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Circular Business Models for the Solar Power Industry - Guide for Policy Makers

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Abbreviations

B2B	Business-to-business
B2C	Business-to-consumer
BMS	Battery management system
CAPEX	Capital expenditures
CdTe	Cadmium Tellurite
CE	Circular Economy
CED	Cumulative energy demand
CENELEC	European Committee for Electrotechnical Standardization
CRMs	Critical raw materials
DSO	Distribution System Operators
EEE	Electrical and Electronic Equipment
EOL	End-of-life
EPR	Extended Producer Responsibility
EV	Electric vehicle
EVB	Electric vehicle battery
FTE	Full-time equivalents
GHG	Greenhouse gas emissions
GPP	Green Public Procurement
GW	Gigawatts
GWh	Gigawatt hours
IEC	International Electrotechnical Commission
LCA	Life Cycle Assessment
LCOE	Levelized cost of energy
LFP	Lithium-iron phosphate
LIB	Lithium-ion batteries
NIBs	Sodium-ion batteries
O&M	Operating and maintenance
OEMs	Original equipment manufacturer
PGMs	Platinum group metals
POM	Put on the market
PSS	Product-service-system
PV	Photovoltaic(s)
REEs	Rare earth elements
ROI	Return-on-investment
SMEs	Small and medium-sized enterprises
SSBs	Solid-state batteries
WEEE	Waste Electrical and Electronic Equipment
Wp	Watt peak

Executive Summary

Background and scope

Solar power and electric vehicles (EV) are set to play a leading role in the achievement of the 2030 EU renewable targets and the commitment to carbon neutrality by 2050. Importantly, solar photovoltaics (PV), in combination with energy storage, also has the potential to significantly enhance European energy security, provide citizens and industry with competitive energy, and lead to the creation of thousands of jobs in manufacturing, installation, maintenance, and end-of-life management. While the expected rapid growth of the solar power sector over the coming decade will bring along various resource and waste management challenges, following a circular economy strategy can ensure that these will be handled in a proactive and future-proof manner. Furthermore, a circular economy approach will offer the European solar industry new business opportunities in the design and manufacturing of circular-ready products, as well as in the reuse, refurbishment and recycling of older solar panels.

In response to the emerging resource and waste challenges of the solar power and battery sectors, the CIRCUSOL Innovation Action project (funded by the Horizon2020 programme of the European Commission) explored a number of innovative approaches and strategies towards circular business models in these two sectors. Specifically, the project focused on four circularity strategies: (1) reuse of discarded PV panels in second-life applications, and enabled through service-based business models; (2) repurposing of EVBs in second-life applications, specifically for stationary storage of solar power, and enabled through service-based business models; (3) ecodesign of PV panels; and (4) recycling of PV panels through innovative techniques.

This guide for policy makers is based on the lessons learned in the CIRCUSOL project from 2018-2022. It compiles key findings from the project and seeks to sketch out pathways and strategies on the way forward. As such, the report aims to contribute to a debate across policy makers, industry representatives, experts and other stakeholders about a potential future policy and governance framework that could catalyze the transition towards circular and resource-efficient solar power and EV battery sectors in Europe.

Feasibility and desirability of circularity in the PV sector

Assessments carried out within CIRCUSOL clearly show the technical feasibility to repair and refurbish defect and decommissioned PV modules, both onsite and offsite, and redeploy them in a second-life application, accompanied by generating social and environmental benefits. Modules experiencing early- and midlife failures are particularly suitable for this. Quality-testing and fast and low-cost repairs are possible and detailed guidelines and recommendations to ensure customer confidence in reuse modules are under preparation. Economic viability and customer acceptance in the EU is currently limited to few specific cases. Demand for second-hand exists outside Europe, and particularly in low-income regions with insufficient access to modern energy services, however, lack of appropriate local EOL treatment facilities in these regions can compromise the environmental benefits. Experience in CIRCUSOL with service-based business models as a catalyst for the deployment of reused modules was mixed. While such models were successfully implemented in some pilot projects, it was also found that many home owners have strong preferences for purchasing and owning a PV system.

Feasibility and desirability of electric vehicle batteries for stationary energy storage

Repurposing used EVBs for stationary storage applications has received increasing attention in recent years, as shown by an increasing number of research publication on the topic, as well as the deployment of numerous pilot projects around the world. In line with the experience in other pilot projects, the technical feasibility of repurposing discarded EVBs and deploying them in a second-life application for the stationary storage of solar power has been successfully demonstrated. Demand for stationary battery capacity will increase, due to continued diffusion of non-dispatchable renewable energy sources. Batteries, either new or repurposed, can also provide various grid services such as capacity support, distribution power quality or contingency grid support.

It is still debated under which conditions repurposed batteries will be able to be economically competitive with newly manufactured batteries in the stationary energy storage market. The cost advantage that repurposed batteries presently have over new batteries is expected to shrink, due to the continued learning curve and economies-of-scale in global battery manufacturing. Presently, the costs for repurposing are amplified through the lack of scale-economies and OEMs reluctance to permit repurposers access to the original battery management system. The environmental benefits of repurposing batteries need to be carefully assessed in order to gain a better understanding under which boundary conditions repurposing could be a desirable circularity strategy. Repurposing of batteries also faces competition from the recycling pathway, which would quicker recirculate battery raw materials into the manufacturing of new EVBs. Finally, the implication of next generation battery technologies on the availability of batteries suitable for repurposing, as well as on the market competitiveness of repurposed batteries in the stationary energy storage market are not well understood yet.

Government interventions and industry initiatives for a circular PV and EVB sector

This report provides an overview of the current status of measures taken by public and private entities which are of relevance for a circularity in the PV and EVB sectors. Cross-cutting government initiatives reviewed are the EU Waste Framework Directive, the so-called Basel Convention and corresponding EU law, policies related to critical raw materials, the EU Action Plan for the Circular Economy, the EU Eco-design Directive and green public procurement. Furthermore, and specifically with regard to circularity of PV modules, the report reviews the (1) the Waste Electrical and Electronic Equipment (WEEE) directive, (2) the preparatory study for the product group ‘solar photovoltaic modules, inverters and systems’ as prepared by the European Commission Joint Research Centre, (3) initiatives for labelling and certification protocols for second-life PV, and finally (4) ecolabelling initiative for PV modules. With regard to circularity of EVBs, the report reviews a number of government, industry and standardization initiatives, such as (1) the Batteries Directive, (2) the New Batteries Regulation Proposal, (3) ANSI/CAN/UL 1974 Standard for evaluation for repurposing batteries, (4) standardization initiatives at IEC and CEN-CENELEC, and (5) the CIRCUSOL battery assessment procedure. A number of the emerging initiatives are expected to addresses many of the issues identified in the CIRCUSOL project

Potential pathways forward

Based on the lessons learned in the CIRCUSOL project, as well as on the literature of barriers towards more circular PV and EVB sectors, the report offers ideas and suggestions on potential pathways forward. The 10 potential pathways forward discussed are:

Address premature defects and decommissioning: PV modules suitable for reuse in a second-life application primarily descend from early-and mid-life failures, damage from extreme weather events, other insurance claims, and early repowering. However, reducing the rate of early-and mid-life failures would be desirable. This could be achieved through the continued development of life-cycle quality management, including good operation and maintenance practices, and the encouragement of such practices through a variety of government and industry interventions.

