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# Circular business models and supporting policies for reusing of photovoltaic modules in the EU

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**Abstract**:
Renewable solar energy is essential to achieve the Paris climate agreement. The EU faces two main challenges. First, the increased photovoltaic (PV) capacity installed today will result in enormous amounts of waste at the end-of-life of PV modules. Second, the EU is currently dependent on the imports of PV modules, manufactured outside the EU using fossil fuel sources and critical raw materials. Circular strategies (i.e., reduce, reuse, recycle) may help address these challenges. Here, we focus on reuse, which according to the EU waste framework directive should be prioritized over recycling. Based on a review of academic and industry literature and exploratory interviews with industry stakeholders and policymakers, we shed light on the reuse business models of PV modules, and the EU policy context. Four main reuse business model archetypes were determined: (1) opportunity-driven diversifier; (2) socially-driven orchestrator, (3) turnover-oriented trader, and (4) state-appointed collector. All reuse business models are shaped by the EU policy landscape. This landscape includes the upcoming Ecodesign requirements for new PV modules placed on the market; the directive on Waste from Electrical and Electronic Equipment (WEEE) determining end-of-life requirements; and in between a regulatory gap related to enforcing potential reuse activities. The identified circular business model archetypes and EU policies are finally discussed to inform potential future research, business, and policy actions to make the European PV industry more circular and resilient.

## 1. Introduction

The deployment of renewable energy sources has been growing significantly in recent years (IRENA, 2022). As one of the most important renewable technologies, solar photovoltaic (PV) power is experiencing a remarkable acceleration reaching 209 gigawatts (GW) of installed capacity by 2022 in Europe (SolarPower Europe, 2022). At this rate, the predicted 891 GW by 2050 may be overtaken (IRENA, 2019; SolarPower Europe, 2022).

This boost in PV deployment entails two key challenges. The first challenge relates to finding adequate solutions for the waste generated by end-of-life PV modules. Projections estimate up to 33 million tons of end-of-life PV modules by 2050 in Europe alone (Czajkowski et al., 2022). Second, the demand for PV creates import dependencies for raw materials as well as PV modules and therefore supply vulnerabilities (Carrara et al., 2020; European Commission, 2022a).

To address both challenges, circular economy (CE) strategies become a key driver. Reduce, reuse, and recycle (3R) are most relevant in the PV industry (Komoto & Lee, 2018; Rabaia et al., 2022). Reduce includes all activities related to material savings through increased resource efficiency, or avoidance of (especially hazardous) materials (Weckend et al., 2016). Reduction activities are either economically motivated (Fraunhofer ISE, 2023) or regulatory motivated, if e.g. hazardous substances have to be disclosed (European Commission, 2020; European Environment Agency, 2021). Reuse includes all activities related to the preparation for reuse as second-hand modules, including PV module collection, transport, storage, cleaning, quality testing as well as simple repair operations like bypass diode(s) or cable connector replacements (Tsanakas et al., 2020; van der Heide et al., 2022). Reuse activities are so far practiced only in niche areas and are not yet considered profitable on a large scale, but are expected to

increase significantly in the future (Deutsche Umwelthilfe, 2021; van der Heide et al., 2022). Finally, recycling includes all activities related to disassembly and delamination of PV modules, as well as material sorting and extraction (Deng et al., 2022). Since the majority of PV module recycling practiced today is downcycling, the recycling of PV modules is still in its infancy, with both technical and non-technical hurdles (Czajkowski et al., 2022; Salim et al., 2019). The legal frame for recycling is provided by the Waste from Electrical and Electronic Equipment (WEEE) directive, which sets targets for collection, recovery, and recycling of PV modules (Chowdhury et al., 2020).

Research on PV end-of-life management is predominantly focused on recycling despite this being the least preferred option in the waste hierarchy (Komoto et al., 2022; Salim et al., 2019). In contrast, little research focuses on PV reuse because of insufficient economic incentives and an unknown legal design framework (Komoto & Lee, 2018; van der Heide et al., 2022). However, estimates suggest that up to 50% of the PV waste modules are suitable for reuse. Thereof, a considerable part are PV modules that have defects upon production or transportation, which therefore have never been installed, and PV modules with infantile failures over the first four operational years (Tsanakas et al., 2020). A substantial amount of those PV modules suitable for reuse is, however, expected to be bypassed by the collection systems as the total amount of collected PV modules in the European Union reported to WEEE is still low compared to the expected amounts (Deutsche Umwelthilfe, 2021; van der Heide et al., 2022). This significantly reduces the volumes for reuse and recycling as PV modules are exported to non-European countries as first reports on emerging illegal trade and disposal of PV modules indicate (INTERPOL, 2020).

