeniable that Chinese manufacturers dominate all the stages of the PV supply chain, from polysilicon production to module manufacturing (Lam et al., 2018; Su, 2013). After manufacturing and deployment in China, solar panels and other high tech materials are exported to other countries for assembly, packaging, and installation (Aziz and Chowdhury, 2012). China's success in the PV industry as a rapid innovation follower has been the result of government-sponsored import-substitution policies where the infant Chinese PV industry has first produced for the local market to then export worldwide when firms reached an international level of competitiveness (Zhang and Gallagher, 2016).

In terms of industry structure, the supply chain for c-Si modules is described as being fragmented, because it is comprised of a plethora of firms specializing in polysilicon feedstock, wafers, cells, and modules (Goodrich et al., 2013a). Research published by the European Photovoltaic Industry Association (EPIA) showed that the number of companies at the lower-end of the upstream supply chain (i.e., firms in charge of sales and installation of PV modules and systems) exceeded those located in the upper-end of the upstream value chain (i.e., suppliers of raw materials and manufacturers of wafers, ingots, and cells) (Shiue and Lin, 2012). However, upstream manufacturers, particularly the suppliers of capital equipment, silicon materials, and silicon wafers, provided the most value added and achieved the highest profits because upstream activities required more firm- and labor know-how, rather than standardized, routine tasks (Su, 2013; Zhang and Gallagher, 2016). In contrast, manufacturers of modules and panels achieved the lowest profits because barriers of entry were low and competition high (Jia et al., 2016).

6.3 MIDSTREAM - BUSINESS MODELS IN THE PV INDUSTRY

Barriers to PV system adoption, among them high up-front costs, long payback periods, and the difficulty of planning and installing a PV system, have spurred the need to look for new business models (BMs), or in other words, new ways of creating, capturing and delivering value (Strupeit and Palm, 2016). In one of its many definitions, a business model has been recognized as a catalyst for the diffusion of sustainable innovations and as an enabler for a more sustainable use of existing technologies (Boons and Lüdeke-Freund, 2013). A BM perspective to PV systems can give insights on how businesses can adapt their value propositions to better solve customer's problems.

The literature of business models for the PV industry focuses on three main configurations: (i) home-owned systems, (ii) third-party ownership (TPO) models, and (iii) community solar systems. In home-owned systems, end-users own the PV system while utilities pay a passive role by providing connection to the grid and net-metering to the end-user (not in all cases). TPO models, on the other hand, are characterized by the elimination of upfront payments and the provision of electricity at a predictable cost over a period from 15-25 years. The TPO model is reliant on a set of contextual conditions (e.g., tax credits, tariffs as well as market and consumer characteristics) that determine its financial viability and deployment trajectories in different country contexts (Shum and Watanabe, 2007; Strupeit and Palm, 2016). Finally, in the community solar scheme, multiple users purchase electricity from an off-site PV park without having to host their own PV systems on-site. More detailed descriptions for each business model are provided next.

6.3.1 HOME-OWNED SYSTEMS AND FEED-IN-TARIFFS (FITS)

In a home-owned system, customers own and finance (directly or indirectly) the upfront costs of their PV system. In some countries the financing for the purchase comes directly from the final user, whereas in others it comes in the form of low-interest loans offered by lending institutions (Jia et al., 2016). This type of business model is mainly targeted to households and SMEs who own a sufficiently large roof (with a good solar orientation and no shadows) and have incentives to reduce the financial burden caused by high electricity costs (Horváth and Szabó, 2018; Huijben and Verbong, 2013). As of today, the electricity generated by practically all home-owned systems has been connected to the grid and is reimbursed by a utility according to a regulated feed-in-tariff rate (FIT) (Strupeit and Palm, 2016). A FIT is an energy-supply policy aimed at attracting investments in renewable energies by means of a payment ($/kWh) to PV hosts for any electricity that is sent back to the grid. This payment is always embedded in a long-term guaranteed purchase agreement that can last up to 25 years.

The German solar industry is a prime example of how feed-in-tariffs have helped the PV solar industry flourish. Germany, which held the world's number one place in PV installations from 2004 to 2012, was a pioneer in passing the "Renewable Energy Sources Act" (EEG) that guaranteed a minimum 20-year feed-in-tariff (FIT) for customers. The German EEG states that the PV electricity fed into the grid by PV installation owners has to be purchased by utility companies at an enhanced price (Hoffmann, 2006). In the case of Germany, the FITs vary according to the PV system capacity (with thresholds of 30 kW, 100 kW and 1000 kW) and installation types (roof-top and field installations) (Grau et al., 2012). So far, more than fifty countries have implemented FIT schemes all over the world, including the Netherlands, Denmark, China, and Germany (Jia et al., 2016). Variations in the payment rates for FITs depend on multiple factors including energy prices and the state of the domestic electric infrastructure across countries.

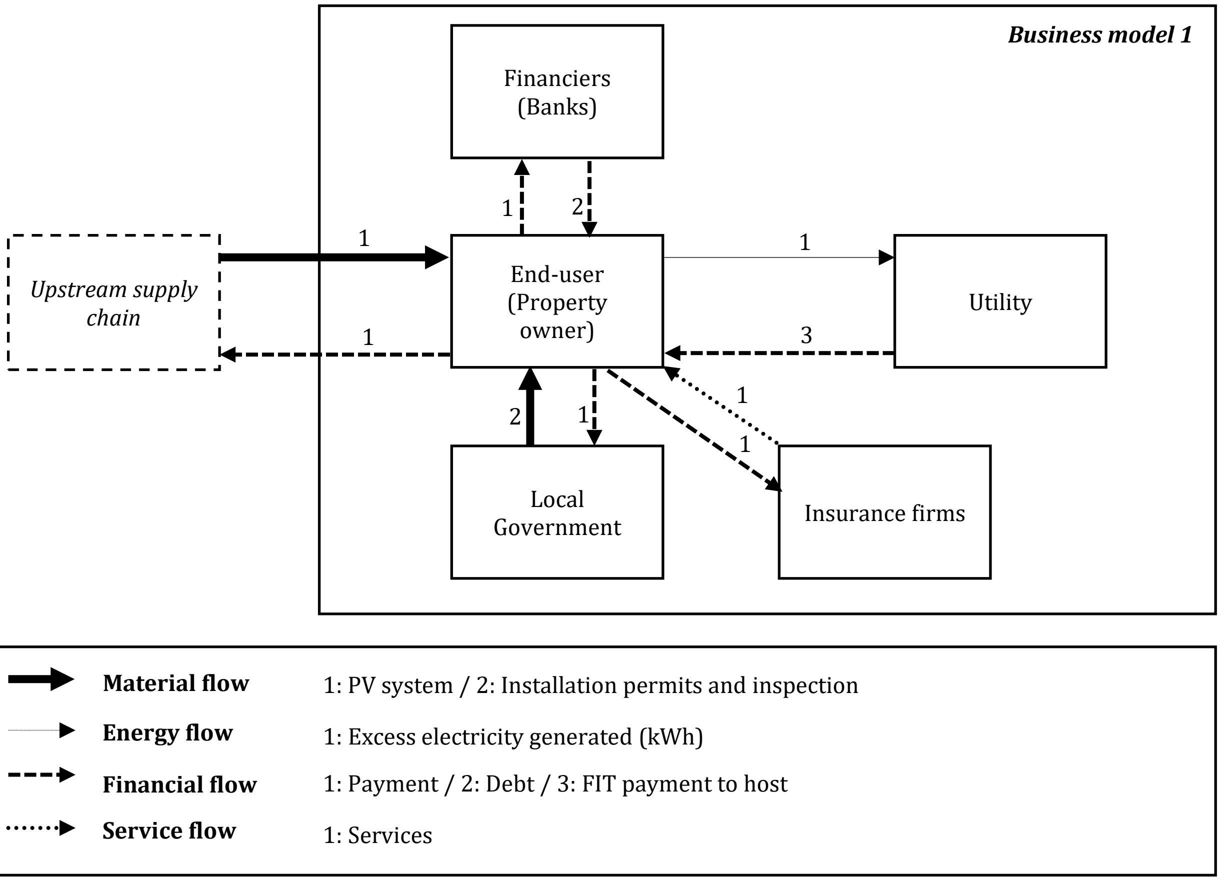

Figure 8 Business model 1: Home-owned PV systems

6.3.2 THIRD-PARTY OWNERSHIP MODELS (TPOS)

Third-party ownership (TPO) models are born as a response to the "high up-front costs, low operating costs" profile of PV energy provision. In a TPO model, solar service firms plan, build, own, operate, and maintain solar PV installations at the customers' premises, selling electricity to them for a predetermined period (Overholm, 2015). Solar service companies provide a full service solution that includes the inspection of the potential installation site, the evaluation of providers and installers (they might be the same entity), the arrangement of financing, insurance, and permits, the negotiation with utilities to sell surplus electricity to the grid, the maintenance of the solar system, and eventually the responsibility for scrapping (Overholm, 2015). While customers or hosts benefit by not having to deal with the high upfront costs associated with PV installations, and by passing the long-term operation and maintenance of the solar installation onto the TPO provider, the service provider benefits from tax credits and the revenues arising from the sale of electricity (Overholm, 2015).