Enhance design for circularity & recovery of critical raw materials: In general, PV modules and EV batteries have not been designed for repair, recycling and recovery of various components and materials, including critical raw materials. This in turn pose challenges to various operations to enhance circularity – repair and repurposing of these products, as well as recycling and recovery of components and raw materials. Design for circularity and recovery of critical raw materials could be enhanced through a variety of regulatory requirements, such as design specifications, stipulating specific recovery targets for critical raw materials or the use of recycled content, mandatory information provision and the use of a digital product passport, amongst others.

Advance preparation for reuse: To date, guidelines and standards for preparation of reuse of PV panels have been lacking, and those for repurposing of EV batteries for second-life is at its infant stage. CIRCUSOL has made key contributions to the development of guidelines and standards for preparation of reuse of PV panels, as well as repurposing of EV batteries. Various contributions on guidelines and standards for preparation of reuse of solar panels, as well as repurposing of EV batteries, such as those developed through CIRCUSOL, should be further adopted and mainstreamed. Further proposed actions to advance preparation for reuse could include (1) a regulatory mandate to provide of refurbishable PV panels to refurbishers, (2) stimulate the development and adoption of automation techniques for testing and re-certification in order to bring down the costs for these processes, and (3) development of guidelines and provision of hands-on training for workers for the dismantling of solar installations and for the transport and handling of modules, to ensure the quality and integrity of decommissioned modules that are suitable for reuse.

Establish data collection and sharing procedures: A key challenge facing the advancement of more effective recycling processes, repair, and re-use activities, as well as estimation of “active” installed PV capacity and track waste, and re-use volumes, is lack of reliable information. To address this challenge, establishing data collection and sharing procedures would provide firms across the value chain with relevant data to enable more effective reuse and recycling activities. In the CIRCUSOL project, a database facilitating the collection and sharing of relevant information was developed as a pilot platform. But this also requires manufacturers to disclose information and enable sharing, which could be mandated through governmental regulations.

Address legal-administrative barriers for service-based business models: In the CIRCUSOL project, demonstrator projects have experienced various types of legal-administrative challenges in the implementation of PSS / service-based business models. One example is the high costs and administrative effort involved for solar service firms to secure ownership rights of service-based PV systems in the cadastre registry. A potential alternative and solution to this present practice of costly and time-consuming entries in public cadastres would be the establishment of a dedicated European-wide registration system for PSS installations. Other type of legal-administrative barriers found can be very context specific, and depending on the

issue, will have to be addressed by making amendments in specific national and subnational legislation.

Investigate feasibility of reuse in underexplored EU market segments: In developed, high-incomes economies (such as the locations of the CIRCUSOL demonstrator sites), PV systems with new components remain the preferred choice, as consumers rely heavily on high efficiency, aesthetics, and warranties. In addition, low-financing costs and good availability of capital, particularly in the market segment of home owners, enable user to purchase new PV systems. There is also still a prevailing mentality for ownership among these user groups. As such, user interest in second-life PV and service-based business models has been found modest. Key actions proposed are to investigate the feasibility of reuse in underexplored EU market segments, such as the commercial and public sector. One concrete policy measure to enhance demand in this area is to enhance the uptake of green public procurement that incorporate the use of second-life PV panels and/or service business models as part of the awarding criteria. In addition, we propose further investigation of the market viability of second-life solar panels for novel applications such as agrivoltaics, floating PV, and off-grid solutions, as well as European countries with middle income levels, where reused panels potentially could play out their cost advantage.

Investigate feasibility of reuse and address end-of-life management in non-EU countries: In developed, high-incomes economies PV systems with new components remain the preferred choice, limiting the market for second-life PV systems. Presently, export of used, functional PV panels to non-EU countries is not well regulated. Existing export regulation is poorly enforced. In many non-EU countries, there are risks with uncontrolled end-of-life management of PV components, entailing environmental risks (e.g. leaching of metals (e.g. lead)), social and health risks in uncontrolled landfilling, loss of (critical) raw materials, and reputational risks for the PV industry as a whole. Despite these challenges, the use of second-life PV systems in many of the non-EU, low-income countries have great potential in providing electricity, especially in areas not connected with the electricity grid. Key actions proposed include the adoption of mechanisms to ensure that only functional modules of good quality are being exported outside the EU. The guidelines developed under the CIRCUSOL project could serve as a good starting point of what could be considered a good quality module. Furthermore, measures should be taken so that facilities for the treatment of solar waste should be developed locally in low-income countries to avoid uncontrolled landfilling at the end-of-life stage. So-called Voluntary Partnership Agreements (VPAs) could be a potential mechanism to support the sound development of infrastructure for responsible end-of-life management of PV modules in non-EU, low-income countries

Actualise and implement EU battery regulation proposal and standardization for repurposing of EVBs: To date, the lack of dedicated policies, legislation and standards to support repurposing of used EVB batteries has hindered development of the market for second-life batteries. A key action proposed is to support the adoption and implementation of the new battery regulation proposal and related standards. Once adopted, the new battery regulation proposal is anticipated to support repurposing and market development of second-life batteries. Adoption of the law would also enhance circularity by, among others, mandating the use of secondary raw materials. Furthermore, the adoption of the standards IEC 63330: Requirements for reuse of secondary batteries and IEC 63338: General guidance for reuse of secondary cells and batteries will complement the implementation of the new battery regulation.

Strengthen public perception of circular PV and EVBs: Currently, further uptake of second-life PVs and EV batteries faces challenges of not-well developed public and consumer perception. In addition to low level of education and communication about the benefits of circular economy strategies and about waste as a resource, lack of trust on the functioning of second-life PV modules and batteries remains a critical issue to address. In response to this, a key action is to strengthen public perception and awareness about circularity in the solar power and battery sectors. Here, the public sector could take a leadership role, e.g. by inclusion of second-life PV modules as part of the criteria for green public procurement, accompanied by communication campaigns to enhance visibility of PV systems with second-life components. The guidelines and certification schemes, for which the CIRCUSOL project made important contributions, can play a crucial role in enhancing public trust into second-life solar panels and batteries.

A research agenda for a circular PV and EVB sector: Last but not least, the tenth pathway we propose is to develop a research agenda for a circular solar and EVB sector. The CIRCUSOL project has identified a range of avenues for future research. Key actions proposed include (1) the development and calibration of resource and product flow models as well as price models, (2) a holistic assessment of emerging PV and EVB technologies from a circularity perspective, (3) an assessment of the socio-economic and environmental benefits of different circularity strategies, and (4) the evaluation of the actual implementation and effectiveness of a number of new government interventions that are currently in the pipeline.

About CIRCUSOL

CIRCUSOL is a Research and Innovation Action project, running from 2018 – 2022, and funded by the Horizon 2020 Programme of the European Commission. CIRCUSOL wants to unleash the full potential of service-based circular business models in the solar power industry, simultaneously delivering environmental, economic and user benefits. CIRCUSOL brings together 15 partners from 7 different countries. The consortium consists of 5 research centres and universities, 9 industrial players from the PV and battery value chains, and one consultancy firm.

www.circusol.eu

1. Background & Introduction

Growth of the solar market

Solar power is set to play a leading role in the achievement of the 2030 EU renewable targets and the commitment to carbon neutrality by 2050. An accelerated adoption of solar power is central to the EU Solar Energy Strategy (European Commission, 2022a) and the associated REPowerEU plan. This strategy aims to deploy over 320 GW of solar photovoltaic by 2025 and almost 600 GW by 2030.