This paper aims to contribute to the PV module reuse research stream by mapping current reuse business models against the relevant policy context. Since the preferred end-of-life management of PV modules is closely interlinked with regulatory interventions a holistic approach analysing the current state of reuse activities from a business model and policy perspective is chosen. Specifically, we show which business models prevail and which policies are in place or planned that affect reuse activities.

## 2. Method

To map current reuse business models against a policy context and analyse the current state of PV module reuse we applied an exploratory research design. Exploratory research consists of a broad-ranging, purposive, and systematic attempt to discover something new, and leads to an understanding or description of an area (Stebbins, 2001). We chose a multi-method research design to explore immature concepts that need to be described (Creswell, 2014; Morse, 1991). We first conducted desk research, followed by expert interviews.

For the desk research we analysed the emerging research landscape around CE in the PV industry, especially concerning the end-of-life management of PV modules. Besides the academic literature also non-academic literature such as company documents, industry reports, policy documents or whitepapers were considered. For the expert

| No. | Role | Organization | Business model (BM or policy (P) |
|---|---|---|---|
| 1 | Senior researcher | European University | P |
| 2 | Policy officer | European Institution | P |
| 3 | Consultant | Extended producer liability consultancy | BM |
| 4 | Policy officer | European Institution | P |
| 5 | CEO | PV marketplace | BM |
| 6 | CEO | Take back scheme | BM |
| 7 | Project manager | Recycler | BM |
| 8 | Senior researcher | European University | P |
| 9 | CEO | PV marketplace | BM |
| 10 | Policy officer | European Institution | P |
| 11 | Policy officer | European Institution | P |
| 12 | Project manager | Recycler | BM |

**Table 1. Interviewee's role, organization, and type**

interviews we conducted semi-structured interviews with PV experts and stakeholders from industry and policymaking. A total of 12 expert interviews lasting about 1 hour on average were conducted in 2022 and 2023. Table 1 shows an overview of the interviewees.

The collected data was analysed by first familiarizing with the recordings and interview notes, followed by coding the data into initial segments, searching for broader themes, reviewing those themes, and naming those themes (Braun & Clarke, 2021). The steps were conducted individually by the authors and discussed periodically.

## 3. Results

### *3.1 Reuse business models in Europe*

Business models offering reuse, repair and refurbishment activities in the PV industry are gaining momentum. Although these business models, which are mainly carried out by organizations that have no connection to the original manufacturers, are currently seen as rather informal (European Commission, 2020), first business model types are emerging. Our results distinguish four reuse business model archetypes, which are shown in Figure 1.

Opportunity-driven diversifier

Opportunity-driven diversifiers generate value by providing PV system owners an alternative to recycling, which is in line with CE principles of slowing the loop and – more importantly – reduces disposal cost (interviewee 3). This alternative is reuse: by feeding back some of the decommissioned PV modules into reuse, the opportunity-driven diversifier reduces recycling fees for the system owner and opens a new business opportunity for him/herself (interviewees 7, 12).

Socially driven orchestrator

The value proposition of the socially driven orchestrator is to allocate written-off PV modules from commercial companies to social projects through the orchestration of a vast network of partners. On the one hand, this allows commercial companies to present themselves as socially and ecologically responsible without making a financial commitment (interviewee 9). And on the other hand, social projects profit from fully tested, circular reuse PV modules at a reduced price compared to new modules (interviewee 9).

Turnover-oriented trader

The turnover-oriented trader offers PV system owners hassle-free disposal of their PV modules at the end of their service life, while also avoiding the recycling fee. The value proposition is largely profit-oriented without positive impact on people and planet (interviewees 3, 7). Value is created by shipping the PV modules to non-European countries, often without testing all PV modules or testing at all (interviewees 7, 8, 9, 11).

