Sustainable Production and Consumption 35 (2023) 40–54

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Circular economy strategies as enablers for solar PV adoption in organizational market segments

Wim Van Opstal *, Anse Smeets

VITO, 200 Boeretang, 2400 Mol, Belgium

ARTICLE INFO

Article history:
Received 20 July 2022
Received in revised form 17 October 2022
Accepted 18 October 2022
Available online 24 October 2022

Editor: Prof. Idiano D'Adamo

Keywords:
Circular business models
Energy transition
Solar PV
PV reuse
Product-service systems (PSS)
Split incentive problem

ABSTRACT

While the uptake of solar energy has been a success in recent years, PV panels will cause an increasing waste problem in the coming decades. At the same time, it is important to further stimulate investments in solar energy solutions to reach climate ambitions and the Sustainable Development Goals. In this paper, we investigate when circular economy strategies and business models can enable solar energy investments while mitigating its waste problem. We use focus group data from Flanders (Belgium) to address the demand side of different market segments outside the dominant residential market of homeowners. These markets have in common that they are governed or mediated by organizations and contain business-to-business and business-to-government features. Our results show that organizational solar PV investments are mainly driven by lower energy costs, independence, and secured access to energy, and that the uptake of circular solar solutions mainly depends on a viable business case. In most cases, a lack of market development and organizational boundary conditions limit the enabling potential of circular solar options. Given the current energy crisis and challenges stemming from the electrification of mobility, we recommend policy makers to invest in regulatory frameworks that support the implementation of innovative data technologies that enable both improved circularity outcomes and lower operational expenditures.

1. Introduction

Over the past years, the uptake of solar PV has proven to be a significant contributor to the renewable energy transition required to mitigate climate change, and it will continue to do so in an increasingly cost-efficient way (IEA, 2021; IPCC, 2012). Solar PV plays an important role in the achievement of the United Nation's Sustainable Development Goals (SDGs), among which SDG 7 on reliable, sustainable, and modern energy for all, SDG 12 on responsible consumption and production, and SDG 13 on climate action (Global Solar Council, 2020).

With PV deployment surging on a global level, an increasing amount of PV installations are reaching the end of their technical lifetime or suffer from early defects. As a result, PV waste is accumulating and will only continue to do so in the coming years. In quantitative terms this is estimated to translate to 1.7–8 million tons of waste by the end of 2030 and up to 60–78 million tons of cumulative waste by 2050 (Gautam et al., 2021; IRENA and IEA-PVPS, 2016). Recent research shows these numbers could be much higher when also considering repowering PV installations (i.e. replacing panels with new, more efficient ones) before they have reached their technical lifetime of 30 years (Atasu et al., 2021). This could make sense from an economic perspective, but has proven unfavorable in terms of environmental performance (IEA PVPS, 2021). Apart from improved recycling options, keeping products and components in use also results in higher levels of circularity. Lifetime extension of PV panels can be realized via reuse and repair strategies (Radavičius et al., 2021; Tsanakas et al., 2020).

Circular business models are considered drivers of the circular transition, as they have the potential to encourage smart product design and resource efficiency, lifetime extension and reuse of products, and residual value capture from by-products or 'waste' (Bocken et al., 2016). Circular business models aim to maintain the value of products and materials as long as possible, reduce environmental impacts, and deliver customer value (Bocken et al., 2019). One of the more prominent circular business models are Product-Service Systems (PSS). They represent a variety of value propositions that companies can offer to their customers, always consisting of a combination of product and service elements. PSS are considered to be able to decouple revenue generation from material and product consumption and waste generation (Tukker, 2015). This given the fact that in most PSS models the manufacturer remains in some way responsible for the use and end-of-life phase of the product involved in the PSS, creating incentives to increase lifetimes, and to make design choices that enable circular strategies reuse, repair, remanufacture, or recycling. PSS models, however, have

* Corresponding author.
E-mail address: wim.vanopstal@vito.be (W. Van Opstal).

https://doi.org/10.1016/j.spc.2022.10.019

to be designed carefully, as they do not automatically imply improved circularity or sustainability outcomes (Moro et al., 2022; Zink and Geyer, 2017).

In order to reach SDG 12.5 (a substantial reduction of waste generation through prevention, reduction, recycling, and reuse), circular economy strategies and business models may contribute to tackle both the challenge of improving solar PV take up and the waste problem that comes with solar PV investments. Research on the enabling effect of circular solutions on solar PV investments mainly focuses on PSS models in residential applications for homeowners (Drury et al., 2012; Schmidt-Costa et al., 2019), leaving market segments that are governed or mediated by organizations underexplored (Hoen et al., 2019; Reindl and Palm, 2021). However, organizational segments share some distinctive features when considering the impact of circular solutions on investment decisions.

Firstly, circular solutions may remove current organizational, technological, or regulatory barriers for investments in durables and capital goods in Business-to-Business and Business-to-Government markets (Yang and Evans, 2019). Secondly, organizations may be willing to pay a circular premium for circular solutions, reflecting a higher willingness to pay for circular goods (Colasante and D'Adamo, 2021; D'Adamo and Lupi, 2021). While the concept of a circular premium also applies to households, for organizations the willingness to invest in circular solutions may be motivated by concerns to remain future proof towards clients, employees, and investors who consider environmental, sustainability, and governance (ESG) criteria increasingly important (Alda, 2021; Sciarelli et al., 2021). Moreover, recent research shows that the adoption of circular strategies helped companies during the COVID-19 epidemic to remain resilient (Borms et al., 2023). Finally, organizational market segments sometimes struggle with a split incentive problem when it comes to investments in durable or capital goods. Split incentive problems occur when owners of a property are not able to fully grasp the benefits of their investments, resulting in suboptimal investment decisions for both owners and users. They particularly arise when the financial consequences of decisions on energy consumption and investments are decoupled, as is often the case in organizational market segments (Bird and Hernández, 2012).

Most research on circular solar solutions focuses on technological aspects of PV recycling and dismantling (Contreras Lisperguer et al., 2020; Contreras-Lisperguer et al., 2021; Farrell et al., 2020; Radavičius et al., 2021; Tsanakas et al., 2020), taking into account the impact of the EU **Waste Electrical and Electronic Equipment** (WEEE) directive (Chowdhury et al., 2020; Deng et al., 2019). Another line of research investigates supply side mechanisms, including circular business models and barriers for service providers to implement circular solar solutions (Emili et al., 2016; Hamwi et al., 2021; Hamwi and Lizarralde, 2017; Lundqvist, 2020). Rabaia et al. (2022) review technical challenges to progress to solar circularity solutions and present a circular PV industry business model and a comprehensive research roadmap to address engineering gaps along the value chain (Rabaia et al., 2022).

Nevertheless, a lack of studies on the demand side of circular solar solutions is an important research gap, since it leaves the procurement and use phase of solar PV panels largely neglected. End-consumers play a central role in the transition towards a circular economy (Antikainen et al., 2018). As stakeholder engagement is key to establish and strengthen a sustainability culture in companies along the solar value chain (Deng et al., 2019; Salvioni and Almici, 2020), it is important to learn about perspectives, barriers, and enablers of end-consumers as well. Barriers and enablers for non-residential property owners to invest in solar PV have been studied recently in a literature review and an empirical study in Sweden, but no reference is made to circular strategies (Reindl and Palm, 2021).

Therefore, the main research question in this paper is how and when circular strategies and business models enable solar PV investments in organizational market segments. These market segments include non-owner residential markets (social, rental, and collective housing), public sector markets (public infrastructure, schools, health and social care), and commercial markets (companies and commercial real estate). We use semi-structured interviews and focus group data to explore and identify barriers for PV adoption and assess the enabling potential of circular solutions. These circular solutions include PSS models, PV reuse, end-of-life strategies, and the potential role of data technologies to improve product use, maintenance, design, and recycling.

The novelty of this paper stems from its focus on the demand side of organizational market segments, where we assess value propositions and identify barriers and enablers for several circular solutions. We also contribute to the literature by identifying organizational boundary conditions for investments in solar circular solutions and provide a critical appraisal of several sustainability aspects of solar PSS models. Our research contributes to a broader understanding of how circular solar options may align solar PV investments with waste mitigation strategies in organizational market segments. Our results are relevant to deepen our understanding of the impact of circular solutions on a broader range of organizational investment decisions. It also provides an empirical illustration of recent conceptual contributions on increasing sustainability of supply chain operations in the era of Industry 4.0 (Kumar et al., 2021) and safeguarding sustainability aspects when designing PSS-models (Moro et al., 2022).

Flanders (Belgium) is a relevant region for this study since it is an open and industrialized economy that can be expected to provide a fertile soil for the development of markets for new technological innovations. As a region, Flanders provides also a highly regulated and multilayered policy setting with well-developed, yet heterogeneous organizational market segments. This allows us to investigate elements of public-private interactions and take into account organizational diversity between public, non-profit, and for-profit market segments.

Research on solar PV in Flanders mostly focuses on residential market segments of homeowners (Beliën et al., 2013; De Groote et al., 2022, 2016; De Groote and Verboven, 2019) or on the green current certificate system that has been used to spur investments in solar PV (De Boeck et al., 2016; Huijben et al., 2016; Verbruggen, 2004; Verbruggen and Laes, 2021). Other literature on solar PV in Flanders focuses on the formation of renewable energy communities (Conradie et al., 2021; Felice et al., 2022), the use of digital technologies to foster energy transition (Van Summeren et al., 2021), or forecasting techniques that estimate the solar PV waste stream in Flanders up to 22,000 tons per year in the coming years (Peeters et al., 2017). Organizational market segments for solar PV have been considered briefly in a study on barriers and enablers for the Flemish energy transition, considering options such as remote net metering, building-integrated PV, and mentioning barriers including asbestos and a lack of clarity regarding regulations for prosumers (Laes et al., 2019).

The rest of this paper is structured as follows. Section 2 contains a concise literature review on other studies looking into circular solar strategies and business models and barriers for solar PV investments by organizations. In Section 3, we provide details on the focus groups and its preparatory interviews of which the results are presented in Section 4. Section 5 contains a discussion on the conditions upon which circular solar strategies and business models can be an enabler for solar energy adoption in organizational market segments. We also define organizational and sustainability boundary conditions and discuss limitations of this research. In Section 6, we draw conclusions, provide policy recommendations, and identify avenues for further research.

2. Literature

In this section, we present a non-technical literature review on solar circular strategies and business models, and on the uptake of solar PV in organizational market segments.

2.1. Literature on solar circular strategies and business models

Recycling is considered the default pathway for decommissioned PV to date, as PV panels contain critical raw materials, toxic materials, and precious materials such as silver, high-grade silicon, lead, and solar-grade glass. An important burden to date is the laminated sandwich structure of panels which makes it hard to separate components (Contreras-Lisperguer et al., 2021; Radavičius et al., 2021). Nonetheless, repair and reuse are valid and even preferred alternatives from a circular economy perspective for panels which have not yet reached their technical lifetime. The circular economy prioritizes satisfying the entire technical lifetime over recycling based on the principle of keeping products at their original and highest value in the economy, for as long as possible (Tsanakas et al., 2020). Lifecycle Assessment (LCA) results have shown that satisfying the 30-year technical lifetime of PV panels, be it via lifetime extension or reuse, is also favorable from the broader sustainability perspective. Repowering the installation, and thus replacing and recycling panels earlier (every 10 or 15 years) results in a higher environmental impact per kWh of electricity produced. This is not fully compensated by recycling benefits or the higher efficiency of the new panels, even when component replacements are required or when panels are transported over considerable distances for reuse (IEA PVPS, 2021).

As mentioned earlier, PV waste does not only originate from panels reaching their technical lifetime or repowering. It is estimated that up to 80 % of the PV waste stream can consist of products that got defected or failed during production, transportation, or their first operational years (IRENA and IEA-PVPS, 2016). Partners within the Horizon 2020 CIRCUSOL project and consulted experts estimate that about 45 %–65 % of these panels can be repaired or refurbished (Tsanakas et al., 2020). However, additional value creation opportunities to be realized via PV reuse within circular business models remain systematically underexposed (Lundqvist, 2020; Rabaia et al., 2022).

Nevertheless, circular business models such as PSS have the potential to overcome investment barriers, allowing consumers to benefit from solar energy without having to purchase a PV installation (Tukker, 2015). There are multiple PSS set-ups possible for PV (Emili et al., 2016). The most common options are leasing and Power Purchasing Agreements (PPA). Leasing involves a Use-Oriented PSS (Tukker, 2004), where the consumer pays a monthly or yearly fee in exchange for access to a PV system and the energy it produces. A Power Purchase Agreement (PPA) is considered a Result-Oriented PSS (Tukker, 2004), where the consumer pays a predetermined fee per kWh of electricity generated by the PV system. These fees are often lower than grid prices and contracts typically run for 15–20 years. Other forms of Third-Party Ownership (TPO) include third-party models for energy savings such as Energy Savings Companies (ESCOs) and business models for demand response. Energy Savings Companies develop, install, and finance performance-based projects, typically 5–10 years in duration, centered around improving the energy efficiency or load reduction of facilities owned or operated by customers (Vine, 2005). Demand Response Business Models (DBRM) incentivize consumers to make temporary reductions in their energy demands to balance grid supply and demand (Hamwi et al., 2021; Hamwi and Lizarralde, 2017).