Solar PV has multiple advantages that make it particularly suitable to meet today's energy and climate challenges. Solar PV can be rolled-out rapidly and provides emission-free electricity during its use-phase, making the technology a keystone in climate mitigation strategies. Importantly, vast reductions in the cost of PV over the past decades have turned the technology into one of the most competitive sources of electricity. As such, solar PV can provide EU citizens and industry with affordable energy as well as increase the resilience of energy users towards volatile fossil fuel prices. Solar PV, in combination with energy storage, also has the potential to significantly enhance European energy security, both at an individual as well as community level.

The solar industry is also an important source of employment creation, and the continued growth of the sector will lead to the creation of jobs in manufacturing, installation, maintenance, and end-of-life management. Revitalizing the PV manufacturing base in the EU offers opportunities to reinforce the EU's industrial leadership, while ensuring that solar products are up to the EU consumer's high standards. Calls for a reestablishment of PV panel manufacturing in Europe have become more prominent recently (Bett, 2020) in the context of enhancing European economic and energy autonomy, and to decrease dependency on non-European producers. In December 2022, the Commission formally launched the European Solar Industry Alliance (European Commission, 2022b) aiming to support scale-up of manufacturing of innovative and sustainable solar PV products in the EU, amongst others.

Growth of the electric vehicle market

Similar to the solar PV sector, the market for electric vehicle (EV) batteries has been growing significantly, and is set to further expand massively over the next two decades. In 2021, EV sales in Europe increased by 65% compared to the previous year, accounting for 2.3 million vehicles and 17% of all new car sales (IEA, 2022a). The EU's 'Fit for 55' package aims average CO₂ emissions of new cars to come down by 55% from 2030 and 100% from 2035 compared to 2021 levels (European Commission, 2021). The EU Sustainable and Smart Mobility Strategy anticipates at least 30 million zero-emission electric vehicles to be on EU roads by 2030 (European Commission, 2020a).

While presently a large part of EV batteries (EVB) manufacturing is still located outside Europe, in May 2018 the European Commission put forward a Strategic Action Plan for Batteries as part of the Clean Mobility Package, with the aim to develop a significant battery industry in the EU (European Commission, 2018). In response to the expected massive increase in demand for EV batteries, a total of 38 battery "giga-factories" were being built or planned in Europe and the UK, as of May 2021. If all plans are met, it is estimated that Europe will have

a battery cell supply of over 1000 GWh by 2030 – enough to electrify 90% of cars sold in Europe by 2030 (T&E, 2022).

Emerging waste challenges and circular economy opportunities

The expected rapid growth of the solar power and EVB sectors over the coming decade will bring along various resource and waste management challenges.

In 2016, the International Renewable Energy Agency (IRENA) published a report, estimating the generation of about 8 million tonnes of PV waste by 2030, which might increase up to 78 million tonnes in 2050. In another scenario study, in which technology progress along with shrinking solar panel prices incentivise users to replace their panels much sooner (Atasu et al., 2021), the volume of solar panel waste could go up even earlier than predicted by the IRENA study. Photovoltaic waste can entail several challenges, such as loss of recyclable resources, including critical raw materials (Ardente et al., 2016). When landfilled or disposed of incorrectly, PV waste can create leachate that is considered hazardous (Maani et al., 2020; Ramos-Ruiz et al., 2017).

With regard to electric vehicle batteries (EVBs), the rapid uptake of electric vehicles will lead to an increased demand for key raw materials and associated resource challenges (environmentally, socially and ethically) and supply-chain risks. Batteries contain valuable raw materials such as cobalt, nickel, and lithium, amongst others. In addition, battery cell manufacturing is highly complex and energy intensive – with energy consumption accounting for a significant share of costs and environmental impacts (Hill et al., 2019). In the use phase, batteries gradually degrade and lose some of their storage capacity which in turn will reduce the driving range of the EV. Hence, increasing quantities of batteries that no longer meet required specifications for usage in an EV will be discarded. According to one scenario, more than 5 million EV batteries would be annually returned in the EU in 2040, with about half of them available for second-life use and half for recycling (Abdelbaky et al., 2021).

Following a circular economy strategy have a potential to ensure that these emerging challenges will be handled in a proactive and future-proof manner. Furthermore, a circular economy approach might offer the European solar and battery industry new business opportunities in the design and manufacturing of circular-ready products, as well as in the reuse, refurbishment and recycling of older solar panels and batteries.

In addition to the environmental challenges associated with solar panel waste, a circular economy approach also brings about economic and business opportunities. CE strategies such as repair, remanufacturing and reuse of end-of-life photovoltaic panels do not only prolong the lifetime and resource productivity of solar panels, but also create new value generation opportunities for firms, users, and society at large. This can include benefits associated with low-cost renewable energy generation, innovative CE solutions and business models, as well as local employment generation and regional economic development.

Likewise, reuse of these batteries in less demanding applications, such as stationary energy storage including the storage of solar electricity, provides an opportunity to enhance their lifetime and resource productivity of the battery materials and embedded energy. According to one estimate, global supply of second-life batteries for stationary applications could exceed 200 gigawatt-hours (GWh) per year by 2030 (Engel et al., 2019)

For both PV and EVBs, a circular economy approach would enable European industry to regain control over resources, and specifically critical raw materials. Maintaining a stable and resilient supply chain will be critical for newly established EVB and PV manufacturing capacities in Europe.

CIRCUSOL project overview

In response to these emerging resource and waste challenges of the solar power and battery sectors, the CIRCUSOL project focused on four circularity strategies:

- Reuse of discarded PV panels in second-life applications, and enabled through service-based business models.
- Repurposing of EVBs in second-life applications, specifically for stationary storage of solar power, and enabled through service-based business models.
- Ecodesign of PV panels.
- Recycling of PV panels through innovative techniques.

Specifically, the CIRCUSOL project aimed to address the transition to a circular solar power system, by (1) developing a circular service design support toolbox for service providers, (2) creating awareness and intense collaboration with stakeholders by initiating and monitoring real-life demonstration projects, (3) developing an asset data platform prototype to share useful information between key stakeholders, (4) developing labelling and (re)certification protocols for second-life PV modules and batteries, and (5) the dissemination of technological innovations to enhance circularity of solar power solutions. Figure 1.1 illustrates an envisioned future circular product service system model that include different types of second-life pathways for PV panels and EVBs.