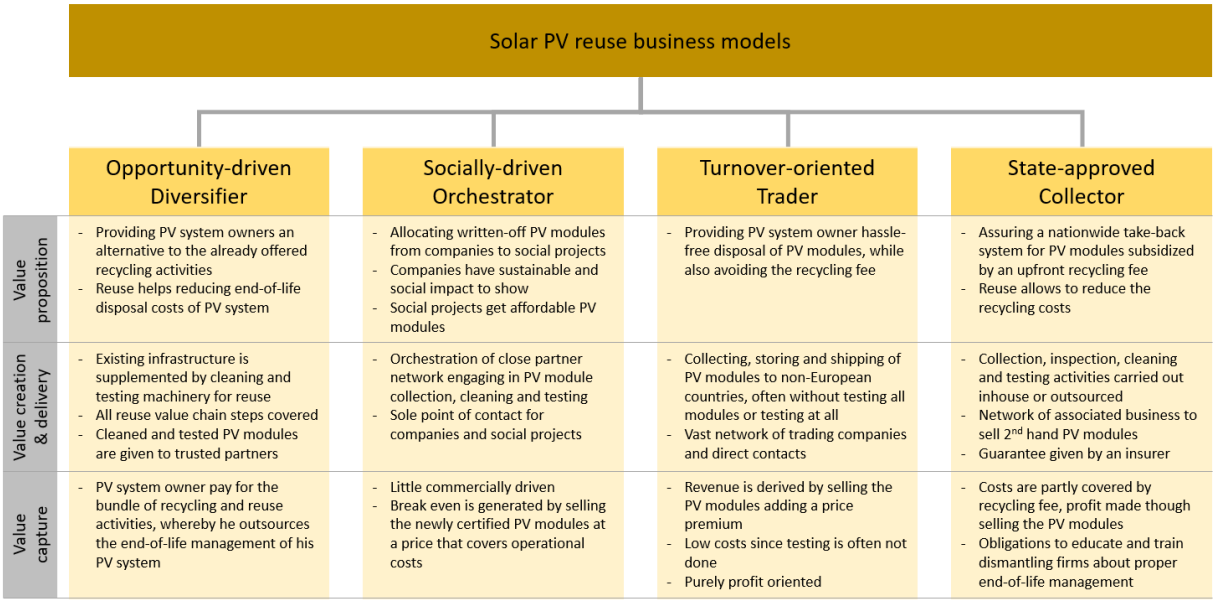


**Figure 1. PV reuse business models**

State-appointed collector

The value proposition of the state-appointed collector is rather directed at the state then other stakeholders, as he ensures a nationwide take-back system for PV modules, which is subsidized by an upfront recycling fee (interviewee 6). Out of the PV modules coming into the collection streams a certain amount is foreseen for reuse (interviewees 3, 6).

Overall, reuse business models for PV modules are accelerating across Europe. Different business model archetypes emerge, which are often also shaped by the respective regulatory environment. As waste streams increase, reuse business models will continue to evolve and adapt.

### *3.2 Policy context for reuse in Europe*

The emergence of CE business models for PV reuse is influenced by the policy and regulatory context. For PV reuse the regulatory context primarily includes upcoming Ecodesign requirements for new PV modules placed on the market and the WEEE directive determining end-of-life requirements. The interviews allowed to crystallize the understanding of policy and regulatory context.

Ecodesign regulation

When new PV modules are placed on the market, the EU envisages new regulations under the name of Ecodesign, which are now being developed (interviewees 8, 11, 12). According to a preparatory study (European Commission, 2020) and a discussion paper (European Commission, 2021), the Ecodesign regulation for PV modules aims: (1) to foster long-term energy yield based on information requirements and a quantitative threshold; (2) to introduce stringent quality and durability tests to withstand prolonged exposure in open-air climate; (3) to set the basis for a unified long-term performance degradation calculation by setting definitions, calculation boundaries and disclosure requirements; (4) to ensure potential repairability of PV modules through a reporting requirement of how to access and replace bypass diodes or the whole junction box; (5) to enable higher recyclability by setting reporting requirements on the dismantlability of certain product components and the material disclosure of selected raw materials: (6) to establish a standardized basis of the ecological profile of PV modules based on a life cycle assessment approach focusing mainly on the global warming potential, also referred to as the carbon footprint. Going forward towards legally binding actions for PV modules, emphasis is expected to be placed on: (1) resource efficiency requirements; (2) carbon footprint requirements; (3) and information requirements (interviewees 9, 10, 11).