Under a TPO model one can differentiate between two types of financing methods: (i) leasing and (ii) Power Purchase Agreements (PPA). In the lease model, customers (i.e., property owners or lessees) pay the installer/developer a fixed monthly installment, regardless of the system's energy production, and consume the electricity generated by the PV system. Conversely, in the PPA case, customers buy electricity (kWh) from installers at a predetermined price each month, usually at a rate lower than the one offered by the local utility. This is a way for residential and business customers to incorporate predictability in volatile electricity markets. Contracts under the PPA model usually range from a 15 to 25 years, period after which customers can buy or return the PV system to the service provider, or renew their contracts (Strupeit and Palm, 2016). Independent of the contract type, customers in leasing and PPA models typically pay monthly fees for hosting a PV system and consuming PV electricity.

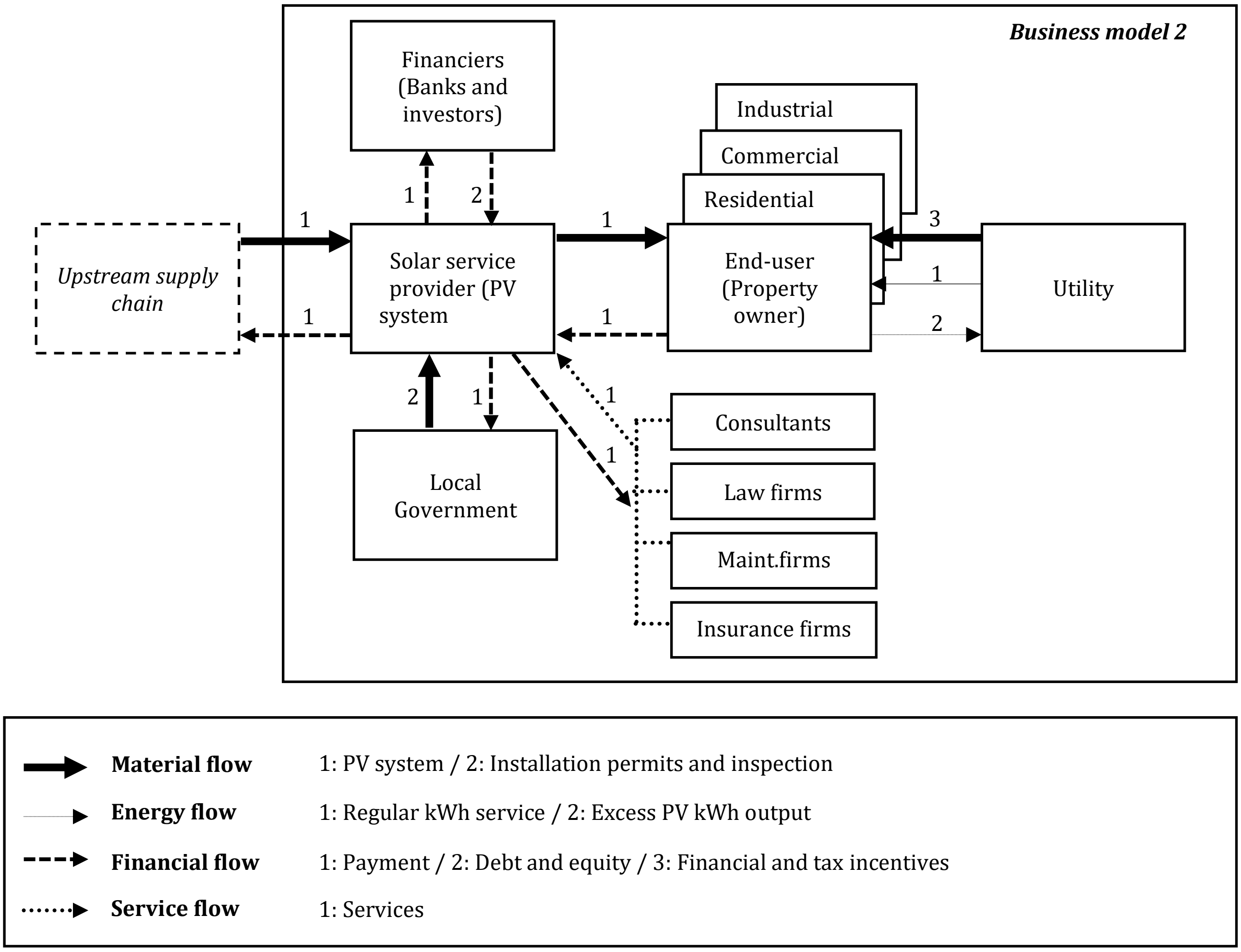

Figure 9 Business model 2: TPO model

Solar service firms operate as intermediate nodes that connect end-customers (i.e., property owners) with an ecosystem of partner firms that include PV system providers, government agencies, and financial institutions (Overholm, 2015). This is not the case for the owners of home-owned systems, who must interact directly with installers and maintenance firms, banks, government agencies, and insurers (Strupeit and Palm, 2016). The third-party ownership model is especially strong in the United States, where it emerged back in 2005 by serving commercial, institutional, and residential customers. After the success of this model in the United States, other countries, such as the UK, the Netherlands, and Singapore, have followed the lead and supported the deployment of similar systems (Overholm, 2015; Strupeit and Palm, 2016).

6.3.3 COMMUNITY SOLAR

In a community model, multiple users purchase electricity from an off-site PV park or garden without having to host their own PV systems on-site (Huijben and Verbong, 2013). Users that subscribe to this model lack either a suitable roof for installing a PV system (e.g., shaded, aged or damaged rooftops) or property ownership rights (e.g., people who rent or lease instead of owning, people who are planning to move). Under a community-shared business model, participants can purchase rights of the total output of the solar system without the need to pay any upfront costs or deal with the technical complexity of the PV installation. In return, subscribers receive credit on their energy bills. Alternatively, customers can pay an upfront fee to finance the costs of the project, thereby purchasing an equity stake in the revenues from a portion of the plant (Horváth and Szabó, 2018).

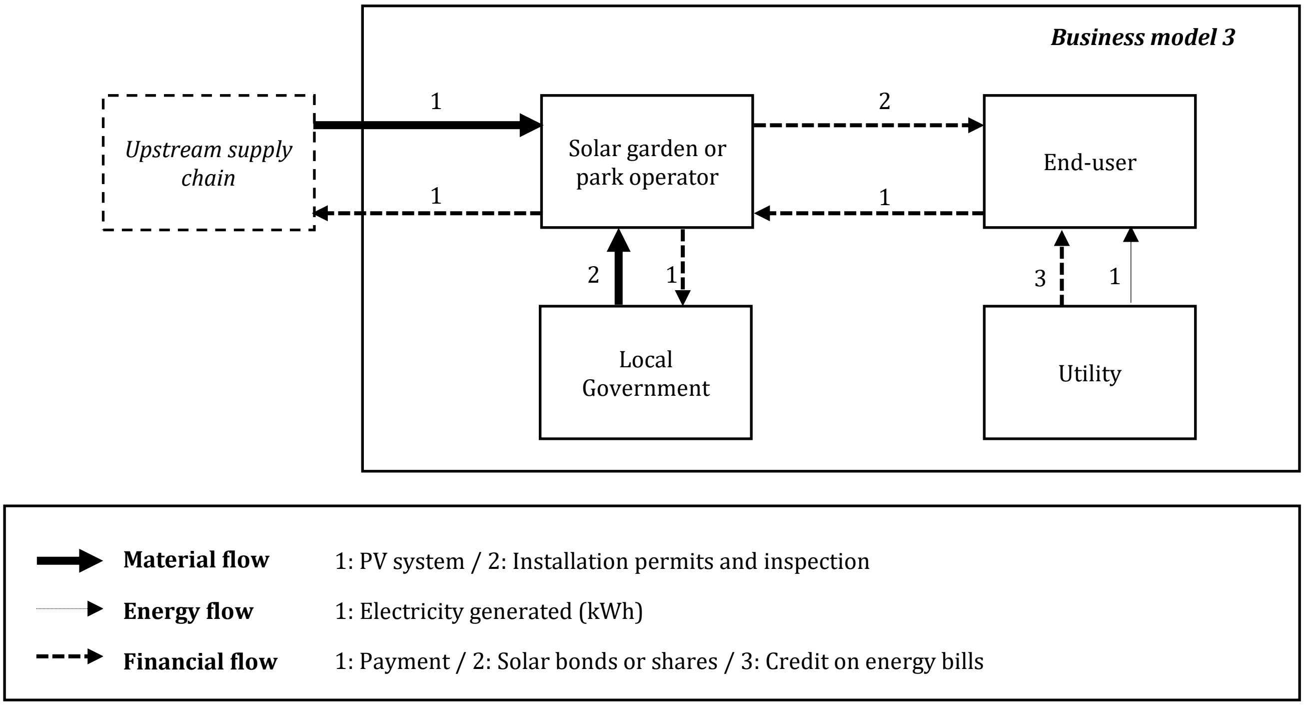

Figure 10 Business model 3: Community-solar model

Table 8 Characteristics of the main business models in the PV industry

Characteristic	Home-owned	Third-party	Community solar
PV System location	Roof of end-user	Roof of end-user	External roof
PV System size	Small	Small to medium	Large
PV System owner	End-user	Solar service provider	External entity
Investment	End-user	External party	End-user
Payment of upfront costs	Yes	No	No
Repayment of initial investment	Energy bill	Energy bill	Energy bill