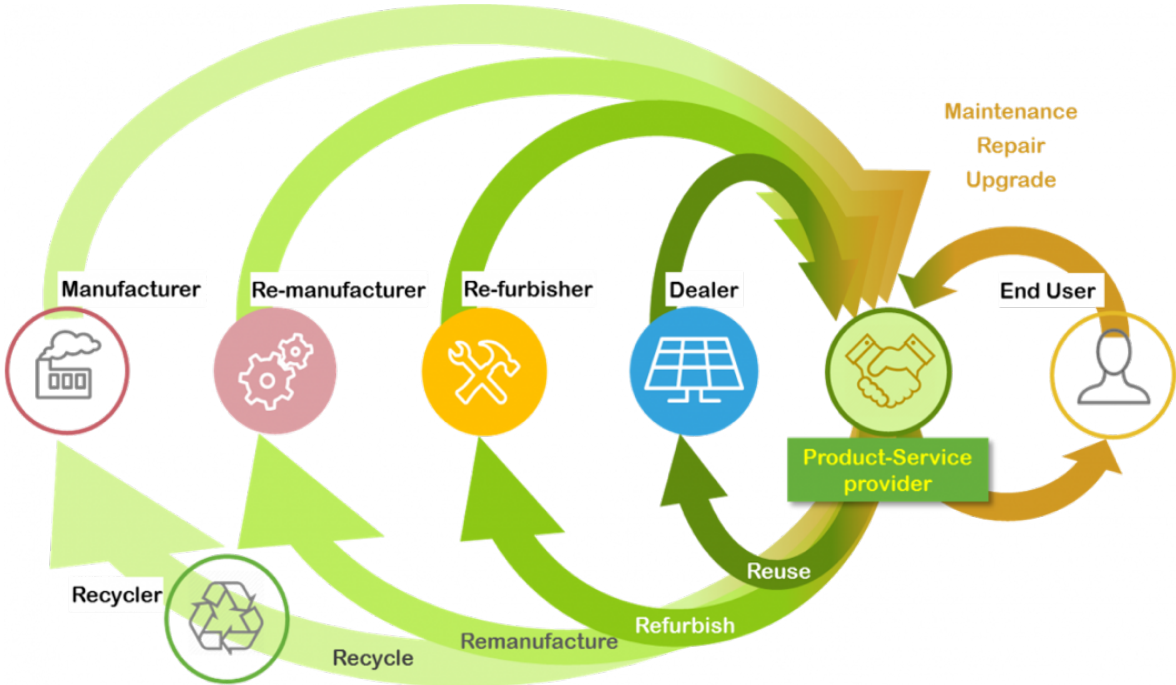


Figure 1.1 Circular product service system model, incorporating different circularity strategies

Box 1 shows drivers and guiding principles for a circular power system that were developed by the participating business and research organizations, and that form the CIRCUSOL vision.

Box 1: CIRCUSOL vision: Drivers and guiding principles for a circular power system.

AN ENVISIONED CIRCULAR SOLAR POWER SYSTEM ...

... creates added value for the future *and* the current natural & human environment.

... embraces the bigger picture

BY balancing economic, environmental, health, social and individual value(s) within decision-making or more specifically within business definition and creation

BY creating long-term as well as short-term benefits through circular solar power services, without any (major) trade-offs.

BY aligning the (renewable) energy transition with the circular economy transition: this involves balancing operational energy benefits (for end users) of solar power solutions with embodied energy/resources benefits (for product/service providers).

BY taking into account the entire life span of renewable energy solutions (such as PV and battery systems), beyond their intended application and their initial service period. This includes key life cycle stages, such as manufacturing, installation, operation, monitoring, replacement, logistics, remanufacturing, reuse and recycling.

... is resource responsible

BY taking care – in an effective and efficient way – of natural, human and financial resources required for (solar) energy services.

BY avoiding the use of scarce primary resources and creating zero waste within the production, remanufacturing of renewable energy product systems, including photovoltaics and (stationary) batteries.

BY aiming for net carbon (or greenhouse gas) negative services, by using renewable energy sources in the operational phase as well as in the (re)manufacturing and logistic stages.

BY including the entire life cycle environmental impact of energy solutions in decision-making; integrating a comprehensive set of environmental indicators, instead of only looking at climate change.

... embraces resilience towards future micro-economic shocks and policy shifts.

BY adapting easily to social and technological evolutions, such as ‘self-sufficiency’, ‘digitalization’ and ‘smart cities’.

BY developing robust businesses which are less or not sensitive to (modifications in) financial stimuli created by public authorities.

... is accessible and desirable for all

BY providing affordable solar power solutions for end-users, business stakeholders and society.

BY making circular solar power ‘sexy’ for end-users, business stakeholders and society, by being service-oriented and providing short-term as well as long-term benefits

BY deploying services that fit the needs of different types of users and operating at various scales.

... embraces transparency over the entire value network

BY fostering the access to (non-confidential) data and useful information.

BY sharing a diversity of knowledge within the value network (of PV and battery systems).

BY monitoring good and bad practices, in order to share valuable lessons

Pathways, policies & strategies towards circular solar power sector and battery sectors in Europe

This report is based on the lessons learned in the CIRCUSOL project in the period 2018 - 2022. It compiles key findings from the project and seeks to sketch out pathways and strategies on the way forward. As such, the report aims to contribute to a debate across policy makers, industry representatives, experts and other stakeholders about a potential future policy and governance framework that could catalyse the transition towards circular and resource-efficient solar power and EV battery sectors in Europe.

The report is structured as follows. **Chapter 2** provides an overview on the state-of-art of reuse of PV modules from a number of perspectives, including sources of modules suitable for reuse, applications for reused modules, as well as an analysis of the economic, environmental and social desirability of module reuse, amongst others. **Chapter 3** offers the equivalent type of information in regard to repurposing of electric vehicle batteries. **Chapter 4** provides an overview of the current status of measures taken by public and private entities which are of relevance for a circularity in the PV and EVB sectors. The chapter starts with the government interventions relevant to the circularity of both PV and EVP sectors in the EU, followed by the product-specific interventions, industry and standardization initiatives. In **Chapter 5**, we offer ideas and suggestions on potential pathways forward. They are based on the findings of the CIRCUSOL project and on the literature of barriers towards a more circular PV and EVB sectors, as summarized in Chapter 2 and 3 of this document. Furthermore, we also reflect upon the existing and emerging landscape of government interventions, industry and standardization initiatives and propose some additional action points. **Chapter 6** contains the conclusions.

2. Reuse of photovoltaic (PV) modules

Analysing the opportunities for reuse of PV modules has been a key aim of CIRCUSOL. This involved the need to first gain insights into sources of PV modules suitable for reuse to be able to understand the characteristics of the supply side. Secondly, it was critical to investigate the economic, social and environmental desirability of reusing PV modules, and to benchmark reuse pathways with other circularity strategies, such as recycling. Third, it was important to explore existing and potential applications and market segments for reused PV panels. Based on the results of these steps, it was then possible to identify barriers at different levels towards reuse of PV panels, and finally investigate the potential role of service-based (PSS) business models as an enabler for reuse of PV panels. This chapter provides a summary of the key findings, as obtained throughout the project.

2.1 SOURCES OF PV MODULES SUITABLE FOR REUSE

At present, a large share of the current PV waste stream consists of product defects that have occurred due to production, transportation or infant failures over the first four operational years. It is estimated that currently up to 80% of the PV waste stream comprises of such “young” modules, rather than modules that have reached the end of their designed technical life. The estimate is that it is possible to repair or refurbish approximately 45-65% of these modules, thereby postponing the time when these modules eventually will reach the recycling stage (van der Heide et al., 2021).

The factors leading to decommissioning of PV modules vary and can be classified as either need-based or incentive-based. Decommissioning of the PV modules because of damage, defect, age, or performance can be considered as need based (Pareek, 2021) and these can broadly be categorized into three groups: (1) infant failures, (2) midlife failures, and (3) wear-out failure, see Figure 2.1. In many cases, failures occur due to defects of a single component, e.g., cell cracks or bypass diode failures); whereas the rest of the module structure itself might still remain intact. Field experience indicates typical PV module failure rates of ca 0.15-0.25% per year, meaning that approximately 2% of the entire fleet of a PV plant is predicted to fail after 11-12 years (Tsanakas et al., 2019). Another source of need-based decommissioning are PV modules that have been damaged by severe weather (van der Heide et al., 2021). Furthermore, in some situations healthy panels are decommissioned well before reaching the end of their technical lifetime, e.g. when as part of insurance claims and due to economic factors an entire string is replaced even if only one module is damaged (Rajagopalan et al., 2021).

