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# Towards a Circular Photovoltaic Economy: The Role of Service-based Business Models

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**Keywords**: Photovoltaics, Circular Economy, Business Model, Product-service System.//

**Abstract**: Solar photovoltaics (PV) has experienced tremendous market growth and has large potential in the urgently needed transition towards a low-carbon energy system. The continued growth of the sector will, however, evoke new sustainability challenges with regard to efficient material use as well as end-of life management of PV products. The aim of this paper is to provide an overview of potential Circular Economy actions in the PV sector, and explore the present and potential future role of service-based business models in operationalizing these actions. Based on a review of academic and industry literature, the paper structures the circularity actions according to the ReSOLVE framework. The analysis also distinguishes between the role of product-oriented, use-oriented and result-oriented product-service systems (PSS). Results show that to result-oriented business models have primarily been implemented in order to facilitate the adoption of PV deployment. Product-oriented PSS are widespread with the service component involving maintenance, repair, insurance and warranties. The paper further explores opportunities of service-based business models to enhance additional circularity actions such as a sharing, optimisation and looping, which so far are mostly in a conceptual or pilot stage only. Expanding beyond current practices, the paper explores future pathways of service-based business models to catalyse a range of additional circular economy actions in the PV sector, and discusses some of the associated key challenges and gaps in knowledge.

## Background

Amongst the various renewable energy technologies, solar photovoltaics (PV) is anticipated to become one of the fastest growing markets. Despite its significant potential in contributing to low-carbon electricity generation, the sector's reliance on linear business model logics undermines its full sustainability potential. In particular, as PV markets will continue to expand, so will the volume of discarded PV products entering the waste stream. End-of-life PV module waste is projected to increase to over 60-78 million metric tons cumulatively by 2050 (IRENA, 2016). Although interest in the research and policy community towards more circular practices in the PV sector has gradually increased, implementation remains constrained by a bundle of policy, economic, social and market barriers. Specifically, lack of profitability, absence of regulatory incentives, weakly developed collection and recycling infrastructures, as well as missing coordination between market stakeholders, inhibit material flow looping in the PV sector (Salim et al. 2019). Hence, there is a great potential to develop circular business models for the solar industry that allow for closing and slowing resource loops, through strategies of repair, reuse, remanufacturing and recycling (Bocken et al., 2016).

## Purpose

Innovative business models that rely on the principles of product-service-systems (PSS) have been proposed as a key enabler to catalyse the transition towards a circular economy (Tukker, 2015). In the PV sector, leasing and third-party ownership business models, have already been in use for over a decade and they have been effective in reducing customer-sited barriers to PV adoption (Horváth & Szabó, 2018). More recently, attention has also been directed towards the role that service-based business models could play in enabling circular material flows in the PV sector. The European H2020 project CIRCUSOL ("Circular Business Models for the

Solar Power Industry”) aims to develop and validate the market viability of second-life PV products through a co-creative approach with end users and the entire value chain. Yet, a systematic analysis about the full potential of service-based business models as an enabler for a circular economy with focus on the photovoltaic sector is missing. For this rapidly expanding sector, a review of circular economy strategies such as optimization, repair, life-time extension and sharing, is lacking. As a first step towards a more comprehensive understanding, the objective of this paper is to provide a more holistic perspective on the opportunities for a circular economy in the PV sector through service-based business models.

## Methods

We develop an overview of current and potential circular service business models for the solar industry, building on business model and solar photovoltaics literature, as well as initiatives observed in industry. Data collection comprised of a review of the academic and grey literature on industry practices in PV deployment, business models, operation, and end-of-life management. Furthermore, to gain insights into recent industry and R&D efforts towards CE in the PV sector, the data collection also involved a review of relevant R&D projects co-funded by the European Horizon 2020 programme during 2014 – 2019.