Partially taken from Huijben and Verbong (2013)

6.4 DOWNSTREAM - END-OF-LIFE MANAGEMENT OF PV SYSTEMS

The appropriate end-of-life management of PV waste is of outmost importance, not only for the collection and recycling of important raw materials such as aluminum and glass, but also for the effective disposal of hazardous elements such as lead (from silicon modules) and cadmium (from thin-film modules). Growing volumes of PV waste also represent an opportunity to create value activities across the PV value chain and an avenue for achieving combined environmental and socio-economic benefits for multiple stakeholders. At this stage of the value chain, most authors focus on PV panel recycling, while less is reported on PV panel reuse.

6.4.1 PV PANEL RECYCLING

In the PV industry, most R&D activities and funds have been targeted towards improving the efficiency of crystalline silicon panels. Less effort has been devoted to innovative processes for dismantling and recycling PV panel waste. If not properly disposed, EOL PV panels can cause serious environmental problems including: (i) the leaching of lead and cadmium into the environment, (ii) the loss of recoverable resources such as silicon and glass, and (iii) the loss of recoverable rare metals such as silver, indium, gallium, and germanium (Xu et al., 2018).

Because most of the PV systems that are currently in operation have been installed only since 2010, most of the PV waste today consists of pre-consumer waste (i.e., processing scrap from manufacturing) and not of end-of-life PV modules (Kim and Jeong, 2016; Luo et al., 2018; Sica et al., 2018). Although the volume of decommissioned PV panels is insignificant today, one could expect to deal with end-of-life materials from PV panels in the foreseeable future. Forecasts estimate that, given the average lifetime of PV panels (20-30 years), the decommissioning stage of the value chain may start between 2025 and 2030. Furthermore, with PV capacity expected to increase to 1600 GW by 2030, the amount of decommissioned PV panels in the future is also expected to rise. By 2050, it is estimated that around 60 million tons of PV waste will be lying in landfills. The volume of PV waste does not solely correlate to production quantities, though. Other factors such as the forecasted panel's useful life, the amount of waste during manufacturing, the proportion of premature waste (during transport and installation), as well as the failure rate during use are also important (Corcelli et al., 2018).

The few available old or damaged PV panels have been, so far, processed in general-purpose glass recycling facilities where only glass and aluminum frames are recovered. The remainder of materials is often burned[4]. Al and glass thus account for a large fraction of the materials in PV panels and the non-recycling of these materials would mean a considerable loss of resources for the industry. Also, the incentives to recover silicon, panels' main raw material, are high because silicon production is an energy-consuming process and the energy and cost needed to recover silicon from recycled solar panels are reportedly equivalent to one third of those of manufacturing silicon directly (Xu et al., 2018).

Gaustad et al. (2018) report that many elements critical to emerging PV technologies, such as indium, tellurium, and gallium, today exhibit near-zero recycling rates. Indium, for instance, is present in amorphous silicon and copper indium gallium selenide panels. Gallium is present in copper indium gallium selenide panels, concentrated photovoltaic panels, and emerging panel technologies (Xu et al., 2018). Although these metals account for about 1% of the panel volume, their value is significant, and their non-recirculation would signify a loss for manufacturers and the industry in general. The main challenge here is to recycle these valuable metals at the highest possible purity level.

Recycling technologies

Multiple recycling technologies experimenting with mechanical, thermal and chemical recycling exist. However, only three known industrial-scale closed-loop supply chains of PV systems: (i) Deutsche Solar for recycling c-Si modules, (ii) First Solar for thin-film CdTe modules, and (iii) PV Cycle for recycling both technologies. Recycling steps vary according to the type of PV module. For instance, the process for recycling crystalline silicon modules can be divided into three macro steps: (i) disassembly of the panel to separate aluminum, glass parts, and the junction box (ii) thermal treatment (i.e., pyrolysis) in order to ease up the binding between the cell elements, and (ii) chemical treatment for the recovery of Si, Cu, and Ag (see Figure 9). This type of treatment, however, may entail that some hazardous elements such as Cd, Pb, and Cr are released into the environment. At the end of this process, the recovery rate for glass is 95% and almost 100% for aluminum. According to Sica et al. (2018), one of the main limitations of this process is that it requires various manual activities, which limits the production efficiency of the process. Conversely, for CdTe modules, the steps involve disassembly, shredding and milling, film removal, solid/liquid separation, glass rinsing and recovery, and precipitation and filtration (Kim and Jeong, 2016). As pointed out before, the attention is placed more on thin-film module recycling, as it guarantees a higher profit thanks to the presence of precious materials (Adamo et al., 2017).

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[4] A typical silicon panel is made up of 65-75% glass, 10-15% aluminum, 10% plastic, and 3-5% silicon Xu, Y., Li, J., Tan, Q., Peters, A.L., Yang, C., 2018. Global status of recycling waste solar panels: A review. Waste Management 75, 450-458..

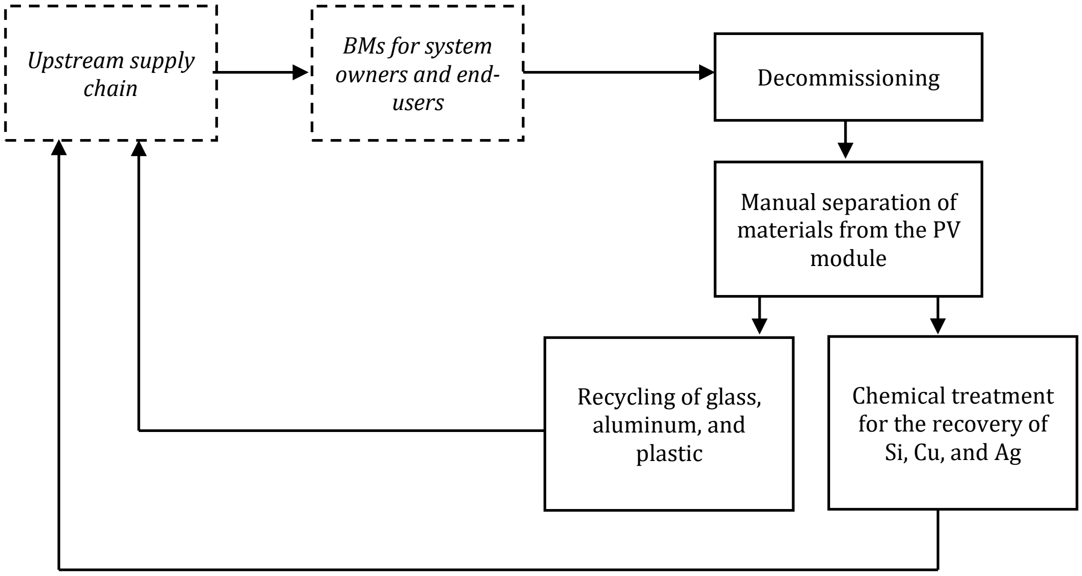

Figure 11 Recycling process for c-Si modules [5]

All in all, the materials resulting from the recycling process can be either used in new manufacturing cycles, sent somewhere else for additional treatment, or sold to secondary markets (Kim and Jeong, 2016). Some authors have also highlighted the drawbacks of the current recycling methods for PV panels. One of the drawbacks is that the more the recycled material in new PV panels, the greater the probability for lower electricity generation. This is so because the quality of recycled materials is lower than that of virgin materials. Furthermore, adequate recycling can only be achieved when PV waste is not mixed with other type of waste so that cross-contamination does not take place (Besiou and Wassenhove, 2016).