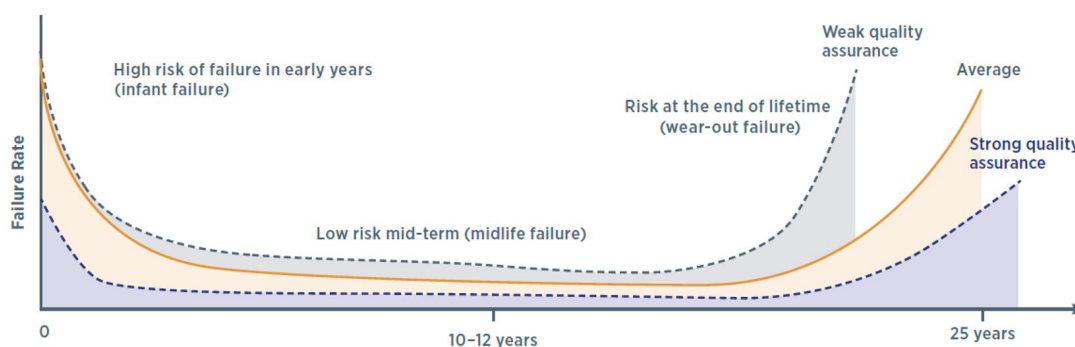


Figure 2.1 Failure curve of solar photovoltaics (IRENA, 2017)

Another reason of decommissioning relates to economic factors when PV systems are repowered as a conscious decision of the owner or operator who wish to boost the production yield and/or financial performance of an existing plant (Pareek 2021)¹. Some scenarios suggest that progress in technology, along with declining solar module cost prices can incentivize users to replace their panels long before the end of their technical lifetime (Atasu et al., 2021), leading to a potentially rapid increase of decommissioned modules. This form of early repowering depends on a number of factors, such as characteristics of the individual PV installation, the regulatory framework and the economic return to PV-system operators (Aleo Solar, 2022; Parnell, 2022; Zoco, 2018).

For the coming decade it is expected that the volume of older PV modules that were commissioned in the first decade of the 2000s will increase in the PV waste stream, as these modules will have reached the end of their technical lifetime. These modules with an age of around 20 years and with rather low efficiency will though not be relevant for reuse (van der Heide et al., 2021).

Rather, relatively “young modules” with an age of < 10 years are the most attractive ones from a technical and financial perspective to be reused in a second-life application. Their remaining technical lifetime is still considerable, their efficiency is still rather close to the one of recently manufactured modules, and they have passed the phase of early-life defects.

Preparation of modules for reuse

CIRCUSOL has investigated and demonstrated the technical feasibility to repair and refurbish defect and decommissioned PV modules. Preparation of those modules that are technically and financially feasible for reuse in a second-life application can require a number of steps, such as collection, sorting procedures, minor repairs, and quality checks (e.g., visual inspection, electroluminescence tests, flash tests, and isolation measurement). CIRCUSOL report 3.2 (van der Heide, 2022) provides detailed guidelines for the preparing for reuse that ensure sufficient PV module quality while still being economic. This involves the application of several testing/inspection methods and a correct re-labelling of the modules. Accompanying the guidelines is a decision tree for checking and sorting of decommissioned PV modules. Presently, technical requirements to qualify potentially re-usable PV modules for reuse are under consideration in technical standardizing committees, but they have not been formally adopted yet (see Section 4.2.3).

¹ Presently, the regulations inherent to many feed-in tariff schemes disincentivize early repowering before the end of the entire term (e.g. 20 years) that PV system operators are entitled to a guaranteed feed-in rate. For users or solar firms this complicates to boost the power output of an existing installation through repowering, and reuse the older panels at another location where their lower output still would be sufficient.

2.2 ECONOMIC, SOCIAL AND ENVIRONMENTAL DESIRABILITY OF REUSING PV MODULES

Reuse of PV panels in a second-life application can bring along tangible social, environmental and economic benefits, if benchmarked against a recycling pathway.

Social aspects

The reuse of PV modules can entail various social benefits, including employment creation for a local workforce both in the decommissioning and the re-installation sites. Employment from decommissioning and end-of-life management will grow significantly over the next years, as a large number of PV-systems will reach the end of their operational life. For Europe, industry association Solar Power Europe estimates that the number of solar jobs from decommissioning and recycling alone are expected to grow from 14,000 full-time equivalents (FTEs) in 2021, to 34,000 FTEs by 2025, and to 57,000 FTEs by 2030 (Solar Power Europe, 2022). While numbers about the employment creation potential associated specifically with the reuse of PV panels are still lacking, preparation of electric and electronic waste (WEEE) for reuse has been estimated to lead to the creation of 63 jobs per 1000 tons of WEEE (RREUSE, 2015).

Furthermore, the reuse of good quality panels in rural and non-electrified areas in low-income countries could alleviate energy poverty, and bring along various social benefits, especially in regard to education and employment opportunities, as well as gender equity issues. These aspects are closely linked to the achievement of Sustainable Development Goal 7 “Ensure access to affordable, reliable, sustainable and modern energy for all” (UN, 2022).

Environmental aspects

From an environmental perspective, reuse of PV modules is generally favourable over recycling and other forms of end-of-life treatment, such as landfilling. Results of life-cycle assessment (LCA) studies show that satisfying the 30-year service lifetime of PV panels is clearly favourable from an environmental perspective (IEA-PVPS 2021). Earlier replacement and recycling (e.g., every 10/15 years) results in higher environmental impact per kWh. The environmental impact of minor repairs (e.g. junction box repair) is minimal, and likewise the environmental consequences of transporting a repurposed module to a different location even over long distances (10000 km) is moderate, and still favourable over a recycling scenario (Rajagopalan et al., 2021).

In a scenario where reused PV panels replace the use of diesel generators, e.g., in low-income countries, additional positive environmental impacts occur through reduction of local air pollutants and GHG emissions. However, in low-income countries with no regulation or enforcement of electronic waste management, a major risk at the end-of-life through uncontrolled landfilling does prevail (van der Heide et al., 2020).

Finally, extending the lifetime of PV modules through reuse could provide more time to explore and develop waste treatment methods and increase material recovery through high-quality recycling (van der Heide et al., 2021).

Critical raw materials

The consumption of raw materials needed to manufacture PV panels is expected to increase drastically in the coming decades in order to achieve climate targets and the goals outlined in the European Green Deal. Given the dependency of the EU industry on imports for many raw materials (with some of them exposed to vulnerabilities in its supply), the topic about the future demand for raw materials for solar PV (and other green technologies) has received growing attention. If the visions to re-establish PV manufacturing in Europe at large scale (ETIP-PV, 2021; Solar Power Europe & EIT InnoEnergy, 2021) materialize, European demand for materials like germanium, tellurium, gallium, indium, selenium, silicon and glass will increase significantly. Mining of virgin (critical) raw materials is also widely associated with a range of negative environmental and social impacts, such as land and ecosystem degradation, water, soil and air pollution through toxic chemicals, as well as labour safety violations and health issues among the mining workforce and in adjacent communities.