Barriers encountered when introducing circular business models in general, and PSS models in particular, include supply chain and sourcing barriers, regulatory hurdles, lack of market acceptance and trust, limited access to financing, liability risks due to limited certification opportunities etc. (CEPS, 2021; Van Opstal et al., 2021). Additionally, typical barriers for the implementation of circularity across supply chains also apply. These include investment risks, lack of (access to) proper waste management, poor resource quality, lack of market demand and acceptance, and limited awareness on data technology opportunities (Kumar et al., 2021). Data technologies, however, are considered to play a significant role to increase supply chain transparency and give access to relevant product and performance information during the use phase, creating possibilities to open reuse markets (Antikainen et al., 2018; CEPS, 2021; Radavičius et al., 2021).

Technologies such as Big Data, Artificial Intelligence, Internet of Things, data analytics, blockchain and smart products enable for process and system optimization within companies (Stankovic et al., 2017), help minimize waste, promote product lifetime extension via optimization of product performance and preventive maintenance (Ellen MacArthur Foundation, 2016), and minimize transaction costs. They also provide increased potential for closing material loops by improving traceability and transparency across product life cycles and value chain actors (Pagoropoulos et al., 2017), as information about product locations enables increased accessibility and improves the opportunities for end-of-life collection, refurbishment, remanufacturing, and recycling (Bressanelli et al., 2018).

2.2. Literature on the uptake of solar PV

Most studies on the uptake of solar PV focus on residential market segments of homeowners in industrialized countries. A growing body of knowledge has been established on motivations of households to invest in solar PV, highlighting the importance of economic factors (Bauwens, 2019; Jacksohn et al., 2019), peer effects (Rai et al., 2016), pro-environmental norms, trust in installers (Wolske et al., 2017), trust in government policies (De Groote et al., 2022; De Groote and Verboven, 2019), and the overall importance of perceived benefits (Schulte et al., 2022). Economic and situational constraints are often considered main barriers, especially for low- and middle income adopters (Engelken et al., 2016; Wolske, 2020). Research on solar PSS models in residential market segments validates its ability to reduce or eliminate up-front adoption costs, facilitating PV adoption among younger, less affluent, and less educated households (Drury et al., 2012; Palm, 2020). Solar PSS models also have been shown to reduce technology risk and complexity, alleviating operations, maintenance concerns (Rai et al., 2016; Rai and Sigrin, 2013), and learning costs (Överholm, 2015). The value offering for customers can be easily summarized as '*receive solar energy with a minimum of hassle, on better terms than what they could buy grid electricity for*' (Överholm, 2017).

Studies on the uptake of solar PV in other residential markets focus on specific challenges in social housing, private rental housing, and collective housing. In social housing markets, scholarly attention has been given to the role of tenant awareness and attitudes, of economies of scale in procurement, to operations and the flexibility to provide ancillary services, and to means to reduce the social and financial costs of energy to tenants (Agbonaye et al., 2020; Bahaj and James, 2007; Lee and Shepley, 2020; McCabe et al., 2018). Concerning private rental markets, research on PV adoption concerns its effect on rental prices and the need to change tenancy laws to facilitate greater solar uptake on rental properties (Best et al., 2021b, 2021a; Chegut et al., 2020; Nelson et al., 2019). Students, renters and non-homeowners are largely excluded from solar PV deployment due to housing tenure and ownership type (Reames, 2020; Sovacool et al., 2022). Likewise, in collective housing settings such as multi-apartment buildings or co-housing settings, organizational and regulatory barriers provide extra challenges for PV adoption (Brankov et al., 2020; Komendantova et al., 2018).

Research on the uptake of solar PV for public sector infrastructure highlights decision criteria in a broader context to increase energy performance and construct climate neutral buildings, identifying innovative application possibilities of solar PV and ways to increase self-consumption in buildings that often share the characteristic to be closed outside office hours (D'Adamo et al., 2020; Grande-Acosta and Islas-Samperio, 2020; Silva et al., 2020). The latter applies most specifically to schools (Ciacci et al., 2022; Kolokotsa et al., 2019), but it is considered less a problem for residential health and social care facilities that operate in a 24/7 setting (Lagrange et al., 2020; Vourdoubas, 2015). Both schools and health and social care facilities share the trait that they have to comply to public procurement rules in many industrialized countries.

Research on the uptake of solar PV by companies, including shopping malls, hotels, office buildings, and commercial real estate companies, focuses on technical hurdles (Ghaleb and Asif, 2022), the consequences of differential financing methods (Feldman and Margolis, 2014), methods to evaluate the return of solar PV investments (Leskinen et al., 2020; Vimpari and Junnila, 2019), possibilities to optimize self-consumption (Lang et al., 2016), regulatory measures, optimizing feed-in-tariffs (Mah et al., 2018; Margolis and Zuboy, 2006), and legal challenges to change existing electricity supply contracts in non-residential settings (Reindl and Palm, 2021). Specifically for farms, solar PV can provide shading next to electricity production (Amaducci et al., 2018; Mamun et al., 2022; Pascaris et al., 2021).

While the price of solar PV installations dropped significantly during the last decade, non-homeowner solar PV markets are considered to be under-developed, facing significant barriers to reach its potential (Hoen et al., 2019). These market segments have a strong organizational component and share challenges with respect to regulatory barriers, organizational procurement processes, corporate governance, and principal agent problems such as split incentive problems between owners and users (Bird and Hernández, 2012).

In a recent study on the uptake of solar PV in non-residential markets, solar PSS models have been identified as a promising pathway (Reindl and Palm, 2021). When evaluating PSS models outside Business-to-Consumer markets, market acceptance has been identified to be dependent on pricing, risk and flexibility, trust, performance, knowledge lead of the provider and core competencies and activities of the client (Schenkl et al., 2014). Creating sustainable PSS value propositions could be improved by maximizing utilization of resources and skills, employing effective operations, and aligning the PSS solution with economic, ecological and social concerns (Moro et al., 2022). Solar PSS has been documented as a sustainable alternative to increase the adoption of PV systems, taking into account this triple bottom line (Schmidt-Costa et al., 2019). However, research on the demand side of organizational market segments for circular solar solutions has been largely lacking.

3. Methods

In order to evaluate the potential of the circular economy to enhance investments in solar energy, we need to combine technical, economic, environmental, and policy perspectives. Since PV policy in Flanders evolved quite significantly over the years, including major controversies (De Groote et al., 2022; Juwet and Deruytter, 2021; Stam, 2018; Verbruggen and Laes, 2021), it is important to grasp undocumented and implicit knowledge of stakeholders who were close to these developments. Therefore, we organized three focus groups, to document, discuss, and exchange perspectives of key stakeholders in organizational market segments in Flanders. Focus group research has been identified as a suitable method to gain an in-depth understanding of complex and multifaceted issues, capturing perceptions, opinions, and feelings of people underlying their behavior (Gailing and Naumann, 2018; O. Nyumba et al., 2018; Scheller et al., 2021). Focus group research is most commonly used to provide an in-depth exploration of a topic about which a lot of implicit knowledge and experiences are not documented yet (Stewart and Shamdasani, 2014).

Focus group research on solar energy has been performed earlier to obtain perspectives, perceptions, and experiences of various stakeholders to improve the design of solar energy schemes and evaluate the uptake of PV investments (Chen et al., 2021; Kokchang et al., 2018; Lee and Shepley, 2020; Powell et al., 2021). In the rapidly evolving research domain of circular business models and strategies, examples of focus group research are testing value propositions of circular business models (Bocken et al., 2021, 2018; Bocken and Antikainen, 2019) and understanding challenges of stakeholders in evaluating circular business models (Toxopeus et al., 2021).

We identified market segments after long listing potential markets outside the dominant residential market for homeowners. The market segments we selected, were grouped into the following three focus groups:

- Non-owner residential markets: including social and private rental housing, and collective housing (where residents only partially own the building they live in). These market segments have in common that third parties, such as social housing associations, landlords or associations of co-owners, are involved in the decision-making process.
- Public and social infrastructure: including municipalities, schools, and health and social care facilities. These market segments have the production of (quasi) public goods, public procurement procedures and not-for-profit objectives in common.
- Companies and commercial real estate. These market segments share the commercial function of the infrastructure they invest in.

The background of this study is a larger European Union's Horizon 2020 research and innovation project on circular business models and strategies for solar PV. Therefore, we also used results of these focus groups in another publication that focuses on market-specific regulatory and institutional barriers and enablers for solar PV adoption in general within the market segments we addressed (Van Opstal and Smeets, 2022). In this paper, however, we investigate the enabling role of circular solar solutions while paying specific attention to the organizational aspects of the market segments under study.

Our focus groups were prepared and analyzed by applying policy document analysis, performing semi-structured interviews, and literature analysis in an iterative way. Focus group participants were selected to represent the demand side of the market. Supply side actors were deliberately not included in the focus groups, because commercial considerations, such as e.g. ongoing public procurement procedures, may have contaminated a free and open discussion among the participants. The identification process to select participants started in August 2021. After we ensured the participation by all major relevant actors in the market segments we selected, we organized three focus groups in the period December 2021–February 2022. An anonymized list of participants is included in Appendix B (Tables A.2–A.4).

To ensure qualitative discussions with balanced contributions of participants that represent complementary perspectives, a critical issue was to align agendas of participants while stressing the importance to show up at the meeting. Due to Covid restrictions, and to lower barriers for participation, they were organized via a MS Teams meeting and supported by Miro boards. Utilizing Miro boards before starting the discussion on a topic mitigated the risk of groupthink and reputational pressures (Kahneman, 2011), and allowed moderators to deepen the understanding of dissenting viewpoints and experiences while increasing data validity (Greenbaum, 1998). All focus groups discussed the same items, were moderated by both authors, and observed by two PhD researchers. We consider the use of common set of items across focus groups, as well as the presence of the same moderators and observants during all three focus groups as critical to safeguard data validity. The sessions were recorded, under approval of all participants, who also approved an informed consent declaration before participating at the Miro boards.

The duration of these focus groups was between 2 and 2.5 h. After transcription of the recorded sessions, results were analyzed independently by the two researchers. This included combining input from Miro boards and discussions, followed by pragmatical content analysis (Stewart and Shamdasani, 2014). Afterwards, a joint analysis included a discussion among the authors on different interpretations, followed by a compilation and presentation of our findings to a consortium meeting of the CIRCUSOL project to verify and extend them. Subsequently, a first version of our analysis was sent to all focus group participants to verify accuracy.

As already mentioned, we prepared our focus groups with semi-structured interviews to include the perspective of the supply side of the market. During these interviews, we invited respondents to identify relevant stakeholders to be included in the focus groups, to identify relevant barriers and enablers for different market segments, and to propose relevant questions to include in our focus groups. An anonymized overview of interview respondents is included in Appendix A (Table A.1). Afterwards, preliminary focus groups results were communicated again to the same set of interviewees for feedback, after which focus group participants were invited to comment on our final analysis. Including these feedback-loops limited the number of factual errors and prevented misinterpretations.

4. Results

When studying multiple market segments, market-specific institutional parameters may generate different opportunities and challenges. In this paper, however, we focus on barriers and enablers that are shared among the wide array of non-homeowner market segments we investigated. In order to translate lessons from these results towards other regions, focus group participants identified two major background parameters to take into consideration.

A first background aspect is the fact that policy and industry level initiatives increasingly focus on energy performance and climate neutrality, rendering investment in solar PV just one aspect in a broader exercise of strategic sustainable real estate planning. Recent systemic developments, including high energy prices and the war in Ukraine, only fostered the urgency to act. Compared to more costly investments in insulation or a deep refurbishment of the infrastructure, however, investing in PV panels can seem a quick win to enhance the energy performance of a building. On the other hand, it is not interesting to install PV panels on bad quality roofs, on buildings that reach their end-of-life, or on infrastructure of which the functionality will be altered in the years to come. Taking these decisions, it is crucial not only to look into capital expenditures (CAPEX), but also to take all operational costs (OPEX) throughout the lifecycle into account. However, one should also take into account the fact that an underconsumption of energy may cause other types of costs. Think of the negative health consequences of living in poorly heated houses, or of more expensive (or polluting) alternatives companies may opt for when cutting down on heath or cooling.