On July 2012, the European Union introduced extended producer responsibility (EPR) legislation by regulating the collection and recovery of end-of-life PV modules as EU Waste Electrical and Electronic Equipment (WEEE). The so-called "WEEE Recast" required all EU member states to transpose the Directive into national law by February 2014 and required all PV panel manufacturers, regardless of their geographical location, to finance the costs of collecting, recovering, and recycling all the PV panels sold in Europe (Besiou and Wassenhove, 2016; Xu et al., 2018).

6.4.2 ENVIRONMENTAL ISSUES RELATED TO THE DISPOSAL OF PV PANELS

Some of the critical environmental issues associated with the disposal of EOL PV panels include losses of scarce metals (e.g., silver, gallium, indium, and germanium) and conventional materials (e.g., aluminum and glass), plus the release of hazardous metals (e.g., cadmium, lead, tellurium, and selenium) and toxic gases (e.g., hydrofluoric acid) into the environment (Adamo et al., 2017; Corcelli et al., 2018). Of particular concern is the leaching of hazardous materials such as Pb and Cd, which takes place when the glass that encapsulates the PV cells is broken down or damaged (Xu et al., 2018). Cadmium, for instance, is believed to cause the Itai-itai disease and to be toxic to fish and wildlife, as well as to the human body. Once absorbed in the human body, cadmium can cause lung, kidney, and bone damage (Shiue and Lin, 2012). Furthermore, recycling costs reportedly depend on whether PV modules contain hazardous waste such as those described above (Besiou and Wassenhove, 2016). Toxic heavy metals sink in the residues from recycling, turning it into special waste that needs to be sent to a hazardous-waste landfill (Xu et al., 2018).

6.4.3 COST

Various authors report on the lack of profitability resulting from the recycling PV panels. Current low volumes of EOL PV panels not only make recycling expensive, but also decrease the incentives

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[5] Taken from Sica, D., Malandrino, O., Supino, S., Testa, M., Lucchetti, M.C., 2018. Management of end-of-life photovoltaic panels as a step towards a circular economy. Renewable and Sustainable Energy Reviews 82, 2934-2945.

manufacturers have to proactively engage in recovery and recycling schemes in the near future (Besiou and Wassenhove, 2016). High transportation and collection costs, as well as high capital costs needed to establish collection and recycling centers, including the necessary machinery as well as the chemicals and other materials required in the recycling process, mean it is not economical to recycle at low waste volumes. High recycling costs also increase competition for landfilling (i.e., it is cheaper to landfill than to recycle) and the incentives for low value recycling (i.e., no material separation before recycling) (Besiou and Wassenhove, 2016). The question is also whether the recovery cost of certain materials is economically competitive so that it won't compromise the competitive position of the respective PV technologies.

6.5 GOVERNMENT ROLE IN SUPPORTING THE PV VALUE CHAIN

There is widespread knowledge that the diffusion and the demand for PV systems are a function of economics and regulatory incentives, both of which rely, to a great extent, on governments and supranational bodies (Sawhney et al., 2014; Yang and Zou, 2016). Incentive policies of various kinds have in fact helped make the deployment of solar installations more affordable for manufacturers and consumers given the high-tech, high-investment, and long-payback-period profile of the PV industry (Chen and Su, 2017).

Government intervention is pervasive along the PV value chain and is critical in facilitating research development, demonstration, deployment and recovery of PV systems. The first two activities relate to upstream efforts to address the scientific and technical aspects of renewables. The last two, on the other hand, refer to the downstream institutional, market, social and environmental aspects of the technology (Shum and Watanabe, 2007). Hence, government policy can be targeted to either push technology or pull demand from the marketplace. Whereas the former includes support for R&D, subsidies and tax credits, the latter refers to cash rebates, direct investments, loan guarantees, subsidies, tax incentives, and feed-in tariffs (Migendt et al., 2017). China's solar industry, for instance, flourished since 2006 when the government decreed various renewable energy sources as the primary industry support for the 11th 5-year plan (2006-2010) (Jia et al., 2016). Government support came in the form of subsidies for solar manufacturers and subsidies for panel installations for consumers. Besides subsidies, the Chinese government also resorted to tax rebates, free land for production, low interest government loans, and feed-in-tariffs to reach its clean energy targets.

Governments will be even more critical in the years to come as they will streamline regulations, permitting, and interconnection for new business models, pass legislation to increase landfill and material costs to favor more reuse, and also introduce regulations that may reduce the uncertainty about the volume of expected EOL PV panels (Besiou and Wassenhove, 2016; Newman et al., 2009).

7 EV battery value chain (Li-ion batteries)

Similar to the description of the PV value chain in the preceding sections, the following pages introduce the different stages and stakeholders in the electric vehicle (EV) value chain. The coupling of PV systems with battery energy storage systems (BESS) will become increasingly more prevalent in the future, as governments and consumers become Increasingly more aware of the energy management benefits of these coupled systems.

7.1 INTRODUCTION TO EV BATTERIES

Battery electric vehicles (BEVs) have become one of the preferred avenues for decarbonizing the transport sector and the economy in general. Sales of EVs have been on the rise over the past years, driven by falling battery costs and an increasing awareness on the side of customers and institutions about the environmental benefits of divesting from fossil fuel-powered vehicles. Only in 2017, over one million electric vehicles were sold, and, in the same year, the number of electric vehicles on the road surpassed the three million worldwide (International Energy Agency, 2018). Lithium-ion batteries (LIB) is the most common type of battery used in electric vehicles, making up more than 60% of the global EV market. The main advantages of lithium-ion batteries, the same technology that powers consumer electronics such as smartphones and tablets, are their high cell voltages, high energy and power density and low self-discharge (Stenzel et al., 2014).

The high upfront costs of EV batteries continue to represent one of the most important barriers for the mass market adoption of EVs, despite the falling battery prices. Besides investments in R&D and manufacturing processes aimed at reducing battery costs (e.g., through material reduction, new material development, higher process efficiencies, and scale economies), battery second life has been proposed as a way to generate new revenue streams that may drive cost discounts for EV buyers (Martinez-Laserna et al., 2018; Neubauer et al., 2015). Furthermore, with the forecasted increase in the number of EVs on the road, the question remains as to what is to be done with the several batteries that are likely to be removed from electric vehicles by 2030.

Giving EV batteries a second life as a stationary unit for renewable energy storage, stands as an avenue for prolonging batteries' lifetime and delay costly recycling. Incorporating a circular view to the EV battery chain, promises to bring about multiple benefits including the lengthening of the asset's lifetime (i.e., through reuse), as well as decreasing reliance on virgin raw materials for manufacturing (i.e., through recycling) and their imports from third countries. This section is aimed at providing an overview of the EV battery value chain, including strategies at EOL such as reuse and recycling.

7.2 UPSTREAM EV BATTERY VALUE CHAIN

The EV battery upstream value chain can be summarized into four value-added steps: (i) raw material extraction, (ii) cell and module manufacturing, (iii) battery system manufacturing, and (iv) integration of the battery into the electric vehicle (see Figure 12). Research and development activities span all stages upstream and will therefore be discussed first.

7.2.1 RESEARCH AND DEVELOPMENT FOR LITHIUM-ION BATTERIES

After conducting a patent analysis, Golembiewski et al. (2015) reported that between the years 2000 and 2011, LIBs patenting activity encompassed: (i) cell components, (ii) the assembly of secondary cells, and (iii) the electric propulsion within the vehicle. From all these, patents for cell components achieved the highest number, thus providing a glimpse on the high interest placed by the industry on the research of individual materials, their combinations, and their effects on the electrochemical processes of EV battery cells. A focus on cell components is not only evident among incumbent firms, but also among start-ups, which, surprisingly, tend to introduce incremental improvements to existing technologies rather than radical solutions (Sick et al., 2018).

Research on cell components was controlled by electronics manufacturers, followed by automobile manufacturers, and to a lesser degree by chemical and battery manufacturers. Electronics manufacturers dominated this research domain because cell technologies have been first used in electronic devices. Automotive firms, in turn, dominated electric mobility patenting. In terms of geographical concentration of patenting activity, Japan was the leader with the highest number of patent applications across the battery value chain, followed by South Korea, China, Germany, USA, and France.