Directive on Waste from Electrical and Electronic Equipment

The WEEE directive introduced by the European Commission in 2012 comes into play at the time the PV modules are withdrawn from the market (interviewees 1, 11). The purpose of the WEEE directive is to contribute to sustainable production and consumption through avoidance, reuse, recycling, or other forms of recovery of such waste (European Union, 2012). PV modules fall under the category four and therefore have a minimum target of 85% recovery rate, whereof 80% shall be reused and recycled (European Union, 2012). Even though PV modules are covered

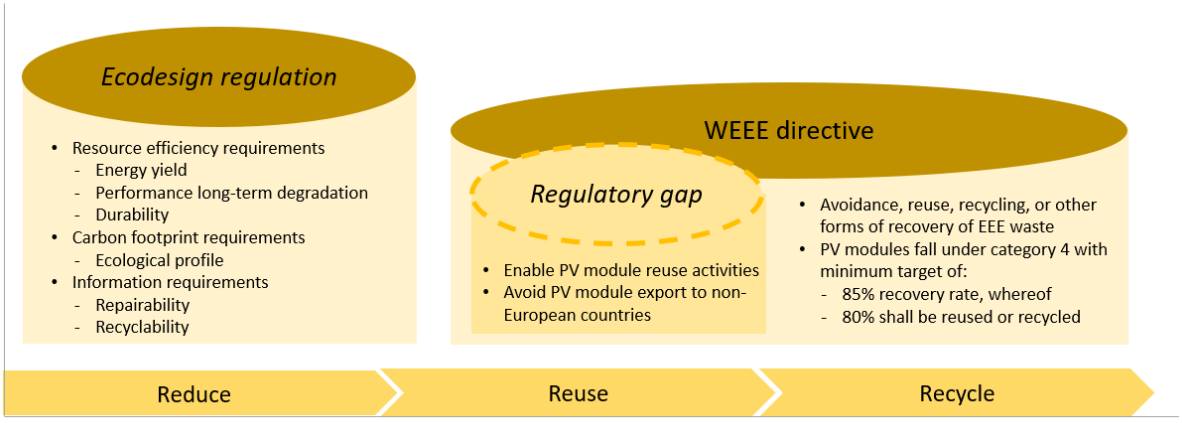


**Figure 2. Policy context of CE activities (reduce, reuse, recycle)**

by the WEEE directive, the regulation is not directly and specifically focused on PV modules (interviewees 4, 8). Only by 2019 PV modules are foreseen to be reported as a separate category as laid down in an implementing decision (European Union, 2019).

Regulatory gap related to enforcing potential reuse activities

Figure 2 shows the different policies elaborated in the context of CE activities (reduce, reuse, recycle).

Neither the upcoming Ecodesign regulation nor the WEEE directive address the enforcement of reuse activities directly (interviewees 8, 10, 12). The resource efficiency requirements within the Ecodesign regulation might foster the durability of PV modules and therefore more potential usage cycles. Additionally, the information requirements on repairability of PV modules might foster reuse activities (interviewees 2, 8, 10). However, the information requirements are not linked with specific mandatory reuse actions and PV modules are seen as difficult to repair comprehensively in practice (interviewees 5, 7). The WEEE directive on the other side, includes reuse as an option to deal with electrical and electronic equipment (EEE), but foresees no distinguishment between the final end-of-life strategy, meaning between reuse and recycling (European Union, 2012). As a result, adequate data on reuse activities are not yet available, which makes a quantification of reuse activities in Europe nearly impossible (interviewees 3, 5). Since reuse is not statistically reported, nor mandated by the WEEE Directive and generally not considered financially viable, most PV modules are steered towards recycling (interviewees 3, 6, 8, 11).

It can therefore be stated that there is, to date, no mandatory legislation to enforce reuse of PV modules (interviewees 8, 9, 11). As a result, PV modules in today's PV industry still circulate very little as second-hand modules as envisaged in the CE (interviewees 2, 6, 10). This comes in combination with different challenges: (1) PV module reuse business models are currently still niche and therefore policy awareness is low; (2) outflow of PV modules is high due to extensive trade with non-European countries; and (3) reuse and recycling players compete for volume to make their business models profitable (interviewees 4, 5, 7, 8, 9). From a CE perspective this is problematic, as no regulatory incentives are given to reuse activities, which generally are prioritized over recycling according to the EU waste framework directive. From the point of view of businesses operating in the field of reuse, there are uncertainties regarding the legal spheres of operation of their business models.