The analysis is structured according to the six dimensions of the ReSOLVE framework, used in circular business model literature before (e.g. Lewandowski, 2016), distinguishing between the business actions of (1) regeneration, (2) sharing, (3) optimization, (4) looping, (5) virtualizing, and (6) exchange (EMF, 2015). Secondly, the paper analyses how service-based business models can catalyse these business actions in the deployment, use-phase and end-of-life management of PV systems. In this analysis we distinguish between product-oriented, use-oriented and result-oriented services.

## Results

Table 1 provides an overview of our preliminary analysis how the business actions of the ReSOLVE framework could be applied across the entire PV value chain (manufacturing, distribution, distribution and installation, use-phase, end-of-life management). Closing loops for PV products, components and materials will require the development of circular product management strategies, including the redesign of PV products for circularity and the development of quality management schemes for second-life components. Besides, optimisation of the PV system performance can be established through the deployment of high-quality planning, installation, monitoring and maintenance practices. The action of sharing refers to the supply of excess PV electricity to other users, amongst others. Furthermore, PV systems can deliver virtual value, for example by providing grid-supporting services as well as performance data through established ICT platforms. Building on the established ontology of the ReSOLVE framework, we propose to add the cross-cutting action category “facilitate” to the framework. Facilitate involves the reduction of customer-sited barriers for the adoption and use of circular PV-systems.

To date, service-based business models have already been widely used to operationalize a number of these aforementioned business actions. Result-oriented PSS – sometimes also referred to as fee-for-service models – have been instrumental in facilitating PV adoption in a number of geographies. Particularly, in low-income countries these models have catalysed rural off-grid electrification by removing the up-front cost barrier of PV (Muchunku et al., 2018). Similarly, they have catalysed the development of the U.S. solar market (Drury et al., 2012), as they enabled the adoption of PV with low consumer transaction costs, leading to immediate electricity bill savings, along with minimal technical risk during installation and operation (Strupeit & Palm, 2016). In terms of optimizing operation, PV systems deployed under result-oriented PSS were found to exhibit superior operational performance as compared to systems directly owned by the user (Guajardo, 2018). While this could indicate the prevalence of least-life cycle cost thinking on behalf of the solar service firm, empirical evidence that could confirm this hypothesis is scarce and inconclusive. In fact, it has been found that the performance of PV systems deployed by a major U.S. solar service firm is below market average, possibly due to the firms’ rapid market expansion strategy that placed less emphasis on quality and operational efficiency (Wang, 2017).

| | Description | Value chain stage | | | |
|---|---|---|---|---|---|
| | | R&D and manufacturing | Distribution & installation | Use-phase | End-of-life |
| Regenerate | Shift to renewable energy and materials | Design PV products by making use of renewable materials (e.g. wood-made mounting structure) | | | |
| Regenerate | Reclaim, retain and regenerate health of eco-systems | | Use (industrial) wasteland for on-ground PV systems | | Regenerate land used for on-ground PV systems |
| Share | Maximise utilisation of products by sharing them among users | | | Supply excess electricity to other users; facilitate demand side management/and sharing of storage/ capacity at community level | |
| Share | Prolong life through maintenance, repair and design for durability | Design of PV products for reparability and long life/ | Ensure selection of high-quality PV products and high-quality PV installation/ | Enable systematic monitoring & preventive maintenance | |
| Optimise | Increase performance/ efficiency of a product | Increase conversion efficiency of PV modules and inverters; develop building-integrated modules with multiple functions | Ensure high-quality PV installation | Enable preventive and high-quality maintenance; minimize PV system/ downtimes | |
| Optimise | Remove waste in production and the supply chain | Use PV products with secondary quality; reduce/ production scrap in cell manufacturing; / optimise/PV manufacturing/ | Make efficient use of distribution infrastructure; minimize transport damage. | | |
| Optimise | Leverage big data, automation, remote sensing and steering | | Track and trace single PV components | Gather and analyse data of PV yield and performance | Track and trace single PV components |
| Loop | Product reuse or redistribution | Design PV products/ for easy disassembly | Use/PV products/for/ second-life applications | | Enable appropriate disassembly, collection and refurbishment of PV products to facilitate reuse |
| Loop | Product repair, refurbishment or remanufacture | Design PV products/ for easy disassembly/and repair | Remanufacture products disused in other sectors for use in PV applications (e.g. EV batteries) | Use second-hand products/ components/as spare parts | Enable appropriate disassembly, collection and refurbishment of PV products to facilitate reuse |