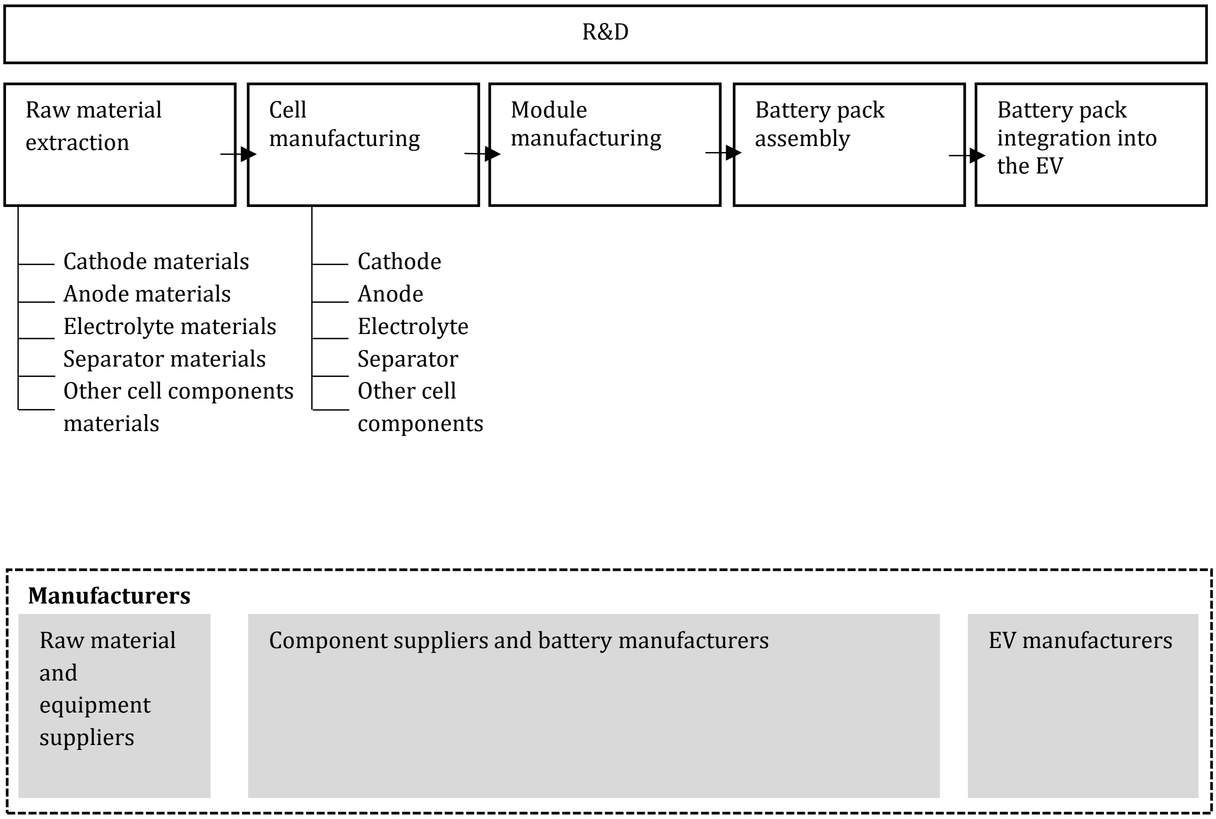

Figure 12 Upstream EV battery value chain

7.2.2 RAW MATERIAL EXTRACTION

Li-ion battery manufacturing relies heavily on a growing supply of cobalt (Co), lithium (Li), nickel (Ni), and carbon (C) or natural graphite. In the automotive industry, these raw materials are believed to constitute a great part of the cost of the vehicle, suggesting their high economic value and the high vulnerability of the industry to future supply disruptions (Gaustad et al., 2018).

Cobalt, a material classified as critical and rare, is the main cathodic element used in LIBs today, making up about 25% of the total battery cost (Gaustad et al., 2018). Cobalt is supplied, in a great percentage (more than half of global production is mined here), by the Democratic Republic of Congo, a region characterized by political unrest (Drabik and Rizos, 2018). China, Russia, Canada, and Australia are other well-established, yet minor, suppliers of cobalt (Sick et al., 2018). Long-term sales forecasts of EVs show that by 2050, the cumulative demand for cobalt would require all reserves known today, a rather worrying scenario when taking into account the geo-political volatility of cobalt's main supplier. This estimation, however, sits on the assumption that cobalt-based battery technologies, will continue to be used by 2050, which is a rather unlikely scenario as cobalt-free technologies are likely to be a reality by this time (Lebedeva et al., 2016).

7.2.3 BATTERY CELL AND MODULE MANUFACTURING

LIBs are made of multiple power-generating compartments called cells. Each cell consists of four elements, namely: (i) a positive electrode or cathode (made predominantly of lithium cobalt oxide, but currently using various other types of Li-containing oxides and phosphides[6]), (ii) a negative electrode or anode (often made of graphite applied to a current collector that powers the EV), (iii) an electrolyte, or lithium salt dissolved in a liquid organic solvent, which plays a central role in battery parameters such as cell voltage,

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[6] Cathode material can be any one of a variety of lithium transition metal oxides, including: Lithium Manganese Oxide ($LiMn_2O_4$), Lithium Iron Phosphate ($LiFePO_4$), Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$), and Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$).

energy density, operational safety, and stability, and (iv) a separator (a thin microporous polyolefin film) that separates the anode and cathode, thus preventing short circuiting (Stenzel et al., 2014; Zheng et al., 2018). Cathode and anode are separated and connected by an electrolyte, which transfers lithium ions from the anode to the cathode and vice-versa.

Cell manufacturing is a highly integrated process that consists of various steps, namely: (i) the production of electron slurries, (ii) coating and processing of electrodes, (iii) filing the electrodes into cans, (iv) adding electrolyte, (v) sealing the cell, and (vi) a final electrochemical formulation step (Sick et al., 2018). The architecture, size, chemistries, and shapes (e.g., cylindrical, pouch, hard casing) of the cells vary according to each manufacturer and even from model to model from each manufacturer (Gaines, 2018). As a final step, cells are grouped together into a module to ensure protection from external shocks, such as heat or vibration. Modules are then fitted into a large battery pack, which is controlled by an electronic battery management system or BMS.

7.3 MIDSTREAM – BUSINESS MODELS FOR 1ST LIFE EV BATTERIES

There are three known business models used for commercializing EV batteries. The first one is quite straightforward and attaches ownership of the LIB to the owner of the EV. The second one enables car manufacturers to retain ownership of the battery throughout its lifecycle through a leasing model. Battery ownership by the EV manufacturer enables the efficient management of batteries and facilitates the secondary applications of retired batteries on a large scale (Jiao and Evans, 2016). The third and last business model is similar to the previous one, except that the EV battery is not owned by the OEM, but rather by a third party.

7.4 DOWNSTREAM - END-OF-LIFE MANAGEMENT OF EV BATTERIES

With the rapid development of LIBs and EVs in recent years, the repurposing and recovery of lithium batteries has become an important area of research. According to Yun et al. (2018), from 2008 to 2018, more than 3000 research papers have been published around this topic. The following sections review reuse and recycling strategies for spent LIBs.

7.4.1 REUSE OF SECOND-LIFE LIBS FOR STATIONARY STORAGE

LIBs are removed from the EV when their maximum capacity has degraded to 70-80% of the original capacity, which occurs about 8-10 years after the vehicle has entered into operation (Neubauer et al., 2015). At this point, and when no longer suitable for EVs, EV batteries can be re-purposed and given a second-life use as stationary storage for PV energy. A business model coupling PV technology with storage devices could help fit this intermittent renewable technologies into the existing power generation system and increase solar energy dispatchability (Corsatea et al., 2016). In the literature, second-life batteries are defined as: “batteries removed from electric vehicles (EV) when their density and power has degraded below the level required for motive applications, but are still performant enough for less demanding stationary applications” (Sun et al., 2018). By exploiting additional value from post-vehicle batteries, the total lifetime of the battery is increased, and recycling is delayed by 3 to 15 years.

Second-life usage for EV batteries can only be accomplished once some issues are resolved, though. Among them: (i) finding out what the costs of refurbishing an EV battery are, (ii) dealing with the decreased efficiency resulting from use in the first life (there is uncertainty surrounding the capacity drop of the LIB after its first life), and (iii) dealing with warranties, reliability and safety concerns, and regulatory barriers that hinder customer trust and product adoption (Olsson et al., 2018; Sun et al., 2018).

Actors and processes in battery reuse

Taking into account that most batteries have been commercialized through a leasing model, the sellers of second-life batteries would include former EV owners, but specially OEMs. Under a leasing scheme, the EV vehicle owner pays a monthly fee for being able to use the battery, but does not own it (Sun et al., 2018). The suppliers of stationary solutions for PV systems would be the buyers of second-life batteries. They would, in turn, supply the battery to the final PV customer. At this point of the value chain, new actors taking care of the conditioning of batteries for a second-life use are likely to emerge. These companies could either be subsidiaries of EV manufacturing companies or stand-alone firms (see Figure 13).