However, considerable uncertainty still prevails about material demand under different technology scenarios. For solar PV technologies there are large differences in material demand between different scenarios, especially for those specific materials used in the manufacturing of PV cells. In the most optimistic case, improvements in material intensities could lead to a net decrease in material demand, whereas in a high demand scenario an increase in demand is expected for all materials, for example a 4-fold increase for silver and up to a 12-fold increase for silicon in 2050 (Carrara et al., 2020).

This raises questions about how lifetime extension of PV panels through increased reuse might affect the supply of (critical) raw materials for the European PV manufacturing industry, in particular in comparison to a business-as-usual recycling scenario. Given the declining material intensity of new generations of PV modules, early recycling of the stock of older generations of material-intense PV modules could potentially free up raw materials that could be fed back to the manufacturing of state-of-the-art modules with lower material requirements. Further research is needed to investigate the role of reuse vs. recycling in this respect.

Economic aspects

From the perspective of the operator, a key requirement for the application of reused PV modules is financial viability, considering that second-hand PV modules typically have a lower efficiency and shorter lifetime than new modules.

Currently, the most economically attractive market segment for reuse of PV panels is the spare parts market. In this niche segment, the most sought-after second-hand PV modules are presently sold for prices of 4–5 €/Watts peak (W_p), about 20 times the price per W_p of today's new modules (van der Heide et al., 2021). The lucrative spare parts market is partly created by technical necessities, as it is most convenient to replace a defect module with an identical one with the same physical and electrical parameters. In addition, feed-in tariff schemes, still being an important support mechanism in many European countries, often require to repair systems having defect modules with identical or similar modules in order to avoid losing the guaranteed feed-in tariff.

Beyond this spare-part market segment, most reused PV modules sell at <50% ($€/W_p$) of the present new module price, reflecting lower performance and shorter remaining lifetimes. Second-hand modules compete with new modules with higher efficiencies and over time

steadily decreasing prices, due to technology learning and economies-of-scale. An important financial aspect to consider are the costs of preparation for reuse that arise from for collection, testing and re-certification of modules. Presently, due to small volumes and the prevalence of manual labour in testing, these costs can make up a significant portion of the market value of reused modules. For example, experience in CIRCUSOL indicates testing costs of 0.12 - 0.20 EUR/kW_p for 180 W_p module (Ben-Al-Lal et al., 2021). These costs potentially could decrease through integrated and automated testing, as well as through the trend towards larger modules.

It is important to note that the lower costs of a reused module will only have a relatively minor effect in the economics of a PV system. Presently, module costs account for only around 30% of the total system cost of a PV system, with the costs for planning and installation work as well as other hardware components (inverter, mounting, cabling, etc.) making up the remainder. This means entails that the turn-key upfront cost for a PV system with reused modules might only be slightly lower, while the yield and remaining module lifetime can be considerably less (van der Heide et al., 2021).

Furthermore, the economics for reused modules can be further comprised, as their lower efficiencies can result in higher capacity-specific costs (per W_p) for mounting and installation. (Wendzich, 2020). The deployment of reused modules in regions with low labour costs might outweigh some of this additional labour time associated with the installation of panels with lower efficiencies.

In a circular solar power sector, eventually all modules (first-life modules not suitable for reuse & second-life modules) shall at their ultimate end-of-life stage undergo recycling in order to recover the raw materials. In current market conditions, recovering materials from post-consumer PV modules is economically not viable, even when the materials such as silicon and glass are recovered to use again in primary silicon or glass for PV modules, the cost for recycled materials in relation to the sales price of new modules. Today's, prices of virgin silicon price are low – USD 37 per kg in October 2021, USD 32 per kg in December 2021 and to USD 44 per kg in July 2022 – compared to the peak price of USD 450 per kg in 2008 (PV CYCLE, 2022). In order to recycle silicon from post-consumer PV modules for use in new silicon cells requires purification due to contamination in the recovered silicon. The same challenge applies to the majority of the current flat glass which contains too much antimony and which cannot be smelted in glass smelters because the melted glass cullets become black instead of white.

2.3 APPLICATIONS AND MARKET SEGMENTS FOR REUSED MODULES

Table 2.1 displays a list of potential applications for reuse of PV modules with their main advantages and disadvantages. In new residential, commercial/industrial or utility-scale PV plants in Europe, second-hand PV modules are presently not competitive with new modules. Therefore, the main types of applications for second-hand modules are (1) the repair of existing PV systems (in particular those where the rule of feed-in-tariff schemes stipulate the exact type of panel), (2) the export of second-hand modules to developing regions where they often find use in off-grid applications, and (3) the replacement of all modules of a PV power plant with second-hand modules in order to extend the lifetime at low cost or mitigate underperformance of existing modules in the plant (van der Heide et al., 2021). As described in Section 2.2, only early and midlife loss modules can be competitive to new modules and this applies across all applications.

To date, several companies and platforms have specialised in the trading of decommissioned and refurbished PV modules and components. Their activities can also include collection and the provision of quality control, repair and installation services. Repaired modules are also typically issued with a 2-year warranty (Tsanakas et al., 2019). The volume of the global reuse market is estimated to be 1 GWp/year, of which 0.3 GWp/year originate from Europe (van der Heide et al., 2021). As such, the reuse market represents only about 0.5% of all new installations, which summed up to 179 GW in 2021 (IEA, 2022b).

Table 2.1 List of existing and potential applications for reuse of PV modules with main advantages and disadvantages

Applications for reuse of PV modules	Main advantages	Main disadvantages
Replacing damaged modules, usually due to severe weather. In case of subsidised PV plants, operators are often required to replace damaged modules by (nearly) identical ones to avoid losing subsidies.	No loss of (high) subsidies. Possibility to complete the installation again in an easy way.	Finding modules (nearly) identical to the damaged ones can be very difficult, leading to high module costs.
Replacing all old modules of a PV plant to extend its operation beyond initial design life of 20–25 years or because the system is severely underperforming.	Lower module costs. Module dimensions are adapted to existing racks and mounting systems.	Much lower module efficiency, lower remaining lifetime, and less warranty versus using new modules.
Reuse of the defect modules in an existing PV plant after onsite repair to prolong the lifetime of the total plant.	No need to search for replacement modules that are hard to find and that are expensive. No additional costs for dismantling and transport.	On-site module repair can be hindered by weather conditions. Can be difficult to reach a particular defect module within a system, or the rear side of modules
Installing modules in a new PV plant which can be of commercial- or utility-scale.	Lower module costs.	Much lower module efficiency, lower remaining lifetime, and less warranty versus using new modules. Limited cost savings since PV modules contribute only 1/3 of total PV system costs.
Installing modules in a new residential PV system.	Lower module costs.	Much lower module efficiency, lower remaining lifetime, worse aesthetics and less warranty versus using new modules. Limited cost savings since PV modules contribute only ca. 30% of total PV system costs.
Exporting modules to developing regions for installation in new small/ medium-sized PV systems (often off-grid), e.g., for home energy applications, battery charging, solar Wi-Fi, solar irrigation, refrigeration for agriculture	Lower module costs, making solar power more accessible to low-income groups Users having lower requirements for panel aesthetics & increased tolerance towards modules with no warranties Off-grid solar solutions can replace environmentally harmful energy sources, reduce carbon-related emissions, increase rural electrification levels, raise living standards, and support employment opportunities in disadvantaged communities.	Much lower module efficiency, lower remaining lifetime, and less warranty and lack of certification on performance versus using new modules. Concerns about lack of infrastructure and processes for responsible end-of-life management.
Other novel applications	Low-cost 2 nd -hand modules could unlock new customer segments which cannot afford new PV.	