A second important aspect is the evolution of the supportive policy landscape. During the last decade, policies to support investments in PV in Flanders shifted from a very generous system of tradable green current certificates towards several attempts to revert on previous promises and the invention of new taxes to compensate for the budgetary consequences of this overly generous system, resulting in political commotion and popular mistrust (Boccard and Gautier, 2021; De Groote et al., 2022; De Groote and Verboven, 2019). Mistrust in the political and institutional environment only grew when the Flemish government had to revert its 2020 promise to ensure net metering for another 15 years after a Judgement of the Belgian Constitutional Court in January 2021. As legal uncertainty and a lack of institutional quality deteriorates the investment climate for any asset, this resulted in a drop of newly installed solar capacity of 59 % between 2020 and 2021 (Flemish Government, 2022).

4.1. Solar PV: why (not)?

According to focus group participants, there is a broad consensus that the advantages of investing in solar PV include the easy access to renewable energy, an increase in the future proof value of the infrastructure, and an opportunity to maximize self-sufficiency while reducing energy costs. PV installations decrease the dependency on external energy suppliers and lower the exposure towards increasing grid prices. PV is considered as a quick and modular solution, compared to other renewable energy sources such as wind or biomass. Among focus group participants, PV is considered a proven technology, with a good track record and increasingly predictable production figures. Technological developments result in decreasing CAPEX per Wp, in a reduction of required roof space, and into lower energy prices and payback times in an era where grid energy prices surge.

A key disadvantage of solar energy is the location-dependent yield and possibilities, because of its dependency on weather conditions and required (roof) space. Another disadvantage is often the mismatch in timing between energy production and consumption.

The main barriers to invest in solar energy, as pointed out in all three focus groups, are the upfront CAPEX, potential issues with roof availability, quality, and stability, and follow-up costs with respect to monitoring and maintenance. At the time of the focus group, arguments referring to the negative perception following political decisions and legal uncertainty still outweighed the emerging energy crisis and the war in Ukraine. Other barriers include regulatory limitations to make use of the technological potential for energy sharing, technical limitations, and uncertainties with respect to the use of stationary batteries, and legal uncertainties when multiple users share the same roof.

So, what could enable the adoption or solar PV? General enablers that were mentioned in all focus groups include the need to see a reliable and empirically informed business case that show positive end-user returns in a post net-metering era. Increasing energy prices, however, made this case increasingly obvious in the few months between the first and the last focus group. According to most focus group participants, the most important reasons to invest in solar PV are not its renewable or green features, but lower energy costs, independence, and secured access to energy. Other enablers include group purchasing, peer-to-peer energy sharing within buildings, local energy communities, and clear and sufficiently high injection fees. Alternatives for low injection fees include the promotion of batteries (also at a shared level), systems for shared (light) electrical vehicles, and other technological and regulatory initiatives that focus on optimizing auto-consumption. All participants see the electrification of mobility as an important driver to invest in extra solar energy capacity, but also here regulatory bodies have to provide the necessary technical and regulatory frameworks (including bi-directional EV charging, demand control, etc.).

Noteworthy is the fact that multiple participants advise the promotion of citizen energy co-operatives as trustworthy (member-based) service providers. Another important observation is that participants are not aiming at general subsidies (such as green current certificates or one-time subsidy schemes to invest in PV or batteries) or green loans systems, as long as the business case for solar energy is positive. For the latter argument, we must take into account the historically low interest rates at that time.

4.2. Product-service systems as an enabler?

As mentioned earlier, PSS models are considered to be among the key enablers for increased PV circularity, as they provide an opportunity to decouple performance (access to electricity) from the physical installation (Tukker, 2015). Given the historically favorable investment climate for PV in Flanders, sales models are dominant among all segments (Respondents 1–2 and 4). When PSS models are implemented in the business-to-business and business-to-government market they often take the shape of PPAs (Respondents 1–2 and 5). In practice, the service provider is in charge of the installation, monitoring and maintenance of the system while the customer pays a predetermined, lower-than-grid fee for the generated electricity. After the agreement expires (e.g. after 20 years), system ownership is typically transferred to the customer (Respondents 1 and 2).

The major advantage of a solar PSS model, as indicated by the focus group participants, is the fact that users do not have to bear the upfront capital expenditure. Nor do they have to bear the investment risk and the burden for repair and maintenance. Solar PSS models also provide strong incentives to service providers to optimize the installation dimension (avoiding upselling) and incentives for long product use, high quality installations (including optimized roof positioning), and opportunities for refurbishment. Most of these arguments specifically apply to result-oriented PSS models (PPA). Costs are predictable and clear, and instead of having to appoint and train internal staff members, professional service providers have more adequate skills for monitoring and repair. Another reason why PSS contracts could speed up solar PV investments within organizations, is that these could be considered as operational expenses while CAPEX investments could need the approval of the Board of Directors.

Focus group participants, however, also mention some disadvantages of solar PSS models in general. Firstly, a third party (the PSS service provider) enters the picture and skims off part of the profit the solar energy installation generates. For investors focusing at ROI, this renders solar PSS models unattractive compared to PV ownership. Secondly, solar PSS models with fixed prices may turn out to be disadvantageous when grid prices drop. Focus group participants also mention the lack of internal knowledge building on PV installations as its maintenance and repair are taken care of by the service provider. This may cause a lock-in situation. Internal support for PSS models may as well be limited, was technical co-workers could fear to lose duties and responsibilities. Also, end-of-contract options should be very clear – a matter we will discuss later.

An administrative barrier to adopt solar PSS are some legal complexities: e.g. notarial registry of the installation is required in order to prevent the PV installation to become part of the real estate by incorporation, ensuring ownership rights of the service provider. An economic barrier is the limited return on investment (ROI) of solar PSS for geographically scattered small installations. More importantly, however, are a predominant culture of owning assets, although this is far more important in residential homeowner markets, and scepsis towards the unknown (as solar PSS models are not that common in Flanders, compared to e.g. the US). Also, contract durations of 20 years seem long to many participants. Some participants therefore point out it would be interesting to have the possibility to buy the installation after a certain amount of time. Focus group participants representing companies and commercial real estate express their interest in short-lived PSS contracts, which would avoid service provider lock-in on the longer term and which would lower barriers for PV adoption for start-up companies in particular.

According to focus group participants, the most important enablers entail a clear communication on the expected profitability for clients (as was the case for solar PV adoption itself) and including a solar PSS offer into extended service packages including technical equipment (heating, ventilation, sanitation, …). Ever increasing regulatory requirements on energy performance are mentioned, as well as a trigger to step into a PSS model, especially when it is not feasible or desirable for clients to carry the investments themselves. Finally, tax benefits and VAT reductions were mentioned to help this market develop.

4.3. The case for 2nd life PV panels

From a circularity perspective, PV repair, and reuse with the aim of extending its lifetime is preferred over the recycling pathway. The reuse of PV panels can be defined as the utilization of discarded PV modules that are still in a working condition (Rabaia et al., 2022). Within the CIRCUSOL project, 2nd life PV is defined as PV panels which have not yet reached their technical lifetime but have been decommissioned for reasons of repowering, early defects, insurance claims, etc. (Radavičius et al., 2021; Tsanakas et al., 2020). Reuse, refurbishing, or remanufacturing allows for 2nd life pathways to develop, be it in the same or in alternative (e.g. off-grid, stand-alone charging stations for micro-mobility) applications, preferably until they do reach their technical lifetime of 30 years (Respondent 7).

Focus group participants see the ecological advantages of lifetime extension of PV panels by reusing them. The combination with a PSS model, however, is considered as a necessary condition to opt for 2nd life PV panels, since most PSS models let the service provider bear the technical risks of these panels. Participants indicate this offer could be interesting when it is embodied in a solid service model including repair, maintenance, and control.

As disadvantages, focus group participants point out that the business case for 2nd life PV panels will only be feasible for larger projects. In small scale projects, labor costs for removal, testing, reinstalling panels and increased expected maintenance rates are simply too high. Secondly, there is a strong competition of cheaper and more efficient virgin PV panels that require less roof space to generate the same amount of energy. Finally, many participants point out there are many questions on quality and performance and there is a lack of regulation on warranties. While PSS models could resolve most of these issues, the business case should be interesting enough to attract service providers that are willing to offer a sustained and sustainable service in this market segment.

According to both interview respondents and focus group participants the main barrier towards adopting 2nd life PV panels is scepsis towards the unknown. Moreover, markets for 2nd life PV panels are incomplete. There is a lack of market-available supply because of a lack of demand and vice versa, and there is hardly any proven track record. This market is hard to develop as new PV panels become more efficient and cheaper. Also, the general perception of 2nd life material is an issue, including safety concerns and the fear of a lack of aesthetic uniformity.

Key enablers, according to focus group participants, include solid warranty regulations and clear testing protocols for 2nd life PV panels, the unburdening of clients of technical risks (by offering repair and monitoring), and showcasing clear, evidence-based business cases. For the latter, it is crucial to demonstrate that the levelized cost of energy (LCOE) of 2nd life PV panels is lower than that of virgin PV panels. Also, if governments would include embedded carbon emissions of materials into their public procurement criteria, this would also increase the competitive advantage of 2nd life PV panels. Participants also suggest integrating reuse of PV panels in the Flemish Materials Decree and the Flemish Regulation on the sustainable management of material cycles and waste. Finally, a structural collaboration between manufacturers of virgin PV panels and suppliers of 2nd life panels would increase trust and its technological feasibility. However, as one participant points out: "*Why don't we try to develop the market for as-a-service contracts first, without adding the complexity of using 2nd life PV panels?*" (Participant 1.7).

4.4. End-of-life alternatives

In Flanders, the dominant model in solar PSS contracts includes a transfer of ownership of the installation after a contract duration of 20 years (respondents 1–2 and 4–5). With increasing expected lifetimes of PV panels and slower than expected degradation rates of 0.7 % per year, the installation could easily continue to provide energy for another decade (Frischknecht et al., 2020). Because inverters have been replaced after 15 years already, it would be inefficient to demount the installation. On the other hand, participants of all focus groups unanimously point out the concern that they may be left with an old and inefficient installation and that maintenance stops right a moment the need for it becomes the most urgent. Also, the costs for demounting the installation are left to the customer. Another concern of participants is the fact that a time horizon of 20 years may incentivize service providers to maximize profits by choosing 'cheap' solutions with a limited residual value. A final concern is the fact that also some organizational knowledge transfer is required that allows customers to perform adequate monitoring and maintenance.

Therefore, a modified model could be the transfer of ownership where users can opt-in for a service contract for the years beyond the PSS contract duration. Alternatively, clients could sign up for contract extensions with no transfer of ownership and demounting services at end-of-life. Many service providers in Flanders are only now starting to think of alternative service possibilities, since their earliest contracts often date from ten to fifteen years ago (respondent 1–2 and 4). Models with extended services would have the benefit of continued servicing and provides an incentive for service providers to optimize installations in terms of repairability, maintenance, long lifespans, and refurbishment strategies. However, as manufacturers do not tend to keep spare parts in stock for 20 years, the importance of 3D-printing and additive manufacturing will only increase. PSS contracts with continued service agreements would provide the right market pull for the development of these technologies. On the other hand, participants point out that they want to prevent a long-term lock-in with the same supplier. Multiple participants also indicate that PSS contracts could even be embodied in larger integral design-build-finance-maintenance (DBFM) solutions for utilities. With respect to barriers, participants mention the importance of transparent quality monitoring, to avoid informational asymmetries between clients and service providers (which could be abused for upselling and lock-in situations).

In a third model, service providers take back the installation after a contract duration of 20 years. This would allow customers to refurbish their roofs (whenever necessary) and to optimize energy production with more efficient technologies that require less roof space per Wp. Focus group participants also indicate this would give a supply boost to a 2nd life PV market. Given the high labor costs in Flanders, however, if could be very inefficient to remove installations that still perform well to reuse them elsewhere. On the other hand, this model could stimulate technologies that are more flexible to install and demount, allowing for shorter-term PSS contracts, lowering the barrier to adopt solar PSS models.

A key observation is that most focus group participants had no clear and well-developed vision yet about end-of-contract and end-of-life opportunities. Participants saw the added value of the discussion and were happy to contribute to it, but at the same time the thought process only started when these questions were proposed in the first place. It was also clear that many participants were surprised by the fact that solar panels have an expected lifetime beyond the contract duration of 20 years. The focus on avenues for lifetime extension was welcomed. Therefore, focus group participants were invited to share potential solutions they see for high value reuse. These included farms and public spaces such as roadsides.

4.5. The potential role of data technologies

Data technologies can contribute to increased circularity in general by improving process efficiency, providing insight in the availability, location, and condition of products, facilitating product lifetime extension, and limiting transaction costs. While the gradual abolition of (analog) net metering was poorly received in Flanders, the introduction of (digital) smart metering does provide some opportunities for automated data gathering on PV consumption and production profiles. These can be provided by grid operator Fluvius and linked to existing tools and energy databases. Within the CIRCUSOL project an asset database is being developed to facilitate the deployment of 2nd life PV by providing data on properties, manufacturing, installation, usage and post-usage of PV in the field (CIRCUSOL, 2022). This can enable feedback loops to foster design for reuse, design for repurposing, and design for recycling (Deng et al., 2019).