| | | | | | |
|---|---|---|---|---|---|
| | Product recycling | Design PV products/ for easy disassembly | | | Enable appropriate collection and recycling of PV products |
| **Virtualise** | Deliver utility virtually | | Use IT for planning and/permitting of PV systems | Use IT for remote monitoring, fault detection, and yield optimization | Use IT for second-life product management |
| **Exchange** | Replace old materials with advanced non-renewable materials | Replace scarce materials (e.g. silver) with more abundant materials (e.g. copper) | | | |
| | Apply new technologies | | Catalyse market introduction of/novel PV technologies | | |
| **Facilitate** | Remove/// reduce customer-sited barriers for/ (circular) PV/ adoption | | Reduce/user-sited/ transaction costs and risks/associated with planning and installation | Reduce/user-sited/ transaction costs and risks/associated with operation and maintenance | Reduce/user-sited/ transaction costs and risks/associated with end-of-life management |
| | Remove barriers to upfront finance | | Provide financing for upfront investment | | |

**Table 1. Overview of current and potential business actions towards a circular economy in the photovoltaic sector.**

Note: Since not all CE actions are applicable to all value chain stages, certain table cells/remain blank.

Actions based on Adhya et al. (2016), Ahlgren Ode & Lagerstedt Wadin (2019); ApollonSolar (2019); Behrangrad (2015); BestRes (2019); Brenner & Adamovic (2017); CIRCUSOL (2018); Drews et al. (2007); Drury et al. (2012); EcoSolar (2017, 2018a, 2018b); Einhaus et al. (2018); Guajardo (2018); Hamwi & Lizarralde (2017); Horváth & Szabó (2018); IRENA (2017), Kim et al. (2019); Klise & Balfour (2015); Lam & Yu (2016), Muchunku et al. (2018); Müller & Welpe (2018); Peeters et al. (2018); PVADAPT (2019); Rogers (1999); Mukhopadhyay & Suryadevara (2014), Schmidt-Costa et al. (2019); Sharma et al. (2016); Sica et al. (2018); SolarPower Europe (2018); Strupeit & Palm (2016); SuperPV (2019); Tang et al. (2018); Rai et al. (2016); Rai & Sigrin (2013); Vanadzina et al. (2019); Wainstein et al. (2017), Wambach (2017); Wang (2017); Woyte et al. (2014); Xu et al. (2018).

While this set-up potentially could facilitate life-time extension or controlled collection and end-of-life management of PV systems, little empirical/ evidence exists, presumably due to the still relatively novel character of/ the business model. A variant of the result-oriented PSS model are use-oriented PSS, generally referred to as leasing models in which the property owner (as lessee) pays to use the equipment instead of purchasing the generated power. In the U.S., solar PV/leasing is often used in states that do not allow power-purchase agreements inherent to the result-oriented PSS (Ardani & Margolis, 2011).
Still, in most solar markets,/ product-oriented PSS are the dominant mechanism for PV deployment. In this model, solar firms, in addition to selling a PV system to users, also deliver a set of product-related services, such as maintenance, repair, insurance and warranties (Strupeit & Palm, 2016). In general, a key benefit of service-based business models is the opportunity to gather valuable data on performance and service needs on a large number of systems, thereby enabling incremental optimization of system design and operation (Rogers, 1999). It also allows for easier repair, reuse and recycling and other life cycle benefits (Tukker, 2015). In the market segment for commercial and utility-scale PV, systematic monitoring and preventive maintenance is fairly common, seeking to maximise PV yield and reduce system downtimes. Service contracts/ typically have some result-oriented elements such as minimum availability, guaranteed response

times and performance-based reimbursements (Klise & Balfour, 2015; SolarPower Europe, 2018). Despite its potential to optimize PV yield, systematic maintenance services in the residential PV market are much less widespread yet (Peeters et al., 2018), due to issues with data availability and quality, less favourable economics, and a different set of PV users who typically are not solar professionals (SolarPower Europe, 2018).