Compiled from Franco & Groesser (2021), PV CYCLE (2022), van der Heide et al. (2021), and Wendzich (2020).

2.4 BARRIERS TOWARDS REUSE

The CIRCUSOL has encountered and identified a number of barriers towards the reuse of PV modules, see Table 2.2. The barriers span across the entire value chain, and include factors related to product design, markets, information, financial aspects, user acceptance, as well as legal-institutional aspects.

A key barrier to the reuse of PV modules is the continuous high innovation dynamics for new panel generations, as characterized by higher efficiency, lower costs, and more appealing aesthetics. The reuse market is presently still very small, with reverse logistics, preparation for reuse, certification, amongst others, weakly developed. Among users, concerns about performance, reliability, and safety of second-life PV hinders product adoption. Yet, considerable uncertainty and insufficient data about PV panel failures rates, PV waste volumes, and about the quality of second-life panels prevails. On the institutional side, proper government regulation to incentive reuse has been lacking so far. ²

² In addition to solar modules, inverters are a key component of any grid-connected PV system. While inverters have not been within the scope of the CIRCUSOL project, barriers to repair and reuse of these products have also been observed. For example, in some regions requirements by Distribution System Operators do prohibit repair of inverters that are older than 10 years. This means that solar firms need to replace defect inverters beyond a certain age with a new model.

Table 2.2 Barriers towards reuse of PV modules

<p>Design and manu- facturing</p>	<p>Current PV module design does not facilitate repair; manufacturers optimize product design for first life, not for use thereafter (i.e., design for disassembly, refurbishment, and recycling).</p> <p>Technological innovations and evolving consumer preferences for design (e.g., preference for black modules that integrate visually well with roof tiles) result in heterogenous stock of PV modules, which increases search and matching costs for modules that could be reused.</p> <p>Increased efficiency of new PV panel generations favours new modules over reused modules, especially when space is limited and/or mounting costs per m² are high.</p>
<p>Market & value chain</p>	<p>Presently, only low volumes of modules potentially suitable for reuse are available.</p> <p>Lack of collaboration and information sharing across the supply chain.</p> <p>Take back systems and reverse logistics insufficiently developed, e.g. lack of volume, lack of dedicated amounts of PV modules from large-scale PV power plants.</p> <p>Lack of a clear set of instructions or standard or technical specification towards the definition of a reusable PV module, as well as the definition of a reused and hence fit for second-hand sales PV module.</p> <p>Clearly defined roles of producer responsibility, but different actors in the PV value chain are not interested or claim to not be informed.</p> <p>Business models of installations companies are designed for PV systems with new components, and typically do not take account of end-of-life aspects, especially when the average product guarantee is 12 years and the average performance guarantee is 20 years. Lack of awareness of ‘waste occurring in the short term’.</p>
<p>Information</p>	<p>Insufficient accurate data on PV panel failure (e.g., failure types and rates, performance after repair, and collection and repair costs) due to the low volume of decommissioned PV panels and infant PV monitoring systems.</p> <p>Uncertainty about future PV waste volumes.</p> <p>Lack of track and tracing record / identity card of PV modules.</p> <p>Asymmetric information concerning the quality of reused PV panels. Certification and labelling standards are lacking and still under development and warranty schemes are inexistent or incomplete.</p>
<p>Financial</p>	<p>Reused modules compete with new modules with higher efficiencies and over time steadily decreasing prices.</p> <p>Costs for collecting, testing and re-certification of modules are high due to small volumes and the prevalence of manual labour. High costs of sorting reusable from non-reusable PV modules.</p> <p>Customers presently not willing to pay a premium for circularity and for a tested and reused PV module with a warranty.</p>
<p>User acceptance</p>	<p>Lack of awareness and/or poor market confidence in refurbished/recycled PV panels, because there is no set of specifications for tested and guaranteed second-hand PV panels.</p> <p>Concerns about performance, reliability, and safety of second-life PV hinder customer trust and product adoption. A second-hand PV module is still a product which generates electricity and requires thus more attention than, e.g., other refurbished (energy consuming) products.</p> <p>Limited or no product warranty on second-hand PV modules.</p> <p>In developed economies, new PV systems remain the preferred choice, where consumers rely heavily on high efficiency, aesthetics, and warranties.</p>
<p>Political / Institutional / Legal</p>	<p>Lack of proper government regulation to incentive reuse, e.g. lack of technical specification or norm or standard related to the preparation for reuse, and reuse of PV panels.</p> <p>Lack of inspection about the functionality of second-hand PV panels for export to countries outside the European Union.</p> <p>Unclear specification about liability for second-life PV modules, especially when deployed in high voltage use cases.</p>

Compiled from Franco & Groesser (2021), Godinho Ariolli (2021), PV CYCLE (2022), Van Opstal et al. (2021), and Wendzich (2020).

2.5 SERVICE-BASED (PSS) BUSINESS MODELS AS AN ENABLER FOR REUSE OF PV MODULES

A central element of CIRCUSOL has been to test the market viability of service-based business models as an enabler for the reuse of PV modules. Here, the hypothesis was that service-based business models can help to overcome some key barriers to the adoption of used products, such as lack of consumer confidence and uncertainty about performance and remaining lifetime.

Experience from CIRCUSOL has shown that the user interest for service-based business models for the adoption of solar PV varies among different user groups. Overall, private homeowners in high-income Europe have shown little interest in this model. For users, service-based business models are financially less attractive than host-owned systems, there is still a prevailing mentality of owning products, and the exceptionally low capital costs during the past decade have made the purchase of PV systems easy. Among residential homeowners, there is also a preference for maximizing yield from limited roof area as well as aesthetic requirements, both of which put second-hand modules in an unfavourable position.

Outside the dominant residential market of homeowners, CIRCUSOL researchers investigated the viability of circular economy strategies and the role of service-based business models in business-to-business and business-to-government markets for solar energy investments. Focus group meetings and semi-structured interviews conducted in Flanders (Belgium) served to identify barriers for PV adoption and assess the enabling potential of circular solutions, including PSS models, second-life PV panels, end-of-life strategies, and the potential role of data technologies to improve product use, maintenance, design and recycling (Van Opstal & Smeets, 2023)

The results of this CIRCUSOL research show that the advantages generally attributed to solar PPS models, such as unburdening users from upfront capital expenditure, technical and financial risks, and burden for repair and maintenance also apply for business and governmental organizations. In addition, the benefits of solar PSS models to provide incentives to service providers to optimize the installation dimension (avoiding upselling) and incentives for long product use, high quality installations, and opportunities for refurbishment are recognized. The most important enablers are clear communication on the expected profitability for clients and including a solar PSS offer into extended service packages inducing heating, ventilation and sanitation. Furthermore, increasing regulatory requirements on energy performance were highlighted as trigger to a solar PSS model (Van Opstal & Smeets, 2023).