In our focus groups, we discussed four potential applications of data technologies in solar PSS models. In a first model, data technology would allow users to have an enhanced access do their own data (consumption, production, performance). This would allow users to optimize their consumption and service providers to optimize tailor-made solutions for the market segments they serve. Focus group participants point out, however, that interpreting all these data requires adequate training and time. For organizations, this knowledge may get lost in the case of staff changes. In other words, these applications should be sufficiently comprehensible and deliver relevant intelligence to its users. Participants also state that clear agreements should be made with respect to ownership and privacy issues regarding these data.

In a second model, data technologies would allow users to have an enhanced access to anonymized production, consumption, and performance data of other users as well. This would enable users to benchmark their consumption profile with that of similar users and may create a sense of urgency in case of a bad outcome. Service providers would be incentivized to take care of the performance of their installations and data could be applied to develop new services. Likewise, focus group participants mention similar issues with respect to comprehensibility, privacy, and data ownership.

In a third model, data technologies would contribute to open access of product data, including material passports, performance intelligence, and data on recyclability. Focus group participants agree this would provide a strong incentive for manufacturers to enhance their producer responsibility. On the other hand, one participant points out that users have an important responsibility as well with respect to a circular and sustainable use of their products.

The fourth and last model describes how data technologies would provide open access to product data throughout the lifecycle, including product data at the end-of-life stage. This would enhance value chain transparency, including traceability through inner (e.g. repair and reuse) and outer (e.g. recycling) circles. These data could provide intelligence towards manufacturers to increase their insight into the circular use of their products, which in turn can facilitate improved material choices for future products. These data may also improve transparency with respect to predictability and confidence levels of solar energy systems. Focus group participants also see opportunities to link this data to the TOTEM-tool, a tool developed by the three Belgian Regions to help the construction industry to objectify and reduce the environmental impact of buildings (TOTEM, 2022). They also refer to including these data into the environmental product declaration (EPD) of construction materials.

In most cases, focus group participants had no clear idea yet of the business opportunities these developments could bring, except for improved maintenance and monitoring possibilities, and the potential to use data-informed nudging techniques to reduce energy consumption. According to focus group participants, the inclination of organizations to adopt new data technologies is often depending on the personal interest of staff members or board members of these organizations. Governance and organizational design, however, are key to provide a framework where departments and staff members share relevant information and opportunities. One stakeholder participant illustrates these suboptimal information flows as follows: "*the financial department receives and pays energy bills, but actually this information should flow to those responsible for the energy infrastructure*" (participant 1.7). Larger organizations have a superior potential to appoint and train dedicated staff to follow up energy efficiency. This provides organizational leverage to be able to hire external expertise and services. Small organizations that do not have this internal capacity building often only have to offer an empty chair for external experts to provide their advice to.

Sectoral federations, who want to learn from individual energy data of their members, state it is hard to gain access to these data. The proliferation of digital (or smart) electricity meters will improve insights from energy use (with data points for every 15 min instead of yearly data), including access to new (and often free) tools. Focus group participants, however, complain about the lack of willingness to collaborate by service providers and by Fluvius, the organization that manages Flanders' electricity and gas distribution networks. Finally, one participant points out that developing and implementing data technologies for demand control will be crucial in the years to come. According to this participant, the proliferation of solar energy, the electrification of mobility and technologies that allow for bi-directional charging will increase the complexity of grid management enormously (participant 2.7).

5. Discussion

In this section, we discuss our results, confronting them with existent literature and emphasizing novel insights. We also discuss cross-cutting organizational and sustainability boundary conditions that can be identified from our results. Finally, we give an overview of the most important limitations of our research.

5.1. Circular business models and strategies as enablers for solar PV investments

Fig. 1 visualizes the potential of PSS models to enable solar PV investments while mitigating PV waste. The most profound value propositions of PSS remain unburdening customers from upfront investments (CAPEX) and from the risk of follow-up interventions and costs during the use phase, e.g. for monitoring, maintenance, and repairs. This general result was already well documented in the circular economy literature in general (Yang and Evans, 2019), and on literature regarding solar PV (Drury et al., 2012; Emili et al., 2016; Överholm, 2017; Schmidt-Costa et al., 2019) and other durable goods (Boehm and Thomas, 2013; Matschewsky, 2019) in particular.

Following from our focus groups and interviews, we are able to identify additional advantages of PSS models in the context of solar energy. Solar PSS models may provide a strong incentive for service providers to optimize installation parameters, including optimized roof positioning and avoiding upselling of overdimensioned installations towards clients. As PSS service providers build up expertise on monitoring and maintenance, they have a superior capacity to develop knowledge about the use-phase, which may result in lower operational and environmental costs (at least when there is a sufficient amount of competition on the supply side) and positive feedback loops for the design of PV panels and installations. Given the economies of scale of PSS models, end-of-life strategies can also be developed in an increasingly efficient way, providing opportunities for enhanced reuse, repurposing, and superior recycling alternatives.

Literature in PSS models highlights the potential of use- and result-oriented PSS models to increase product reuse (Yang and Evans, 2019). Our focus group results show that PSS models are even considered as a necessary condition for demand side market players to consider PV reuse, as there are lot of concerns with regards to the quality and performance of these panels. Thanks to the risk transfer from customer to service provider a lot of the above concerns can be resolved with PSS models with a strong unburdening dimension. As visualized in Fig. 2, reusing and repurposing 2nd life PV panels may also generate important design feedback loops. Many barriers for PV reuse have been identified already in the literature, including a lack of trust, incomplete warranties, and a lack of supply of reuse PV panels (Curtis et al., 2021; Lundqvist, 2020; Tsanakas et al., 2020). An important additional insight from our focus group results is the need for economies of scale, given high labor costs for removal, testing, reinstalling, and increased expected maintenance rates. Here too, the demand side of the market expects evidence-based business cases that showcase the performance and financial viability of PV reuse.

The impact of different end-of-contract strategies on circularity outcomes and customer preferences in organizational market segments is largely understudied in the field of solar PV. When confronted with PSS contract expiration after e.g. 20 years, it became clear that potential end-of-life strategies are only considered a distant prospect by the focus group participants, which has not been given a lot of thought. Yet, as shown in Fig. 3, different end-of-life strategies may provide differing incentives and opportunities to deal with PV waste mitigation. Removal after 20 years (or even shorter time spans), could incentivize PSS service providers to co-develop reuse and repurpose markets and triggers them to continue looking for superior recycling alternatives and improved

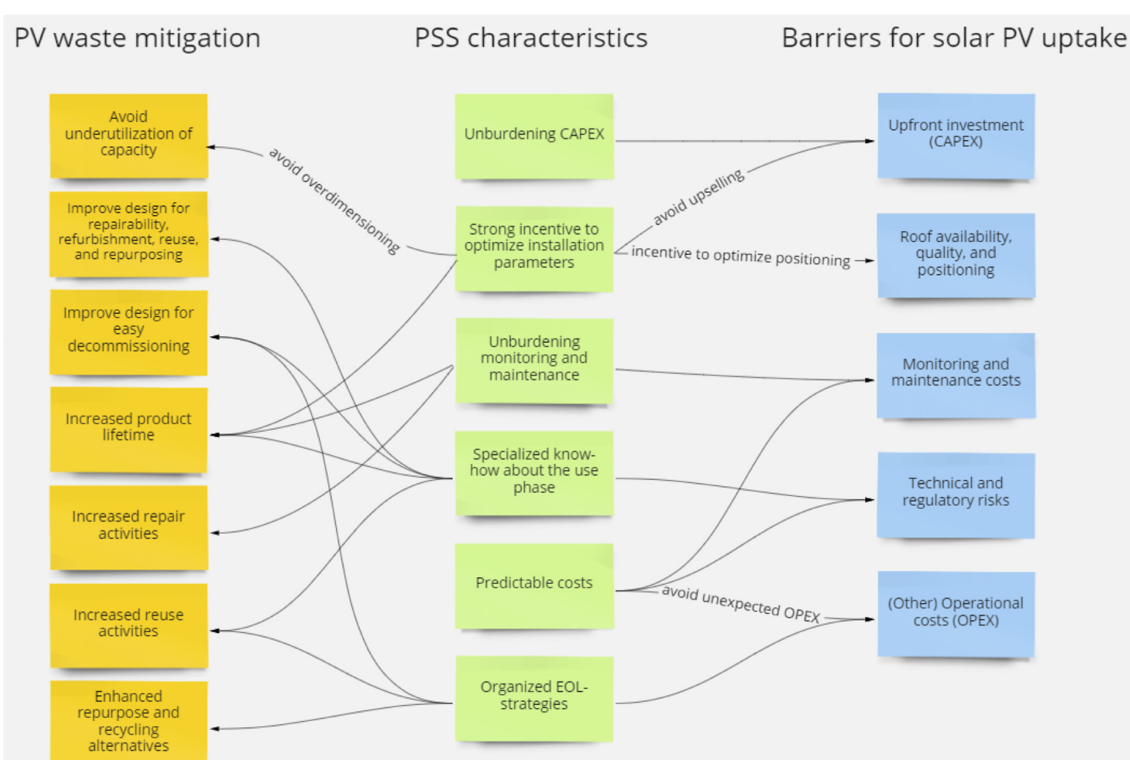

Fig. 1. The potential of circular PSS models to mitigate PV waste and enhance solar PV investments.

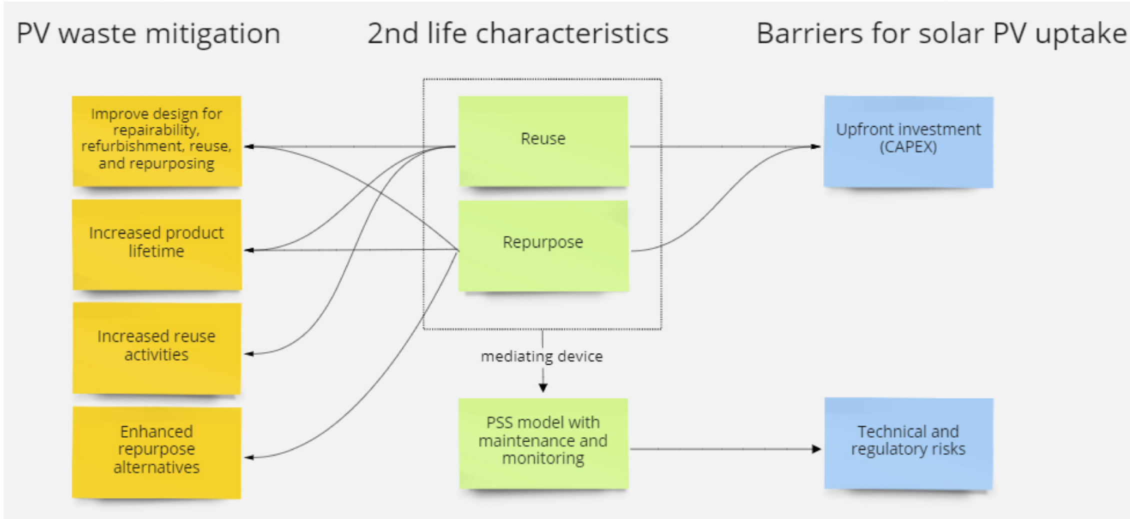

Fig. 2. The potential of 2nd-life strategies to mitigate PV waste and enhance solar PV investments.

design options for easy decommissioning. It also provides opportunities to free infrastructure with limited available roof space and replace old PV installations with much more efficient ones. On the other hand, it is considered inefficient to demount a well-performing installation, both from the circularity as from the financial perspective. Transfer of ownership, on the other hand, limits the underutilization of relatively new installed inverters but provides little circularity incentives for the service provider during the end-of-life stage of the installation. Service contracts following a transfer of ownership foster repair, increase product lifetimes, and may provide feedback loops for improved design. On the other hand, these service contracts may cause lock-in effects.