Across these market segments, a well-established type of maintenance service is the repair of high-value components of PV systems, in particular inverters, which are either repaired either repaired onsite (high wattage central inverters) or in a workshop at the original equipment manufacturer or at third-party firms (low wattage string inverters). Conversely, repair of defect modules is often financially not viable under present market conditions and the continued price reductions for newly manufactured modules. Still, a niche market for second-hand modules exist in the spare parts segment, in particular when a specific module type is not manufactured anymore but can be in high demand to replace a defect module of the same type.

Novel approaches to operationalize circular economy practices in the PV industry through service-based business models are currently investigated and tested. The CIRCUSOL research project aims to catalyse market development for (1) the reuse of PV modules for a second-life application and (2) the remanufacturing of disused electric vehicle batteries and their recirculation to the market in stationary PV systems. Here, the intended role of a service-based business model approach is to enable coordinated product management (collection, sorting, refurbishment, testing, certification) and mitigate user concerns about the reliability, performance and lifetime of second-life PV products.

Exploring opportunities beyond current practices, service-based PSS can potentially catalyse various other circular economy actions in the photovoltaic sector, thereby reducing the specific material footprint per kWh of solar electricity delivered. For example, opportunities exist in maximising the utilisation of PV systems, by sharing excess electricity with other users through micro-grids, aggregations service and trading platforms (BestRes, 2019; Wainstein et al., 2017), as well as by enabling the sharing of electric storage capacity at the community level (Müller & Welpe, 2018; Tang et al., 2018). Delivery of these actions would require the coordination of responsibilities across several partners of the value chain, a role that a solar service firm potentially can adopt.

Service-based business models could also catalyse the market introduction of novel product technologies with a lower environmental footprint, in particular by transferring the risks that users might associate with new product design towards the solar service firm. Examples of products might include novel module technologies that are designed for efficient and low-cost disassembly at the end of life (Einhaus et al., 2018), or mounting structures that make increased use of renewable materials (EcoSolar, 2018a).

## Challenges and gaps in knowledge

Current efforts to repair, reuse or remanufacture PV modules are compounded by practical and economic difficulties. Firstly, at present the availability of modules to be refurbished for second-life use is fairly limited, although this is expected to change in the forthcoming decade with an increasing number of modules reaching an age of 20 years or more. Secondly, the market value of used PV modules remains unclear, in particular as new modules will be available at declining cost levels and competition from novel module technologies may emerge. Furthermore, the market acceptance and business viability of service-based models with a clear circularity focus remains to be further tested.

The review has identified various challenges and gaps in knowledge. Firstly, PV-systems are designed as a long-life product and trade-offs between optimisation and looping may exist. In particular, a better understanding is required whether and when the repowering of PV installations makes financial and environmental sense. Optimizing PV systems from a least-life-cycle cost perspective requires comprehensive data sets. Given the fragmented nature of the market and the relative long operational lifetime of PV systems, improving data resolution and quality is faced with significant challenges.

It is also important to recognized the limitations of service-based business models in operationalizing circularity actions in the PV sectors, and simultaneously acknowledge the need for complementary mechanisms and approaches. For example, implementing circularity in the upstream part of the value chain economy is generally beyond the scope of more deployment-centred business models.

## Contributions

Building on earlier research on the role of PSS as an instrument towards a resource-efficient, circular economy, the novel contribution of the paper is the investigation of service-based business models for a long-life product in distributed renewable energy production. The findings show how service-based business models could help integrate currently fragmented responsibilities and knowledge areas across the PV value chain and thereby remove split incentives, exploit least-life-cycle-cost thinking and benefit from scale and learning effects in circular product management. For practitioners in the PV sector, the paper aims to provide an overview to identify opportunities for circular service-based business concepts.

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