Overall, the regulatory context for PV module reuse business models is tenuous and current policies might not allow scaling up on the industry side. To promote activities that are considered preferable to recycling from a CE perspective, appropriate regulatory frameworks might be needed going forward (Figure 2).

## 4. Discussion and Conclusion

The aim of this paper is to investigate circular economy models based on reuse in the PV industry against the background of EU policy. Despite the drain of a significant amount of PV modules suitable for reuse to non-European countries, reuse business models in Europe are gaining some momentum. Four main reuse business models have been identified, namely the opportunity-driven diversifier, the socially-driven orchestrator, the turnover-oriented trader, and the state-approved collector.

All four business model archetypes are expected to accelerate as PV module waste grows considerably in the upcoming years. However, the relevance of the CE regulatory context, current and foreseen legislative measures might not yet directly support the emergence of reuse business models. Neither the upcoming Ecodesign regulation, which sets rules for placing new PV modules on the market, nor the existing WEEE directive, which determines end-of-life requirements for EEE, contain mandatory measures to catalyse the emergence and scaling of PV reuse business models, to date.

This regulatory gap could be problematic for three reasons. First, it might lead to an indirect prioritization of recycling over reuse through the WEEE directive, which is conceptually in contrast with the EU waste hierarchy framework. Second, the inherent circularity potential might not be fully realized, which could have a negative impact on strategic dependencies. Relatedly, the export of PV modules to non-European countries leads to the export of valuable materials (e.g., aluminium) that are then not available as input factors, again aggravating import dependencies, but also shifts the waste problem to countries that do not have the

infrastructure to adequately deal with this waste. The understanding of the identified reuse business model archetypes is therefore of upmost importance to develop reasonable regulatory interventions, which support those business models that are in line with the overall CE aims of the EU. Figure 3 shows the elaborated relationships and dependencies.

This paper has implications for different stakeholders. Business practitioners will learn four business model patterns for value generation in reuse and best practices to better assess their own stage of development. Policy makers can gain insight into the effective activities and challenges in the reuse business that can be included when considering new regulations or adapting existing ones. To research in the renewable energy field, the paper contributes by analysing emergent circular business models simultaneously against their policy background, by using PV as a case study.

This paper comes with limitations, mainly regarding to its exploratory approach and restricted scope. Further research is needed to examine the business models and corresponding policy context of reuse activities around PV modules in Europe. First, the estimated material flows indicated in Figure 3 should be quantified to get a better understanding of the underlying business models and accurate policy measurements. Second, further research should focus on impeding aspects that complicate the activities of reuse business models, namely issues of product safety, the lapse of warranties, the question of future liabilities, the influence of feed-in tariff agreements, and the importance of the cost of balance-of-systems components. In doing so, research should, thirdly, assess reuse business models from a more holistic perspective, assessing the reuse potential of PV modules also from a demand perspective.

## Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

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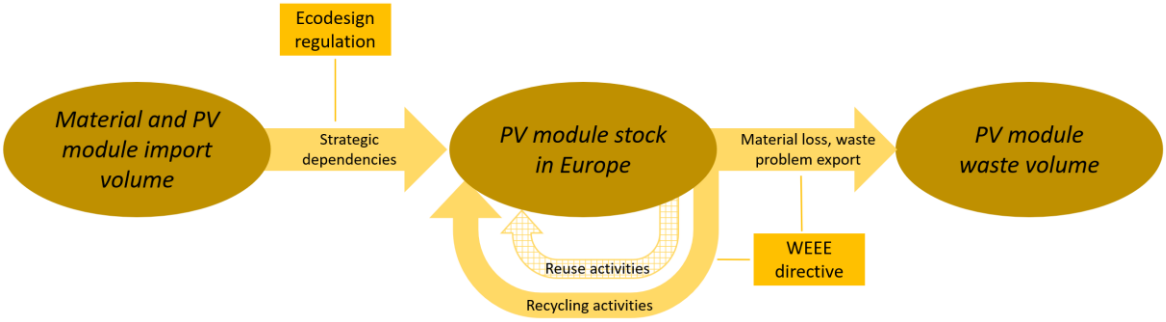


**Figure 3. Implications on PV reuse business models and related policies**

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