In recent years, scholarly attention towards the economic and environmental potential of innovative data technologies in solar energy has been substantial (Antikainen et al., 2018; Hamwi et al., 2021; Kumar et al., 2021; Pagoropoulos et al., 2017; Rabaia et al., 2022). However, business models stemming from new data technologies remain relatively uncomprehended (Hamwi et al., 2021). This is largely confirmed by our focus group results. Our results also confirm the finding that an

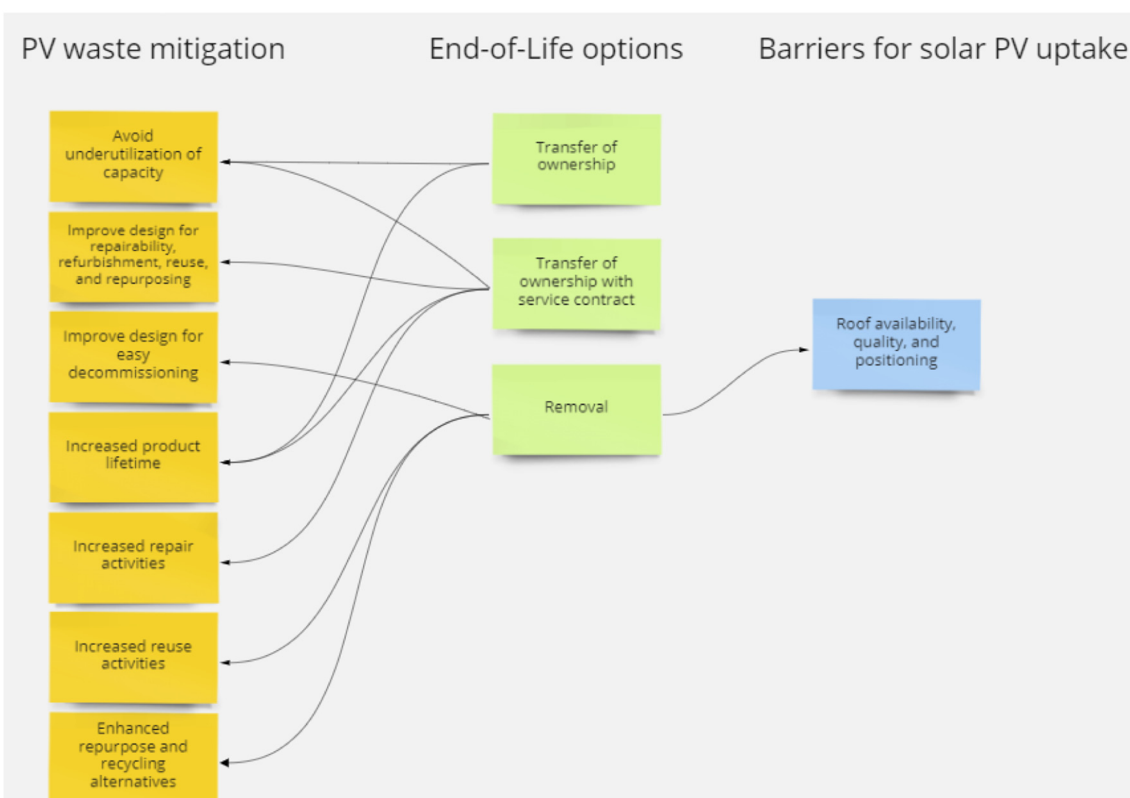

Fig. 3. The potential of end-of-life strategies to mitigate PV waste and enhance solar PV investments.

efficient collaboration in data sharing requires trust and security (Antikainen et al., 2018).

We also identified circularity enhancing possibilities, as visualized in Fig. 4. Improved insights on consumption, production and performance, and material passports could enable and design feedback loops and reduce asymmetric information to stimulate reuse, repurposing, and enhanced recycling activities. Open access to product data, preferably across the entire product lifecycle, could incentivize for increased producer responsibility during the use and end-of-life phase, as well as overall value chain transparency and traceability. Demand control technologies, on the other hand, could help to reduce operational costs (especially when capacity-based network tariffs associated with peak demands come into play) and could alleviate investments needs in grid capacity.

5.2. Boundary conditions in organizational market segments

In order to be attractive for business-to-business and business-to-government markets, circular solar business models and strategies have to overcome some specific barriers. Above all, our focus group results point out that the key determinator of solar PSS success lies in a proven positive business case. The importance of presenting viable case studies for PV investments was suggested earlier in a study on public market segments (D'Adamo et al., 2020). However, this remains a challenge as solar PSS is not widespread in Flanders and example cases are typically very context specific. How this success is defined heavily depends on the financial KPIs applied, which might differ among market segments. While some rely on the cost perspective and take into account the LCOE, for other players the Return on Investment (ROI) might be a key determinator, as well as payback time or Total Cost of Ownership (TCO) (Rabaia et al., 2022).

Our focus group results indicate that many companies do not have a substantial problem to finance the acquisition of a PV installation themselves. Therefore, unburdening CAPEX alone is not a sufficient driver. Unburdening, improved risk management, and contractual flexibility are consequently identified as important boundary conditions to create attractive value propositions in these markets. PSS firms can accordingly incentivize the creation of more durable products, facilitating repair and maintenance, or set up joint-ventures to establish links between manufacturers and customers, or develop integrated energy and mobility solutions. Although service providers have better risk pooling capabilities than individual customers, focus group participants emphasize the need for solid warranty regulations and clear testing protocols to develop trust across stakeholders in the entire value chain.

Next, also in a PSS set-up financial viability is identified as a key boundary condition for the large-scale uptake of 2nd life PV, given that new panels are becoming ever more efficient and cheaper, as pointed out by our respondents. The maturing of the market for 2nd life PV is considered an important enabler, and the integration and streamlining of supply chains for new and 2nd life PV is considered central to realize sourcing of 2nd life PV in an efficient way and at sufficient scale.

In PSS models, technical and organizational risks are transferred to the service provider (Schenkl et al., 2014). This releases organizations from investing in a deep knowledge about operations and maintenance themselves but increases the risk of a lock-in situation in the long run (Yang and Evans, 2019). Most specifically, data technologies may provide numerous interesting applications, but ownership, control, and privacy issues over these data are often mentioned by participants as a major concern when dealing with trusted companies that acquire a significant amount of market power. Regulatory incentives that protect organizations from excess market power are therefore again indicated as one of the key enablers for the large scale introduction of solar PSS models in Flanders, which might sound contradictory as trust in regulatory institutions seems to be at a historic low.

In all three focus groups, split incentive problems have been identified as an important source of suboptimal investment outcomes in organizational market segments. In residential markets homeowners have a strong financial incentive to monitor their energy use. In organizations, however, co-workers do not have to pay energy bills of their organizations themselves, and incentives to reduce energy consumption are often decoupled from organizational divisions that have to decide about investments in renewable energy and energy performance enhancing data technologies. Therefore, organizational design should be

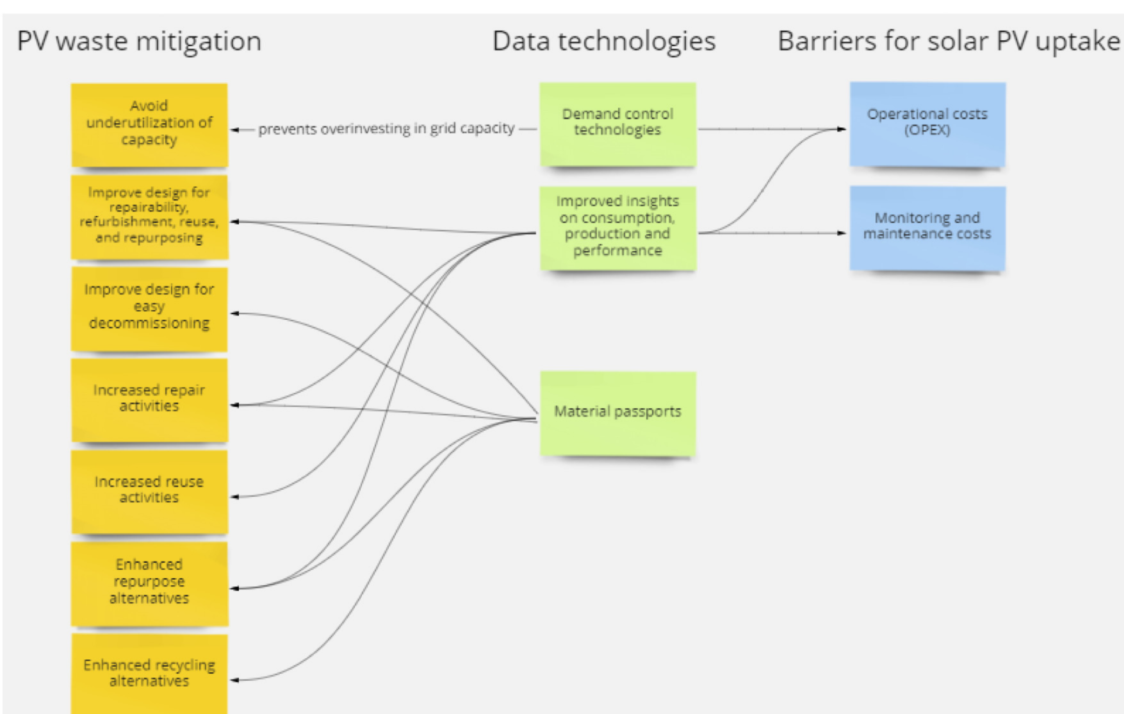

Fig. 4. The potential digital technologies to mitigate PV waste and enhance solar PV investments.

supportive to increase the effectiveness of investments in solar PV. This requires buy-in within organizations, aligning incentives both across divisions as along the chain-of-command. For example, data technologies may provide excellent intelligence to foster energy savings, but organizations should be designed to have its results interpreted by qualified staff with the right mandate to translate this into effective energy savings policies. As pointed out earlier by Kumar et al. (2021), finding skilled workforce that is knowledgeable to do so is a major prerequisite to integrate new technologies and integrate them with the sustainability criteria of the circular economy (Kumar et al., 2021).

Also, dynamics along corporate governance lines may have an impact on the extent to which organizations are willing to invest in solar PV. For public sector markets, including schools and social organizations that have to comply to public procurement rules, also political and bureaucratic dynamics and subsidy schemes come into play.

While assessing organizational boundary conditions that stem from focus group discussions, one almost forgets about an important elephant in the room. As discussed in our introduction, stakeholder engagement is an important enabler for a circular transition (Salvioni and Almici, 2020). Therefore, it is important to investigate customer perspectives to learn about their barriers to invest in solar PV and to assess whether they are willing to pay a circular premium (D'Adamo and Lupi, 2021). Yet, in all three focus groups we notice a substantial interest in financial, technical, and organizational issues, while mostly neglecting the responsibility of the demand side in a circular transition. Focus group participants did not take a proactive stance in considering environmental benefits of PSS contracts or PV reuse, nor did they have a clear idea yet on opportunities stemming from alternative contractual regulations or innovative data technologies. They rather tend to free-ride in a collective action problem by pointing at service providers and regulatory bodies to present viable and financially interesting business cases that are enabling both environmental and economic aspects of solar PV investments.

5.3. Boundary conditions to translate PSS into sustainability

It is important to keep in mind that PSS can to some extent facilitate circularity in the PV industry and beyond, but circularity is not an explicit trait of PSS models. PSS are in the first place focused on finding an integrated bundle of products and services which creates customer utility and generates value (Boehm and Thomas, 2013). Results in terms of their circularity merits from the field remain ambiguous and heavily depend on how the PSS is designed (Matschewsky, 2019; Överholm, 2017). In contrary, a perverse effect of having access to energy at lower-than-grid prices might be an increased electricity consumption as rebound effect (Boccard and Gautier, 2021; Zink and Geyer, 2017).

Another general concern when introducing PSS models is also that products might be returned to the service provider earlier in time than when they are sold to the customer (Tukker, 2015). This could apply to PV as well as the technical lifetime of panels is assumed to be 30 years while typical lease/PPA contracts have a duration of 15–20 years. In addition, if a new PV panel provides more 'value for money' than an existing one in a PPA set-up, the service provider still has an incentive to repower. Our results show that ownership is often transferred to the customer at the end-of-contract stage, which might satisfy this technical lifetime but removes incentives for the service provider to address the end-of-life phase. Finally, as emphasized by focus group participants, the service component of the PSS typically induces increased transportation costs stemming from maintenance, monitoring, or repair. It is important to factor this in, in order to avoid that additional environmental and financial impacts from transport offset the potential circularity benefits generated in the PSS set-up. Circularity in itself is not a goal, but rather an important dimension in the wider sustainability transition (Harris et al., 2021).

Short-term PSS contracts could lower barriers for PV adoption for start-up companies, and flexible contracts could allow users to gain access to the latest technologies without having to invest. Depending on the end-of-life strategies applied at the moment of contract expiration, however, it should be questioned to which extent such set-ups generate any circularity benefits compared to a traditional sales model.

While PSS contracts may offer a quick solution to invest in solar PV, this does not discharge policy makers from the need for a strategic sustainable real estate planning, from the need for a qualitative regulatory framework that prevents legal uncertainties and incentivizes to look beyond long-hanging fruit solutions, and from assessing the impact of PSS contracts on obligations for future generations.

5.4. Limitations

Limitations of this research include its geographical and non-technical scope, and limitations stemming from focus group research. From a geographical perspective, Flanders is a relevant context to study the uptake of new technologies in industrialized regions that contain highly regulated and multilayered policy settings. Yet, in order to be able to grasp the importance of specific institutional contexts, further research could help us to acquire a deeper knowledge about the rise and fall of different solar business models across countries (as illustrated for example by Strupeit and Palm (2016) for German, US and Japanese markets). Flanders is also a less relevant context to draw conclusions for isolated communities or developing countries. Since the latter can be expected to be confronted with a much larger upcoming PV waste problem (Engelken et al., 2016; Gautam et al., 2021), similar research in developing countries would be worthwhile.