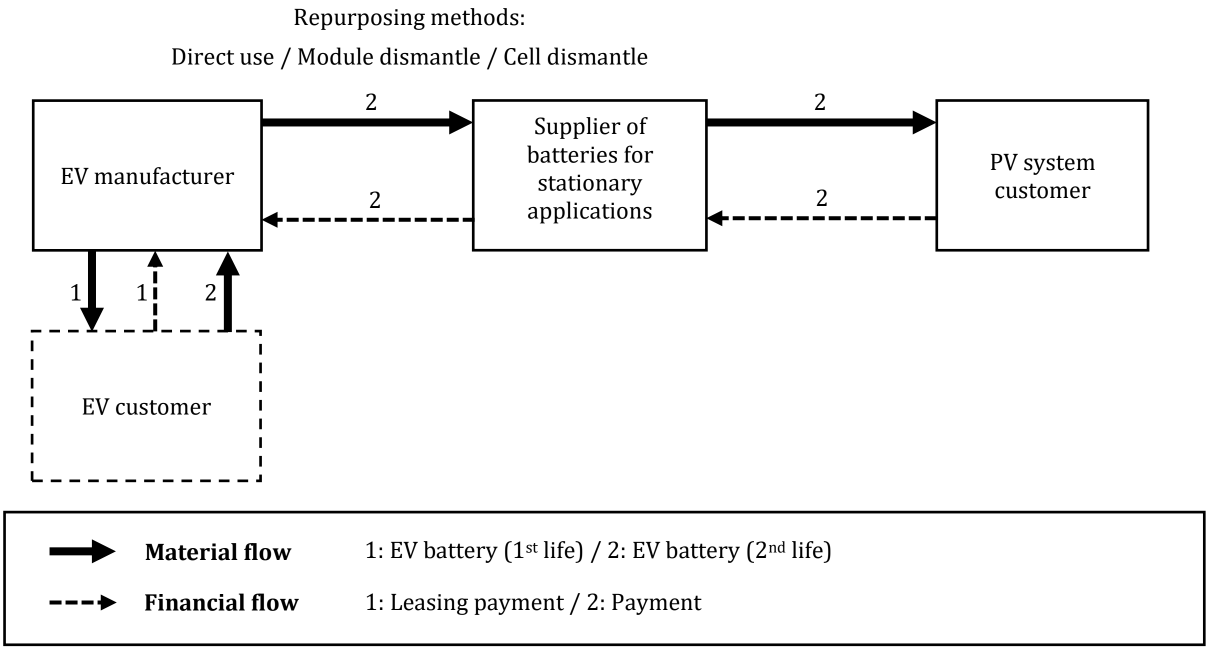

Figure 13 Repurposing flow for 2nd life LIBs

Repurposing methods

Used batteries will need to be tested, sorted, and certified as part of a repurposing process before being commercialized for second-life applications. This is so because modules tend to age differently and the identification of the modules with capacity left for a second use application is critical. To this date, there are three known avenues for repurposing EV batteries: (i) direct reuse, (ii) module dismantle, and (iii) cell dismantle (Canals Casals et al., 2017). Direct reuse is the fastest and cheapest method. Here, batteries are not entirely disassembled, and they are reused with only minimal adaptations. Module dismantle involves dismantling the modules and repacking them again, using a different configuration, according to the modules' remaining capacities. The third and final option concerns dismantling the battery down to the cell level, and just as with the previous case, group cells by their remaining capacity. This process demands harder work, is more expensive, and may be riskier since cell dismantling can be extremely delicate. The choice for a repurposing strategy is furthermore complicated by the different types of EV batteries used for the different car models: more than 20 types according to Canals Casals et al. (2017). Each battery construction display variations in the number and types of cells, physical shape, and chemistry. LIBs are not currently labeled according to their specific chemistry, so that neither refurbishing, nor recycling parties know which kind of LIB they are receiving (Olsson et al., 2018).

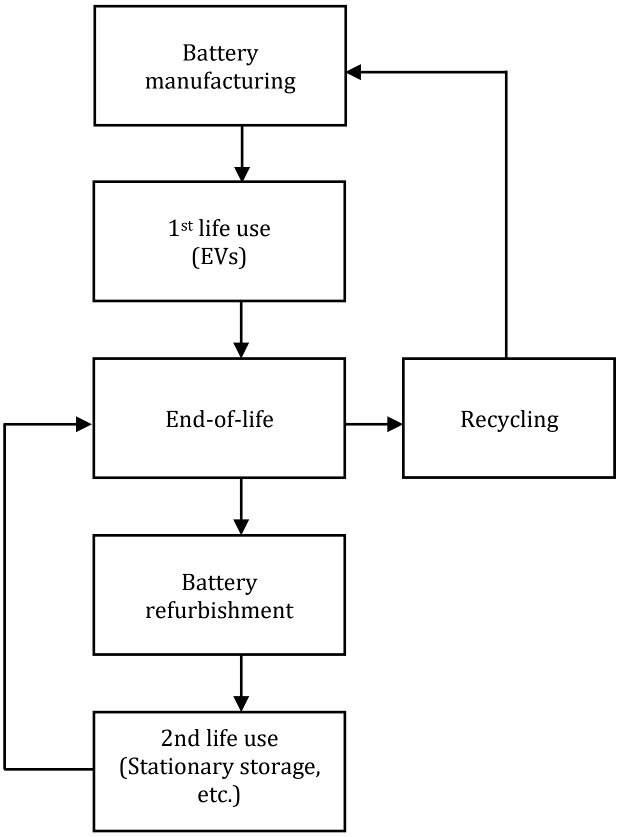

Figure 14 Second-life use for spent LIBs

7.4.2 RECYCLING OF SPENT LIBS

Upon collection, damaged batteries that cannot be repurposed are recycled. Although some progress has been achieved in developing more efficient recycling technologies, the recycling of LIBs still require expensive reagents and complicated treatment steps due to the diversity of materials present in LIBs (Huang et al., 2018). Furthermore, mixing LIBs of different chemistries in the recycling process may introduce impurities to the re-generated products (e.g., electrode materials) that could lead to the inferior performance of the materials. The need to identify and sort spent LIBs before they are recycled becomes therefore imperative.

Li-ion battery recycling is mainly aimed at metal foil and cathode material recovery, with the recycling of other components, such as anode or electrolyte, being rarely reported because their recovery is not cost-effective. Cobalt, a hazardous heavy metal and the main material used in cathodes, has traditionally been the main element in Li-ion recycling. The recycling of cobalt is of concern because the future rise in EV manufacturing is expected to draw considerable cobalt reserves and drive the prices of this element up (Gaines, 2018). However, as manufacturers try to reduce their reliance on cobalt (by switching to nickel as a cathode material, for instance) and to comply with ever stringent regulations on material recovery from batteries, the recycling of other metals, such as Li, Mn, and Ni is becoming more attractive.

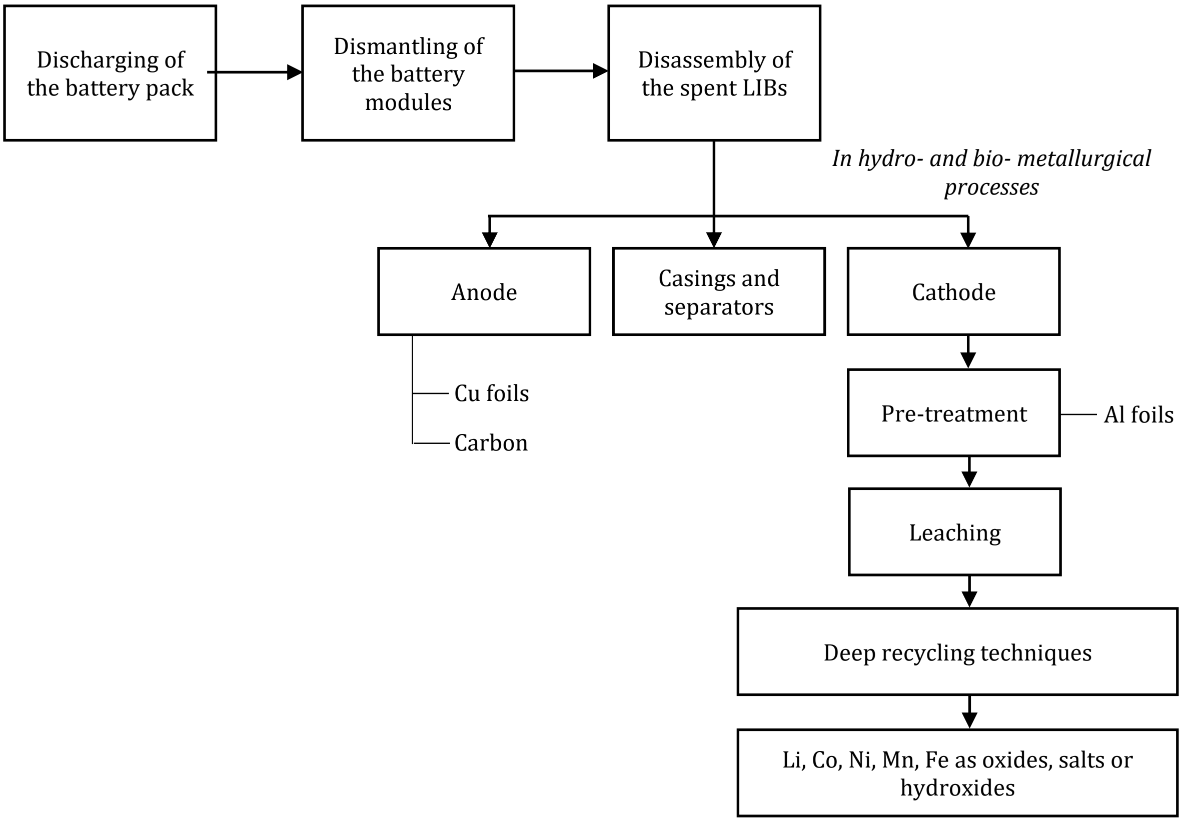

Figure 15 Flow-chart of the recycling process of a LIB [7]