While our research takes into account several institutional, regulatory, and economic aspects of investment decisions in solar PV, we did not include a technical discussion on the impact of technological developments on circularity options, and conversely, on business opportunities for technological innovations stemming from the need for more circular options. Recent research already encompasses a more technical approach (Contreras-Lisperguer et al., 2021; Deng et al., 2019; Farrell et al., 2020; Rabaia et al., 2022; Radavičius et al., 2021; Tsanakas et al., 2020). Further research, as suggested by an anonymous reviewer, may deepen our understanding on circularity opportunities depending on the active layer type of PV panels, and the effects of near IR photons on organic solar cells (OSCs). Also, the development of mathematical models could support decision-making processes for individual organizations, grid operators, and policy makers when evaluating the financial impact of circular solutions and vice versa. Mathematical models could also support decision-making processes on the optimal choice of circularity strategies, e.g. to assess reuse against recycling options in a context of technologies that become increasingly efficient and cheap. This would improve a critical sustainability assessment of circular strategies including PV reuse and PV module recycling (Chowdhury et al., 2020; Deng et al., 2019; Heath et al., 2020).

Thirdly, the use of focus groups has limitations that are well documented (Gailing and Naumann, 2018; Stewart and Shamdasani, 2014). As discussed in the methods section, we tried to mitigate most important pitfalls, such as groupthink, in order to preserve data validity. It is important to point out, however, that focus group research is most suitable to explore undocumented preferences, beliefs, and experiences in a descriptive way. We identified salient barriers and enablers based on both literature, policy documents, and expert opinions. While we did not investigate preferences of end-customers themselves, our research contributes to a broader understanding of how circular solar options may align solar PV investments with waste mitigation strategies in organizational market segments. Further research could therefore investigate confirmatory approaches with end-customers, making use of survey research, large N interviews within specific market segments, data envelopment analysis, and experimental research settings.

6. Conclusions and recommendations

In this paper, we investigated how and when circular strategies and business models may enhance solar PV investments in organizational market segments. Our results indicate that the most important reasons for organizational market segments to invest in solar PV are not its renewable or green features, but lower energy costs, independence and secured access to energy. The demand side of this market is not aiming at subsidies or green loans systems but seems to prioritize a positive business case for solar energy. This narrative does not change significantly when considering circular solar solutions.

While PSS models are recognized to alleviate financial and organizational barriers for solar PV take up, it is still considered a big leap for organizational market segments to divert from a sales-based PV model to a solar PSS model. Major barriers are the a limited availability of demonstrator cases and a lack of proven financial viability. Adding 2nd life PV deployment to this set-up is perceived as highly complex and risky, especially taking into account the current levels of uncertainty 2nd life PV is facing. Conversely, the combination with a PSS model is considered as a necessary condition to opt for PV reuse. In general, solar PSS models are acknowledged to unburden the risk of maintenance and repair, and include incentives to optimize PV system dimensions, performance, and end-of-life processing. Sustainability concerns of focus group participants on solar PSS models include potential rebound effects, suboptimal longevity choices because of ownership transfers at contract expiration, and the carbon footprint of transportation to maintain service levels.

Strategies with respect to PV reuse, end-of-life alternatives, and data technologies are recognized to have an interesting potential to mitigate PV waste. Focus group participants believe that these developments may also entail promising business opportunities. These innovative business opportunities, however, still need a significant amount of business development. Given the current energy crisis, and the upcoming electrification of mobility, this should urge policy makers to develop sound regulatory frameworks that enable new business models on data technologies that align costs savings with superior waste mitigating strategies.

Our findings do not indicate a straightforward willingness to pay a circular premium for circular solar business models in organizational market segments. Nor do we notice a proactive environmental stance with respect to stakeholder engagement for a circular transition. Nevertheless, we are able to contribute to a nuanced understanding of boundary conditions for a transition towards circular business models for durables and capital goods in organizational market segments, including other types of energy sources and installations for Heating, Ventilation, and Air Conditioning (HVAC). As institutional trust is key to foster any kind of investments in sustainable assets, public authorities should develop a long term, substantiated vision on energy policy, to regain trust and to foster the further uptake of solar PV. This should encompass a wider strategy on sustainable real estate planning, including aspects of urban planning and mobility. In order to prevent overinvestment and rebound effects, policies should not focus on increasing injection fees, but on increasing self-consumption. This can be enhanced by alleviating regulatory limitations on energy sharing and to evaluate solar PV investments within broader systemic frameworks than individual buildings or legal entities. This would enable households and organizations with no financial, technical, or legal access to solar PV to participate in the potential of this renewable energy source.

Furthermore, governments should stimulate open innovation on energy related data technologies, increasing the potential for evidence-based decision-making, support the development of solid warranty regulations and testing protocols for 2nd life PV panels, and embed carbon emissions of materials in public procurement criteria to integrate 2nd life solutions, in order to lead by example and generate a market pull for reuse markets. Finally, economic law and policy should prevent negative welfare effects of lock-in situations and the potential abuse of market power in newly developing markets.

Our research leads us to the following research gaps that are relevant for the wider research domains of circular economy and energy policy. Firstly, both policy makers and companies could benefit from enhanced insights and evidence-based toolkit-development of methodologies for business model innovation in highly regulated markets. Secondly, policy makers could benefit from further research on the conditions for market development and implementation of reuse markets, most specifically from the field of law and economics. Finally, academic insights on the split incentive problem could be further developed by studying applications at the crossroads of energy policy and market-specific policies (e.g. housing policy, educational policy, health and social care policy, etc.). Both policy makers and practitioners would benefit from financial and legal tools that stem from these advances, enabling the further uptake of circular business models in a wide array of durable and capital goods.

Consent

Informed consent was obtained from all subjects involved in the study.

CRediT authorship contribution statement

Conceptualization, W.V·O.; methodology, W.V·O; validation, A.S.; formal analysis, W.V.O; investigation, W.V.O. and A.S.; resources, W.V.O. and A.S.; data curation, W.V.O. and A.S., writing—original draft preparation, W.V.O. and A.S.; writing—review and editing, W.V.O. and A.S. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

Acknowledgements

This research has received funding from the European Union's Horizon 2020 research and innovation program (call: H2020-EU.3.5.4) under grant agreement 776680 (CIRCUSOL). The authors would like to thank Lize Borms, Ässia Boukhatmi, Bart Mantels, Roger Nyffenegger, Lars Strupeit, focus group participants, interviewees, and participants at the CIRCUSOL consortium meeting in Berlin (April 21-22, 2022) for valuable feedback and discussions. All remaining errors are the sole responsibility of the authors.

Appendix A. Interview respondents and structure

In this appendix, we provide an anonymized overview of interview respondents (Table A.1) and the interview structure of our semi-structured interviews.

Table A.1
Interviews.

ID	Date	Stakeholder type
Respondent 1	19/11/2021	Service provider 1
Respondent 2	2/12/2021	Service provider 2
Respondent 3	2/12/2021	Researcher 1
Respondents 4 & 5	2/12/2021	Federation of service providers
Respondent 6	6/12/2021	Service provider 2
Respondent 7	7/12/2021	Service provider 3

Interview structure

For each of the three focus groups we prepared (non-owner residential, public sector and commercial market segments), we asked the following questions in a semi-structured interview:

- Given the list of participants we identified already, which participants should we not forget to invite or include?
- What key questions would you like to ask to these focus group participants, if you had the chance to do so?
- Which relevant cases should we know to prepare this focus group?

Appendix B. Focus group participants

In this appendix, we give an overview of the three focus groups we organized (Tables A.2–A.4), including the dates they were organized and a description of the anonymized participants.

Table A.2
Focus group public and social infrastructure (December 7th, 2021).

ID	Professional position	Stakeholder type
Participant 1.1	Energy expert	Federation of municipalities
Participant 1.2	PV expert	Public procurement agency on renewable energy
Participant 1.3	Sustainable infrastructure expert	Supporting association for health & social care facilities and schools
Participant 1.4	Energy expert	Governmental agency for school infrastructure
Participant 1.5	Energy expert	Regional federation of schools
Participant 1.6	Investment manager	Governmental investment company
Participant 1.7	Public finance expert	Bank

Table A.3
Focus group social & private rental housing, and collective housing (December 22nd, 2021).

ID	Professional position	Stakeholder type
Participant 2.1	Policy expert	Association of social rental housing
Participant 2.2	Operational manager	Energy co-operative of social housing associations
Participant 2.3	CEO	Association of tenants
Participant 2.4	CEO	Association of landlords
Participant 2.5	Social Worker	Civil Society project organization
Participant 2.6	President of the Board of Directors	Association for housing for vulnerable households
Participant 2.7	Energy Expert	Environmental civil society organization

Table A.4
Focus group companies and commercial real estate (February 18th, 2022).

ID	Professional position	Stakeholder type
Participant 3.1	Circular economy expert	Employer federation
Participant 3.2	Circular economy expert	Employer federation
Participant 3.3	Energy expert	Federation of farmers
Participant 3.4	Innovation expert	Construction federation
Participant 3.5	Innovation expert	Real estate study center

References

Agbonaye, O., Keatley, P., Huang, Y., Bani-Mustafa, M., Ademulegun, O.O., Hewitt, N., 2020. Value of demand flexibility for providing ancillary services: a case for social housing in the irish DS3 market. Util. Policy 67, 101130. https://doi.org/10.1016/j.jup.2020.101130.

Alda, M., 2021. The environmental, social, and governance (ESG) dimension of firms in which social responsible investment (SRI) and conventional pension funds invest: the mainstream SRI and the ESG inclusion. J. Clean. Prod. 298, 126812. https://doi.org/10.1016/j.jclepro.2021.126812.

Amaducci, S., Yin, X., Colauzzi, M., 2018. Agrivoltaic systems to optimise land use for electric energy production. Appl. Energy 220, 545–561. https://doi.org/10.1016/j.apenergy.2018.03.081.

Antikainen, M., Uusitalo, T., Kivikytö-Reponen, P., 2018. Digitalisation as an enabler of circular economy. Procedia CIRP 73, 45–49. https://doi.org/10.1016/j.procir.2018.04.027.

Atasu, A., Duran, S., Van Wassenhove, L., 2021. The dark side of solar power [WWW Document]. Harv. Bus. Rev. (accessed 8.31.22) https://hbr.org/2021/06/the-dark-side-of-solar-power.

Bahaj, A.S., James, P.A.B., 2007. Urban energy generation: the added value of photovoltaics in social housing. Renew. Sust. Energ. Rev. 11, 2121–2136. https://doi.org/10.1016/j.rser.2006.03.007.

Bauwens, T., 2019. Analyzing the determinants of the size of investments by community renewable energy members: findings and policy implications from Flanders. Energy Policy 129, 841–852. https://doi.org/10.1016/j.enpol.2019.02.067.

Beliën, J., De Boeck, L., Colpaert, J., Cooman, G., 2013. The best time to invest in photovoltaic panels in Flanders. Renew. Energy 50, 348–358. https://doi.org/10.1016/j.renene.2012.06.047.

Best, R., Burke, P.J., Nepal, R., Reynolds, Z., 2021a. Effects of rooftop solar on housing prices in Australia. Aust. J. Agric. Resour. Econ. 65, 493–511. https://doi.org/10.1111/1467-8489.12431.

Best, R., Esplin, R., Hammerle, M., Nepal, R., Reynolds, Z., 2021b. Do solar panels increase housing rents in Australia? Hous. Stud., 1–18. https://doi.org/10.1080/02673037.2021.2004094.

Bird, S., Hernández, D., 2012. Policy options for the split incentive: increasing energy efficiency for low-income renters. Energy Policy, Special Section: Frontiers of Sustainability 48, 506–514. https://doi.org/10.1016/j.enpol.2012.05.053.

Boccard, N., Gautier, A., 2021. Solar rebound: the unintended consequences of subsidies. Energy Econ. 100, 105334. https://doi.org/10.1016/j.eneco.2021.105334.

Bocken, N.M.P., Antikainen, M., 2019. Circular business model experimentation: Concept and approaches. In: Dao, D., Howlett, R.J., Setchi, R., Vlacic, L. (Eds.), Sustainable Design and Manufacturing 2018, Smart Innovation, Systems and Technologies. Springer International Publishing, Cham, pp. 239–250. https://doi.org/10.1007/978-3-030-04290-5_25.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Bocken, N.M.P., Schuit, C.S.C., Kraaijenhagen, C., 2018. Experimenting with a circular business model: lessons from eight cases. Environmental Innovation and Societal Transitions. https://doi.org/10.1016/j.eist.2018.02.001.

Bocken, N.M.P., Strupeit, L., Whalen, K., Nußholz, J.L.K., 2019. A review and evaluation of circular business model innovation tools. Sustainability 11. https://doi.org/10.3390/su11082210.