The recycling of Li-ion batteries is complex due to the diversity of electrode materials, the amount of individual cells in the battery pack, and the variety of cell configurations, shapes and sizes (Huang et al., 2018). The recycling of LIBs comprises two processes: (i) physical processes aimed at separating materials according to different properties such as density, conductivity, and magnetism, and (ii) chemical processes. Physical processes allow the immediate recovery of copper and aluminum metal foils and involve various stages, including mechanical separation processes, thermal treatment, mechanochemical processes, and dissolution processes. Chemical processes, on the other hand, facilitate the recovery of cathode materials and involve stages such as: acid leaching, bioleaching, solvent extraction, chemical precipitation, and electrochemical processes (Huang et al., 2018; Ordoñez et al., 2016). Products resulting from the recycling process are pure chemicals with high purity (see Table 3 from Huang et al. (2018)), electrode materials (e.g., lithium, cobalt, nickel, manganese, iron, etc.) other functional materials (e.g., magnetic materials, electrocatalytic materials, photocatalytic materials, etc.) (Huang et al., 2018).

Although EU legislation suggested EV battery recycling should become economically viable by 2030 (with a target of collection and recycling efficiency rates of 85% and 50%, respectively), there is no regulation dealing with the processing of spent LIBs at end of life in the EU (Drabik and Rizos, 2018). Furthermore, because only few EV batteries have reached end of life, data revealing the costs of EV battery collection, dismantling and recycling is still limited or not even available. Other unknows in connection to the second-life of LIBs are listed in the table below (Martinez-Laserna et al., 2018; Olsson et al., 2018). Economic and technical unknows will need to be addressed for a second-life EV battery model to be implemented and massively adopted.

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[7] Taken from Yun, L., Linh, D., Shui, L., Peng, X., Garg, A., Le, M.L.P., Asghari, S., Sandoval, J., 2018. Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles. Resour. Conserv. Recy. 136, 198-208.

Table 9 Unknowns in the use of 2^{nd} life LIBs

- **Cost structure:** What will be the purchase costs of spent EV batteries and the selling price of second-life batteries? Will second-life EV batteries lead to discounts on new EV-batteries, thus driving EV sales? Can second life batteries truly decrease EV upfront costs? If so, by how much? With a better understanding of battery chemistry and battery management systems, increases in the lifetime of 1^{st} life batteries might be achieved so that the supply of second-life batteries gets delayed. This in turn might have effects on the supply/demand ratio and the price of second-life batteries. How to deal with this tradeoff?
- **Technical structure:** For how long is a spent LIB expected to be useful during its second-life application? What will its power capabilities be? Will there be other technical solutions for energy storage available by the time 2nd life LIBs become an industrial reality?
- **Market competition:** Although standardization of monitoring and diagnostics, packing, and labeling of LIBs could be achieved, would this interfere with the unique value proposition of each manufacturer?
- **Trade and logistics:** Is the geographical location of repurposing/recycling markets of second-life LIBs a barrier or an enabler? What are the barriers and subsidies between countries for the import/export of spent LIBs? The transport of LIBs is costly and highly regulated, and LIBs are often considered hazardous waste. How to deal with this issue?
- **Technology changes:** How do new product launches (i.e., newer EV battery technologies) compete with refurbished batteries? Which new LIB chemistries will be used in the future and how will these perform in second-life applications for energy storage?
- **Customer adoption:** To what extent are warranty, safety and reliability, and regulatory issues critical for customer adoption of 2nd life LIBs?
- **Recycling infrastructure:** Is it likely that large investments in recycling infrastructure for a certain type of battery chemistry get consolidated, when battery chemistries themselves are constantly changing?
- **Actors in the value chain:** Who holds producer responsibility at the different stages of the battery lifetime?
- **Links with utilities:** How to fix the uncooperative relationship between the EV industry and the energy sector in order to promote the use of second life batteries for energy storage?

8 CONCLUSIONS

Solar photovoltaics have experienced explosive growth with the increasing attention on climate change, rising oil prices, and a conducive global regulatory environment. Because PV waste is in direct correlation with the development of the PV market, the rapid expansion of solar PV will inevitably translate into a large number of modules being decommissioned and disposed in the years to come. A similar scenario is forecasted for lithium-ion batteries, which end their automotive life when their maximum capacity has degraded to 70-80% of the original capacity. PV's energy intrinsic features, namely intermittency and variability, turn spent LIBs into suitable units for stationary energy storage. 2nd life LIBs can provide cost savings to residential users, while shifting power from peak demand to off-peak demand times, thus reducing strains on the electric grid (Heymans et al., 2014). Yet, alongside the forecasted boom in EV sales is a proliferation of spent batteries, which will bring a new waste crisis if efficient ways to repurpose or recycle decommissioned batteries are not implemented.

In this article, we develop a mapping of the PV and the EV battery value chains aimed at studying who the main stakeholders in each system are and which interdependencies they share. Owing to the lack of literature on the structure and interdependencies of these value networks, as well as on the extent to which strategies for circularity could transform them, we conducted a systematic literature search based on 112 articles published between the years 2000 and 2018. The systematic literature review showed that most of the published academic content in connection to PV technologies: (i) peaked since the year 2012, (ii) has been primarily published by European research institutions, and (iii) has mostly focused on ways to achieve more efficient and competitive PV systems. Furthermore, almost all the papers that matched the search criteria for the SLR provided a limited perspective on both value chains. That is, they described value activities as starting with raw material procurement and ending with the installation of PV systems and the integration of the LIB to the electric vehicle. None of the papers discussed the upstream value chains together with the intricacies of product design or business model configurations, nor together with issues at EOL such as reuse or recycling.

A value chain view of the industry is intended to allow stakeholders to address circular economy challenges in a holistic, systemic manner. For example, one could think on answers to the following key questions:

- What will be the impacts of raw material scarcity and price fluctuations on the sustainability of the supply chain? and, what are the implications of this scenario for R&D activities and high-value material recovery activities at EOL? (i.e., raw material stage);
- Which PV technologies and battery chemistries will triumph over others in the quest to dominate market share over the medium and the long-term? and, what are the effects of these trajectories on the time delays for adoption, uptake, decommissioning, and 2nd life use of PV systems and LIBs? (i.e., PV and EV battery cell/module manufacturing stage);
- How, depending on the dominant technology, will be the different policy options and industry arrangements for the deployment of innovative business models creating simultaneous value for manufacturers, utilities, and end-customers? (i.e., deployment and business model stage);
- What are the recovery costs for each technological trajectory and at what performance cost and rate will the recovered materials be used in new manufacturing cycles? Also, with new circular tasks to perform (i.e., refurbishment for reuse, recycling, and so on) new actors are likely to emerge. Within this context, what will be the nature of the work performed by these actors and what is their connection to the traditional actor network of the PV and LIB value chain? (i.e., circular economy strategies).

Table 10 and Table 11 provide a summary of some of the main issues, in connection with each stage of both value chains, that emerged during the SLR. For a better understanding, these issues have been classified into various categories such as technical, financial, customer-related, or infrastructure related. As pointed out in the executive summary, the challenges and barriers that both value chains exhibit can be taken as opportunities for the creation of innovative value formulas and policies In the context of a circular economy.