Bocken, N.M.P., Weissbrod, I., Antikainen, M., 2021. Business model experimentation for the circular economy: definition and approaches. Circ. Econ. Sust. 1, 49–81. https://doi.org/10.1007/s43615-021-00026-z.

Boehm, M., Thomas, O., 2013. Looking beyond the rim of one's teacup: a multidisciplinary literature review of Product-Service Systems in Information Systems, Business Management, and Engineering & Design. J. Clean. Prod. 51, 245–260. https://doi.org/10.1016/j.jclepro.2013.01.019.

Borms, L., Brusselaers, J., Vrancken, K.C., Deckmyn, S., Marynissen, P., 2023. Toward resilient organizations after COVID-19: An analysis of circular and less circular companies. Resour. Conserv. Recycl. 188, 106681. https://doi.org/10.1016/j.resconrec.2022.106681.

Brankov, B., Stanojević, A., Nenković-Riznić, M., Pucar, M., 2020. The possibilities for implementation of photovoltaic solar panels in multi-family housing areas. Proceedings of 8th International Conference on Renewable Electrical Power Sources 167–175.

Bressanelli, G., Adrodegari, F., Perona, M., Saccani, N., 2018. The role of digital technologies to overcome Circular Economy challenges in PSS Business Models: an exploratory case study. Procedia Cirp 73, 216–221. https://doi.org/10.1016/j.procir.2018.03.32.

CEPS, 2021. Barriers and enablers for implementing circular economy business models. RR2021-01 p. 58.

Chegut, A., Eichholtz, P., Holtermans, R., Palacios, J., 2020. Energy Efficiency Information and Valuation Practices in Rental Housing. J. Real Estate Finan. Econ. 60, 181–204. https://doi.org/10.1007/s11146-019-09720-0.

Chen, C., Li, J., Shuai, J., Nelson, H., Walzem, A., Cheng, J., 2021. Linking social-psychological factors with policy expectation: Using local voices to understand solar PV poverty alleviation in Wuhan. China. Energy Policy 151, 112160. https://doi.org/10.1016/j.enpol.2021.112160.

Chowdhury, Md.S., Rahman, K.S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, Md., Tiong, S.K., Sopian, K., Amin, N., 2020. An overview of solar photovoltaic panels' end-of-life material recycling. Energ. Strat. Rev. 27, 100431. https://doi.org/10.1016/j.esr.2019.100431.

Ciacci, C., Banti, N., Di Naso, V., Bazzocchi, F., 2022. Evaluation of the Cost-Optimal Method Applied to Existing Schools Considering PV System Optimization. Energies 15, 611. https://doi.org/10.3390/en15020611.

Circusol, 2022. Asset Database [WWW Document]. https://www.circusol.eu/en/topics/asset-database accessed 8.31.22.

Colasante, A., D'Adamo, I., 2021. The circular economy and bioeconomy in the fashion sector: Emergence of a "sustainability bias". J. Clean. Prod. 329, 129774. https://doi.org/10.1016/j.jclepro.2021.129774.

Conradie, P.D., De Ruyck, O., Saldien, J., Ponnet, K., 2021. Who wants to join a renewable energy community in Flanders? Applying an extended model of Theory of Planned Behaviour to understand intent to participate. Energy Policy 151, 112121. https://doi.org/10.1016/j.enpol.2020.112121.

Contreras Lisperguer, R., Muñoz Cerón, E., de la Casa Higueras, J., Martín, R.D., 2020. Environmental Impact Assessment of crystalline solar photovoltaic panels' End-of-Life phase: Open and Closed-Loop Material Flow scenarios. Sustainable Production and Consumption 23, 157–173. https://doi.org/10.1016/j.spc.2020.05.008.

Contreras-Lisperguer, R., Muñoz-Cerón, E., Aguilera, J., de la Casa, J., 2021. A set of principles for applying Circular Economy to the PV industry: Modeling a closed-loop material cycle system for crystalline photovoltaic panels. Sustainable Production and Consumption 28, 164–179. https://doi.org/10.1016/j.spc.2021.03.033.

Curtis, T.L., Buchanan, H., Smith, L., Heath, G., 2021. A Circular Economy for Solar Photovoltaic System Materials: Drivers. Barriers, Enablers, and U.S. Policy Considerations. (No. NREL/TP-6A20-74550). National Renewable Energy Lab. (NREL), Golden, CO (United States) https://doi.org/10.2172/1774574.

D'Adamo, I., Falcone, P.M., Gastaldi, M., Morone, P., 2020. The economic viability of photovoltaic systems in public buildings: Evidence from Italy. Energy 207, 118316. https://doi.org/10.1016/j.energy.2020.118316.

D'Adamo, I., Lupi, G., 2021. Sustainability and Resilience after COVID-19: A Circular Premium in the Fashion Industry. Sustainability 13, 1861. https://doi.org/10.3390/su13041861.

De Boeck, L., Van Asch, S., De Bruecker, P., Audenaert, A., 2016. Comparison of support policies for residential photovoltaic systems in the major EU markets through investment profitability. Renew. Energy 87, 42–53. https://doi.org/10.1016/j.renene.2015.09.063.

De Groote, O., Gautier, A., Verboven, F., 2022. The Political Economy of Financing Climate Policy – Evidence from the Solar Pv Subsidy Programs. https://doi.org/10.2139/ssrn.4119431.

De Groote, O., Pepermans, G., Verboven, F., 2016. Heterogeneity in the adoption of photovoltaic systems in Flanders. Energy Econ. 59, 45–57. https://doi.org/10.1016/j.eneco.2016.07.008.

De Groote, O., Verboven, F., 2019. Subsidies and Time Discounting in New Technology Adoption: Evidence from Solar Photovoltaic Systems. Am. Econ. Rev. 109, 2137–2172. https://doi.org/10.1257/aer.20161343.

Deng, R., Chang, N.L., Ouyang, Z., Chong, C.M., 2019. A techno-economic review of silicon photovoltaic module recycling. Renew. Sust. Energ. Rev. 109, 532–550. https://doi.org/10.1016/j.rser.2019.04.020.

Drury, E., Miller, M., Macal, C., Graziano, D., Heimiller, D., Ozik, J., Perry, T., 2012. The transformation of southern California's residential photovoltaics market through third-party ownership. https://doi.org/10.1016/J.ENPOL.2011.12.047.

Ellen MacArthur Foundation, 2016. Intelligent assets: Unlocking the circular economy potential. p. 74.

Emili, S., Ceschin, F., Harrison, D., 2016. Product-Service System applied to Distributed Renewable Energy: A classification system, 15 archetypal models and a strategic design tool. Energy for Sustain. Dev. 32, 71–98. https://doi.org/10.1016/j.esd.2016.03.004.

Engelken, M., Römer, B., Drescher, M., Welpe, I.M., Picot, A., 2016. Comparing drivers, barriers, and opportunities of business models for renewable energies: A review. Renew. Sust. Energ. Rev. 60, 795–809. https://doi.org/10.1016/j.rser.2015.12.163.

Farrell, C.C., Osman, A.I., Doherty, R., Saad, M., Zhang, X., Murphy, A., Harrison, J., Vennard, A.S.M., Kumaravel, V., Al-Muhtaseb, A.H., Rooney, D.W., 2020. Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules. Renew. Sust. Energ. Rev. 128, 109911. https://doi.org/10.1016/j.rser.2020.109911.

Feldman, D., Margolis, R., 2014. To Own or Lease Solar: Understanding Commercial Retailers' Decisions to Use Alternative Financing Models. (No. NREL/TP-6A20-63216). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1167054.

Felice, A., Rakocevic, L., Peeters, L., Messagie, M., Coosemans, T., Ramirez Camargo, L., 2022. Renewable energy communities: Do they have a business case in Flanders? Appl. Energy 322, 119419. https://doi.org/10.1016/j.apenergy.2022.119419.

Flemish Government, 2022. Solar PV in Flanders. [WWW Document] https://apps.energiesparen.be/energiekaart/vlaanderen/zonnepanelen URL (accessed 8.31.22).

Frischknecht, R., Stolz, P., Heath, G., Raugei, M., Sinha, P., de Wild-Scholten, M., 2020. Methodology Guidelines on Life Cycle Assessment of Photovoltaic. IEA PVPS. https://doi.org/10.13140/RG.2.2.15574.88648.

Gailing, L., Naumann, M., 2018. Using focus groups to study energy transitions: Researching or producing new social realities? Energy Research & Social Science, Special Issue on the Problems of Methods in Climate and Energy Research 45, 355–362. https://doi.org/10.1016/j.erss.2018.07.004.

Gautam, A., Shankar, R., Vrat, P., 2021. End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy. Sustainable Production and Consumption 26, 65–77. https://doi.org/10.1016/j.spc.2020.09.011.

Ghaleb, B., Asif, M., 2022. Assessment of solar PV potential in commercial buildings. Renew. Energy 187, 618–630. https://doi.org/10.1016/j.renene.2022.01.013.

Global Solar Council, 2020. Solar power lights the way towards the SDGs with broad benefits for green recovery plans [WWW Document]. PV Magazine. (accessed 8.31.22) https://www.pv-magazine.com/press-releases/solar-power-lights-the-way-towards-the-sdgs-with-broad-benefits-for-green-recovery-plans/.

Grande-Acosta, G.K., Islas-Samperio, J.M., 2020. Boosting Energy Efficiency and Solar Energy inside the Residential, Commercial, and Public Services Sectors in Mexico. Energies 13, 5601. https://doi.org/10.3390/en13215601.

Greenbaum, T., 1998. The Handbook for Focus Group Research. SAGE Publications, Inc. https://doi.org/10.4135/9781412986151 2455 Teller Road, Thousand Oaks California 91320 United States of America.

Hamwi, M., Lizarralde, I., 2017. A Review of Business Models towards Service-Oriented Electricity Systems, 109–114. https://doi.org/10.1016/j.procir.2017.03.032 Procedia CIRP, 9th CIRP IPSS Conference: Circular Perspectives on PSS 64.

Hamwi, M., Lizarralde, I., Legardeur, J., 2021. Demand response business model canvas: A tool for flexibility creation in the electricity markets. J. Clean. Prod. 282, 124539. https://doi.org/10.1016/j.jclepro.2020.124539.

Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustainable Production and Consumption 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018.

Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., Wade, A., 2020. Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy 5, 502–510. https://doi.org/10.1038/s41560-020-0645-2.

Hoen, B., Rand, J., Elmallah, S., 2019. Commercial PV Property Characterization: An Analysisof Solar Deployment Trends in Commercial Real Estate. p. 65.

Huijben, J.C.C.M., Podoynitsyna, K.S., van Rijn, M.L.B., Verbong, G.P.J., 2016. A review of governmental support instruments channeling PV market growth in the Flanders region of Belgium (2006–2013). Renew. Sust. Energ. Rev. 62, 1282–1290. https://doi.org/10.1016/j.rser.2016.04.058.

Iea, 2021. World Energy Outlook 2021. IEA, Paris.

PVPS, I.E.A., 2021. Preliminary Environmental & Financial Viability Analysis of CircularEconomy Scenarios for Satisfying PV System Service Lifetime. p. 69 Report IEA-PVPST12-21:2021.

IPCC, 2012. Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

IRENA, IRENA IEA-PVPS, 2016. End-of-life management: Solar Photovoltaic Panels. p. 98.

Jacksohn, A., Grösche, P., Rehdanz, K., Schröder, C., 2019. Drivers of renewable technology adoption in the household sector. Energy Econ. 81, 216–226. https://doi.org/10.1016/j.eneco.2019.04.001.

Juwet, G., Deruytter, L., 2021. Territorial and institutional obduracy in regional transition: politicising the case of Flanders' energy distribution system. Camb. J. Reg. Econ. Soc. 14, 301–320. https://doi.org/10.1093/cjres/rsab005.

Kahneman, D., 2011. Thinking, Fast and Slow. 1st ed. Penguin.

Kokchang, K., Tongsopit, S., Junlakarn, S., Wibulpolprasert, W., Tossabanyad, M., 2018. Stakeholders' Perspectives of Design Options for a Rooftop Solar PV Self-consumption Scheme in Thailand. Applied Environmental Research 40, 42–54. https://doi.org/10.35762/AER.2018.40.3.5.

Kolokotsa, D., Vagias, V., Fytraki, L., Oungrinis, K., 2019. Energy analysis of zero energy schools: the case study of child's asylum in Greece. Advances in Building Energy Research 13, 193–204. https://doi.org/10.1080/17512549.2018.1488612.

Komendantova, N., Manuel Schwarz, M., Amann, W., 2018. Economic and regulatory feasibility of solar PV in the Austrian multi-apartment housing sector. AIMS Energy 6, 810–831. https://doi.org/10.3934/energy.2018.5.810.

Kumar, P., Singh, R.K., Kumar, V., 2021. Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers. Resour. Conserv. Recycl. 164, 105215. https://doi.org/10.1016/j.resconrec.2020.105215.

Laes, E., Valkering, P., De Weerdt, Y., 2019. Diagnosing Barriers and Enablers for the Flemish Energy Transition. Sustainability 11, 5558. https://doi.org/10.3390/su11205558.

Lagrange, A., de Simón-Martín, M., González-Martínez, A., Bracco, S., Rosales-Asensio, E., 2020. Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: An application to a hospital. Int. J. Electr. Power Energy Syst. 119, 105865. https://doi.org/10.1016/j.ijepes.2020.105865.

Lang, T., Ammann, D., Girod, B., 2016. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. Renew. Energy 87, 77–87. https://doi.org/10.1016/j.renene.2015.09.059.

Lee, J., Shepley, M.M., 2020. Benefits of solar photovoltaic systems for low-income families in social housing of Korea: Renewable energy applications as solutions to energy poverty. Journal of Building Engineering 28, 101016. https://doi.org/10.1016/j.jobe.2019.101016.

Leskinen, N., Vimpari, J., Junnila, S., 2020. Using real estate market fundamentals to determine the correct discount rate for decentralised energy investments. Sustain. Cities Soc. 53, 101953. https://doi.org/10.1016/j.scs.2019.101953.

Lundqvist, H., 2020. Circular economy among Swedish solar PV firms.

Mah, D.N., Wang, G., Lo, K., Leung, M.K.H., Hills, P., Lo, A.Y., 2018. Barriers and policy enablers for solar photovoltaics (PV) in cities: Perspectives of potential adopters in Hong Kong. Renew. Sust. Energ. Rev. 92, 921–936. https://doi.org/10.1016/j.rser.2018.04.041.

Mamun, M.A.A., Dargusch, P., Wadley, D., Zulkarnain, N.A., Aziz, A.A., 2022. A review of research on agrivoltaic systems. Renew. Sust. Energ. Rev. 161, 112351. https://doi.org/10.1016/j.rser.2022.112351.

Margolis, R., Zuboy, J., 2006. Nontechnical Barriers to Solar Energy Use: Review of Recent Literature (No. NREL/TP-520-40116). National Renewable Energy Lab. (NREL). https://doi.org/10.2172/893639.

Matschewsky, J., 2019. Unintended Circularity?—Assessing a Product-Service System for its Potential Contribution to a Circular Economy. Sustainability 11, 2725. https://doi.org/10.3390/su11102725.

McCabe, A., Pojani, D., van Groenou, A.B., 2018. The application of renewable energy to social housing: A systematic review. Energy Policy 114, 549–557. https://doi.org/10.1016/j.enpol.2017.12.031.

Moro, S.R., Cauchick-Miguel, P.A., de Sousa Mendes, G.H., 2022. Adding sustainable value in product-service systems business models design: A conceptual review towards a framework proposal. Sustainable Production and Consumption 32, 492–504. https://doi.org/10.1016/j.spc.2022.04.023.

Nelson, T., McCracken-Hewson, E., Sundstrom, G., Hawthorne, M., 2019. The drivers of energy-related financial hardship in Australia – understanding the role of income, consumption and housing. Energy Policy 124, 262–271. https://doi.org/10.1016/j.enpol.2018.10.003.

ONyumba, T., Wilson, K., Derrick, C.J., Mukherjee, N., 2018. The use of focus group discussion methodology: Insights from two decades of application in conservation. Methods Ecol. Evol. 9, 20–32. https://doi.org/10.1111/2041-210X.12860.

Överholm, H., 2017. Alliance formation by intermediary ventures in the solar service industry: implications for product–service systems research. Journal of Cleaner Production, Systematic Leadership towards Sustainability 140, 288–298. https://doi.org/10.1016/j.jclepro.2015.07.061.

Överholm, H., 2015. Spreading the rooftop revolution: What policies enable solar-as-a-service? Energy Policy 84, 69–79. https://doi.org/10.1016/j.enpol.2015.04.021.

Pagoropoulos, A., Pigosso, D.C.A., McAloone, T.C., 2017. The Emergent Role of Digital Technologies in the Circular Economy: A Review. Procedia CIRP 64, 19–24. https://doi.org/10.1016/j.procir.2017.02.047.

Palm, A., 2020. Early adopters and their motives: Differences between earlier and later adopters of residential solar photovoltaics. Renew. Sust. Energ. Rev. 133, 110142. https://doi.org/10.1016/j.rser.2020.110142.

Pascaris, A.S., Schelly, C., Burnham, L., Pearce, J.M., 2021. Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics. Energy Res. Soc. Sci. 75, 102023. https://doi.org/10.1016/j.erss.2021.102023.

Peeters, J.R., Altamirano, D., Dewulf, W., Duflou, J.R., 2017. Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders. Resour. Conserv. Recycl. 120, 14–26. https://doi.org/10.1016/j.resconrec.2017.01.001.

Powell, J.W., Welsh, J.M., Pannell, D., Kingwell, R., 2021. Factors influencing Australian sugarcane irrigators' adoption of solar photovoltaic systems for water pumping. Cleaner Engineering and Technology 4, 100248. https://doi.org/10.1016/j.clet.2021.100248.

Rabaia, M.K.H., Semeraro, C., Olabi, A.-G., 2022. Recent progress towards photovoltaics' circular economy. J. Clean. Prod. 373, 133864. https://doi.org/10.1016/j.jclepro.2022.133864.

Radavičius, T., van der Heide, A., Palitzsch, W., Rommens, T., Denafas, J., Tvaronavičienė, M., 2021. Circular solar industry supply chain through product technological design changes. IRD 3, 10–30. https://doi.org/10.9770/IRD.2021.3.3(1).

Rai, V., Reeves, D.C., Margolis, R., 2016. Overcoming barriers and uncertainties in the adoption of residential solar PV. Renew. Energy 89, 498–505. https://doi.org/10.1016/j.renene.2015.11.080.

Rai, V., Sigrin, B., 2013. Diffusion of environmentally-friendly energy technologies: buy versus lease differences in residential PV markets. Environ. Res. Lett. 8, 014022. https://doi.org/10.1088/1748-9326/8/1/014022.

Reames, T.G., 2020. Distributional disparities in residential rooftop solar potential and penetration in four cities in the United States. Energy Res. Soc. Sci. 69, 101612. https://doi.org/10.1016/j.erss.2020.101612.

Reindl, K., Palm, J., 2021. Installing PV: Barriers and enablers experienced by non-residential property owners. Renew. Sust. Energ. Rev. 141, 110829. https://doi.org/10.1016/j.rser.2021.110829.

Salvioni, D.M., Almici, A., 2020. Transitioning Toward a Circular Economy: The Impact of Stakeholder Engagement on Sustainability Culture. Sustainability 12, 8641. https://doi.org/10.3390/su12208641.

Scheller, F., Doser, I., Schulte, E., Johanning, S., McKenna, R., Bruckner, T., 2021. Stakeholder dynamics in residential solar energy adoption: findings from focus group discussions in Germany. Energy Res. Soc. Sci. 76, 102065. https://doi.org/10.1016/j.erss.2021.102065.

Schenkl, S.A., Rösch, C., Mörtl, M., 2014,. Literature Study on Factors Influencing the Market Acceptance of PSS. Procedia CIRP. Product Services Systems and Value Creation. Proceedings of the 6th CIRP Conference on Industrial Product-Service Systems 16, 98–103. https://doi.org/10.1016/j.procir.2014.01.013.

Schmidt-Costa, J.R., Uriona-Maldonado, M., Possamai, O., 2019. Product-service systems in solar PV deployment programs: What can we learn from the California Solar Initiative? Resour. Conserv. Recycl. 140, 145–157. https://doi.org/10.1016/j.resconrec.2018.09.017.

Schulte, E., Scheller, F., Sloot, D., Bruckner, T., 2022. A meta-analysis of residential PV adoption: the important role of perceived benefits, intentions and antecedents in solar energy acceptance. Energy Res. Soc. Sci. 84, 102339. https://doi.org/10.1016/j.erss.2021.102339.

Sciarelli, M., Cosimato, S., Landi, G., Iandolo, F., 2021. Socially responsible investment strategies for the transition towards sustainable development: the importance of integrating and communicating ESG. The TQM Journal 33, 39–56. https://doi.org/10.1108/TQM-08-2020-0180.

Silva, T.C., Pinto, G.M., de Souza, T.A.Z., Valerio, V., Silvério, N.M., Coronado, C.J.R., Guardia, E.C., 2020. Technical and economical evaluation of the photovoltaic system in Brazilian public buildings: A case study for peak and off-peak hours. Energy 190, 116282. https://doi.org/10.1016/j.energy.2019.116282.

Sovacool, B.K., Barnacle, M.L., Smith, A., Brisbois, M.C., 2022. Towards improved solar energy justice: Exploring the complex inequities of household adoption of photovoltaic panels. Energy Policy 164, 112868. https://doi.org/10.1016/j.enpol.2022.112868.

Stam, V., 2018. Solar energy policy transitions in Flanders. Cardiff University & Radboud University, Belgium.

Stankovic, M., Gupta, R., Figueroa, J., Authried, O., Rueth, T., 2017. Industry 4.0: Opportunities behind the challenge. Background Paper for UNIDO General Conference 2017.

Stewart, D.W., Shamdasani, P.N., 2014. Focus Groups: Theory and Practice. SAGE Publications.

Strupeit, L., Palm, A., 2016. Overcoming barriers to renewable energy diffusion: business models for customer-sited solar photovoltaics in Japan, Germany and the United States. Journal of Cleaner Production, Advancing Sustainable Solutions: An Interdisciplinary and Collaborative Research Agenda 123, 124–136. https://doi.org/10.1016/j.jclepro.2015.06.120.

TOTEM, 2022. Tool to Optimise the Total Environmental impact of Materials (accessed 8.31.22) www.totem-building.be.

Toxopeus, H., Achterberg, E., Polzin, F., 2021. How can firms access bank finance for circular business model innovation? Bus. Strateg. Environ. 30, 2773–2795. https://doi.org/10.1002/bse.2893.

Tsanakas, J.A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J., Voroshazi, E., 2020. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. Prog. Photovolt. Res. Appl. 28, 454–464. https://doi.org/10.1002/pip.3193.

Tukker, A., 2015. Product services for a resource-efficient and circular economy – a review. J. Clean. Prod. 97, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049 Special Volume: Why have 'Sustainable Product-Service Systems' not been widely implemented?.

Tukker, A., 2004. Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. Bus. Strateg. Environ. 13, 246–260. https://doi.org/10.1002/bse.414.

Van Opstal, W., Smeets, A., 2022. Market-Specific Barriers and Enablers for Organizational Investments in Solar PV—Lessons from Flanders. Sustainability 14, 13069. https://doi.org/10.3390/su142013069.

Van Opstal, W., Smeets, A., Duhoux, T., Le Blévennec, K., Gillabel, J., 2021. Mid-term Report on Co-created Business Models. VITO, Mol.

Van Summeren, L.F.M., Wieczorek, A.J., Verbong, G.P.J., 2021. The merits of becoming smart: How Flemish and Dutch energy communities mobilise digital technology to enhance their agency in the energy transition. Energy Res. Soc. Sci. 79, 102160. https://doi.org/10.1016/j.erss.2021.102160.

Verbruggen, A., 2004. Tradable green certificates in Flanders (Belgium). Energy Policy 32, 165–176. https://doi.org/10.1016/S0301-4215(02)00262-8.

Verbruggen, A., Laes, E., 2021. Early European experience with tradable green certificates neglected by EU ETS architects. Environ. Sci. Pol. 119, 66–71. https://doi.org/10.1016/j.envsci.2021.02.013.

Vimpari, J., Junnila, S., 2019. Estimating the diffusion of rooftop PVs: A real estate economics perspective. Energy 172, 1087–1097. https://doi.org/10.1016/j.energy.2019.02.049.

Vine, E., 2005. An international survey of the energy service company (ESCO) industry. Energy Policy 33, 691–704. https://doi.org/10.1016/j.enpol.2003.09.014.

Vourdoubas, J., 2015. Possibilities of using renewable energy sources for covering all the energy needs of agricultural greenhouses. Journal of Agriculture and Life Sciences 2, 111–118.

Wolske, K., 2020. More alike than different: Profiles of high-income and low-income rooftop solar adopters in the United States. Energy Res. Soc. Sci. 63. https://doi.org/10.1016/j.erss.2019.101399.

Wolske, K.S., Stern, P.C., Dietz, T., 2017. Explaining interest in adopting residential solar photovoltaic systems in the United States: Toward an integration of behavioral theories. Energy Res. Soc. Sci. 25, 134–151. https://doi.org/10.1016/j.erss.2016.12.023.

Yang, M., Evans, S., 2019. Product-service system business model archetypes and sustainability. J. Clean. Prod. 220, 1156–1166. https://doi.org/10.1016/j.jclepro.2019.02.067.

Zink, T., Geyer, R., 2017. Circular Economy Rebound. J. Ind. Ecol. 21, 593–602. https://doi.org/10.1111/jiec.12545.