Table 10 Summary of facts and unknowns derived from the SLR (PV systems)

	Design	Manufacturing	Business models	Disposal/Take back	Reuse	Recycling
Technical	• Manufacturers optimize product design for first life, not for use thereafter (i.e., design for disassembly, refurbish, and recycling) • Research and development activities concentrate mostly on material technologies and cell efficiency improvements, rather than design for EOL		• Customers perceive refurbished or recycled products as exhibiting lower performance	• When landfilled, PV panels can break and leach toxic chemicals (e.g., Pb, Cd, Cr) and gases into the environment • The amount of generated and collected PV waste depends on various factors, including: the forecasted useful life, production quantities, weight per Wp, production waste in manufacturing, the proportion of premature waste (transport and installation), and failure rate during use	• Accurate data on PV panel failure (e.g., types and rates) is still work-in-progress, due to the low volume of decommissioned PV panels	• Lack of a proper material recovery technologies. Many pilot projects are underway to improve the efficiency of different recycling methods • Current PV module design configurations do not facilitate the proper separation of PV module components • PV panels contain toxic chemicals (e.g., Pb, Cd, Cr) that cannot be removed without breaking apart the entire panel. When the PV cells are separated from the glass that contains them, hazardous substances are likely to be released into the environment • Because of the need for accurate

handling, the disassembly of aluminum frames and other components in the PV panel is highly manual. This limits the production efficiency of the recycling process

- The type and efficiency of the recycling process is determined by the type of module, its design, and its dimensions

- Many elements critical to emerging PV technologies, such as indium, tellurium, and gallium, today exhibit near-zero recycling rates

- There are concerns about the performance of PV panels manufactured out of recycled materials (i.e., the more the recycled material in new PV panels, the

				greater the probability for lower electricity generation)
Collaborative	• Are business models for second life applications in conflict with BMs for first life? • Current BMs do not provide avenues or incentives to refurbish or recycle PV panels	• Lack of coordination and collaboration between producers and recyclers		• The non-disclosure of proprietary product information and different material combinations in PV panels complicate the recycling process
Customer	• Already some BMs prioritize asset access rather than ownership. This may facilitate higher return rates and post processing of			• Lack of awareness and/or poor market confidence of refurbished/recycled PV panels

		decommissioned PV panels		
Infrastructure			• Although some OEMs have implemented take back systems, adequate collection centers and recycling systems/plants are lacking • PV panels are manufactured in key locations, but they are geographically dispersed across the globe	• Lack of adequate collection centers and recycling systems and plants • Risk of overinvesting in capacity due to the uncertainty in the material composition of future technologies and the difficulty in determining future PV waste volumes
Financial	• Although the recycling of PV panels is expected to decrease the economic costs associated with their production, there is still no realignment of operations or asset prices based on recycled materials			• Lack of evidential data on the costs of collecting, dismantling and recycling both types of PV technologies (crystalline silicon and thin-film), due to the low volume of decommissioned PV systems • The recycling EOL PV panels is currently not profitable (high

transportation, collection, and infrastructure costs vs. low volumes of waste)

- The profitability of recycling also depends also on the technology. For instance, thin-film technologies promise higher profit thanks to the presence of precious materials. In the case of c-Si panels, the absence of valuable metals/materials produces economic losses
- Many consumers and OEMs prefer to landfill if it is cheaper than recycling
- With higher cell efficiencies and lower material prices expected in the future: Will the recycling of PV panels make economic sense?

Government regulations				Undefined roles of producer responsibility throughout the PV value chain		Lack of proper government regulation (recovery targets and responsibilities along the value chain) Regulations coupled with subsidies for recovery technologies or shared costs among stakeholders are necessary

Table 11 Summary of facts and unknowns derived from the SLR (LIBs)

	Design	Manufacturing	Business models	Disposal/Take back	Reuse	Recycling
Technical	Most R&D activities concentrate on battery cell components and chemistries (i.e., individual materials and their combinations) Lack of standardization beyond the cell, module, and pack level All possible diffusion paths of the different PV technologies are				Different cell types and battery chemistries make it difficult to repurpose EV batteries The repurposing process in demanding as each cell needs to be controlled and the BMS needs to be set up to fit the battery's new surroundings and application	Recycling is currently unprofitable due to low volumes of waste Due to the low volume of decommissioned PV systems and EV batteries, there is lack of evidential data on the costs of collecting, dismantling, and recycling both types of systems

	key limitations to forecast the trajectory of solar energy production and storage		• There is uncertainty about the remaining battery capacity after its use in 1st life (i.e., the ageing performance of 2nd life batteries) • Most tests measuring the efficiency and longevity of LIBs (for stationary energy storage) have been performed as demonstrations at the laboratory level only
Financial			• Costs associated with the repurposing of EV batteries for energy storage are still unknown
Infrastructure		• The transport of LIBs is costly and highly regulated because it can be considered as hazardous waste • If second-life battery storage is pursued at massive scale, how will grid infrastructure be affected? (in terms of its capacity for external	

		connections) • With the emergence of distributed energy generation and storage energy systems, such as 2nd life LIBs, how can utilities ensure that both cause more good than harm? • Research integrating electricity grids and storage are the two major enablers for the integration of renewable energies into the traditional power distribution grid	
Customer		• Customer concerns about warranties, reliability, and safety hinder customer trust and product adoption	
Government		• Will regulations at the local level (e.g., FITs that enable the sale of excess solar power to the grid) minimize the financial benefits of energy storage?	• Legislation for second life use of LIBs has not been developed in the EU. There has to be a business case for reuse rather than recycling

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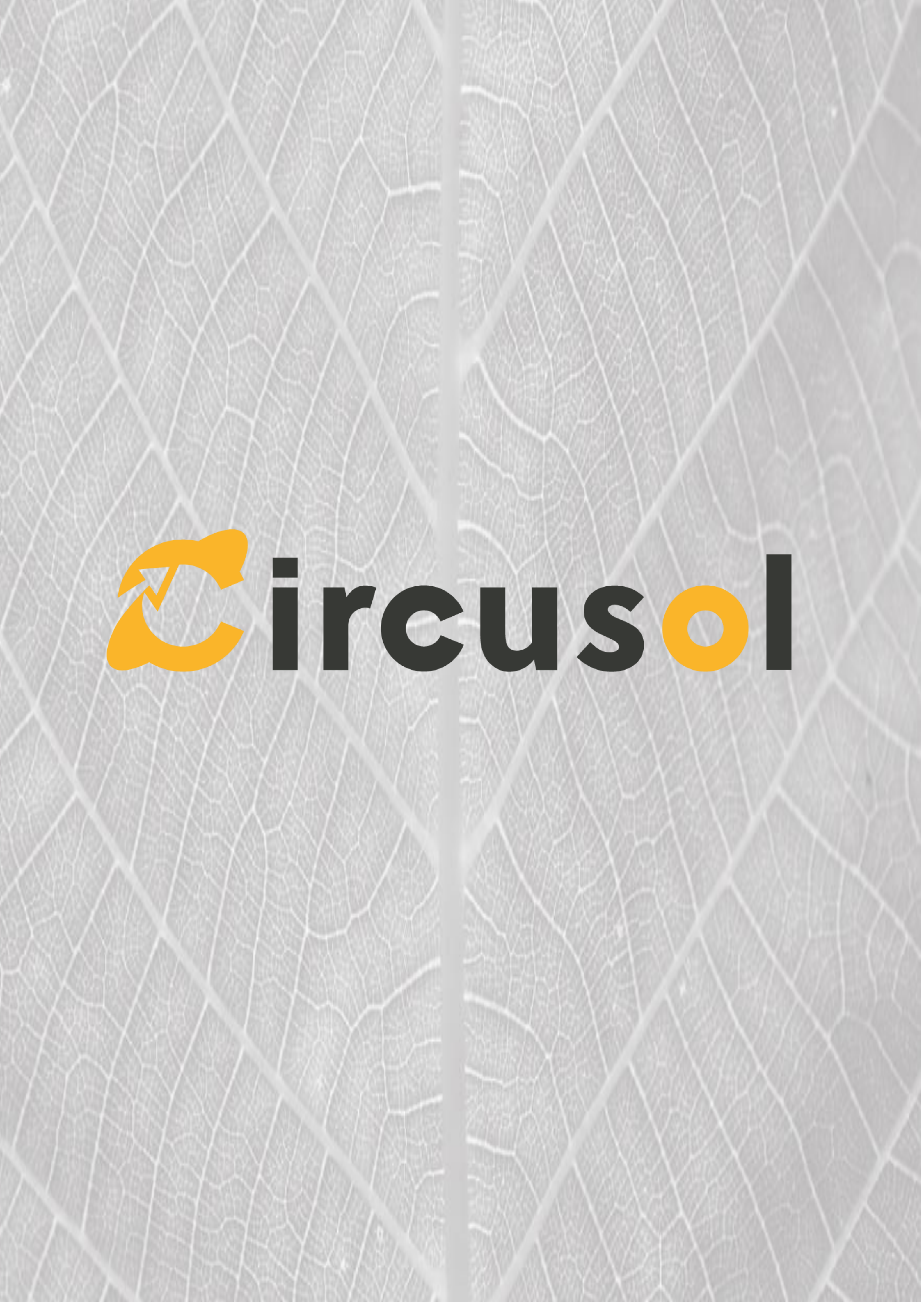

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