Disadvantages of solar PSS, as perceived by the Flemish focus group participants, include lower return-on-investment (ROI) than PV ownership models, long and inflexible contract terms, legal complexities (e.g., notarial registry of the PV installation), and lack of internal knowledge building on PV installations. Also, the predominant culture of owning assets is still present in business and governmental organization, though to a lesser degree than among residential homeowners (Van Opstal & Smeets, 2023).

Focus group participants consider the deployment of reused PV panels through a full-service PSS model as viable, if they can address the lack of a proven track record for second-life PV and warranties and enable transfer of any risks to the PPS firm. This requires a solid service model including repair, maintenance and control as well sufficient project sizes to allow for economies-of-scale that enable lower levelized cost of energy (LCOE) of second-life PV panels than for new panels (Van Opstal & Smeets, 2023).

Focus group participants from governmental and business organization expressed different preferences on how to make PSS models more attractive. In Flanders, the dominant model in solar PSS contracts includes a transfer of ownership of the installation from the solar service firm to the end-user after a contract duration of 20 years. PSS models that would enable users to opt-in for a service contract beyond the PSS contract duration, or alternatively, contract extensions with no transfer of ownership 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. In a third model, service providers take back the installation after a contract duration of 20 years, and potentially forward these panels to a refurbishment and second-life pathway (Van Opstal & Smeets, 2023).

Finally, focus group participants in Flanders pointed out preferences for shorter and more flexible PSS contracts, in order to not be lock-in with the same supplier for extensive periods. While shorter contract periods would lower the threshold to engage in a solar PSS offer, as well as allow users to gain access to the latest technologies, they might be counter-productive from a circulatory perspective (Van Opstal & Smeets, 2023).

For solar firms as potential providers of circular solar services the experience has been mixed at best. The lack of experience about the O&M and EOL management costs of reused panels made it difficult to establish reliable cost calculations for second-life PV systems, making it difficult to get firm-internal buy-in for service-based circular product offer. On the hand, some CIRCUSOL partner firms with more experience in service-based offerings had accumulated more real-life experience about the O&M needs and cost of PV systems equipped with second-life panels.

Beyond the well-established market segment of grid-connected PV, novel applications might offer innovative solutions for the reuse of PV modules through service-based (PSS) business models. One example is the off-grid charging of urban micro-mobility services, as implemented by CIRCUSOL partner SunCrafter. In this B2B model, SunCrafter aims to lease out off-grid charging stations (powered by second-life solar panels) to operators of micro-mobility services such as providers of shared e-scooter services in cities.

Barriers to solar PSS

Finally, experience in CIRCUSOL has revealed several policy aspects that can complicate the uptake of service-based solar power business models. One barrier experienced by CIRCUSOL solar firms in both Belgium and Switzerland is the high cost for registering a PV system in the cadastre. Such registration is important for providers of service-based solar power offers in order to safeguard the firm's right of ownership to PV systems that are deployed on the property of their clients. The high cost for the cadastre registry, however, poses an economic barrier to the financial viability of service-based solar power business models. Solar firms in the CIRCUSOL consortium have highlighted the need for an efficient and low-cost registration system for solar-as-a-service models.

Heterogeneity of requirements from Distribution System Operators (DSO) was experienced as another barrier to the deployment of PV. While this barrier is not specific to solar PSS models only, the variety of technical regulations on a country and even provincial level poses additional complications for solar service firms, such as unnecessary transactions costs and bureaucratic effort and thereby increase of capital expenditures (CAPEX) costs, as well as project delays.

As such, the lack of more uniform technical regulations for the connection of PV systems to distribution grids is an obstacle for scalability of PV.

In Germany, CIRCUSOL partner SunCrafter faces another type of regulatory challenge specific to their envisioned business model of providing charging services for micro-mobility service providers. SunCrafter or whoever was acting as operator of the solar charging stations was going to be classified as a big electricity provider within the meaning of the Electricity Tax Implementing Ordinance (StromStV). Specifically, certain provisions in the Ordinance that seek to avoid the bureaucratic burden of supplier status where electricity tax issues are not at risk do not apply for purely "stand-alone systems" such as the micro-mobility hubs. As such, electricity tax legislation in its current form lead to unmanageable bureaucratic efforts for a firms engaging in certain novel business models, such as off-grid solar-powered charging services for micro-mobility providers.

2.6 FUTURE OUTLOOK

This section has outlined the experience and opportunities for reuse of PV panels for those technologies that presently still prevail in the PV market. It is important to note that rapid developments in PV technology can alter the assumptions and the potential of preparing PV modules for reuse (Wendzich, 2020). In a 10-20 years perspective, decommissioned modules will be mostly of glass–glass type which entails less risks for reuse (less cell cracks, lower degradation and no backsheets issues) and they will be mostly of multi-wire type which makes power output less sensitive to cell cracks (van der Heide et al., 2021). While the better quality and reliability of decommissioned modules are positive for ‘reusers’, they might also delay repowering (van der Heide et al., 2021) and thereby reduce the supply of PV panels available for reuse.

The gradual phase-out of feed-in tariff programmes in favour for other economic models of reimbursement will provide PV system operators with more flexibility and the opportunity to earlier re-power their installations. This can potentially increase the supply of decommissioned modules that then would be available for reuse.

2.7 CONCLUDING REMARKS

In sum, assessments carried out within CIRCUSOL clearly show the technical feasibility to repair and refurbish defect and decommissioned PV modules, both onsite and offsite, and redeploy them in a second-life application, accompanied by generating social and environmental benefits. Modules experiencing early- and midlife failures are particularly suitable for this. Quality-testing and fast and low-cost repairs are possible and detailed guidelines and recommendations to ensure customer confidence in reuse modules are under preparation. Economic viability and customer acceptance in the EU is currently limited to few specific cases. Demand for second-hand exists outside Europe, and particularly in low-income regions with insufficient access to modern energy services, however, lack of appropriate local EOL treatment facilities in these regions can compromise the environmental benefits. Experience in CIRCUSOL with service-based business models as a catalyst for the deployment of reused modules was mixed. While such models were successfully implemented in some pilot projects, it was also found that many home owners have strong preferences for purchasing and owning a PV system.

3. Repurposing of electric vehicle batteries (EVBs)

A second key aim of CIRCUSOL has been to investigate the opportunities for repurposing of discarded electrical vehicle batteries (EVBs), for the storage of solar power in stationary applications. This chapter provides an overview on a number of aspects related to EVB repurposing, including (1) sources of EVBs suitable for repurposing, (2) environmental, social, and economic desirability, as well as a critical raw material perspective of repurposing EVBs, (3) application and market segments for repurposed EVBs, (4) barriers towards repurposing EVBs, (5) the role of service-based (PSS) business models as an enabler to deploy second-life batteries, and finally (6) a future outlook on the next generation of battery technologies and the implications of these developments on repurposing EVBs.

3.1 SOURCES OF EVBS SUITABLE FOR REPURPOSING

The most common scenarios in which batteries have reached the end of their first life are when then battery outlasted the equipment they were in (e.g. in portable electronics) and when they cannot perform the original tasks they were designed for but still maintain some of their characteristics which make them useful in less demanding applications. Electric Vehicles Batteries (EVBs) due to their higher capacity (compared to portable electronics batteries) might be particularly suitable for stationary energy storage applications, such as the storage of solar power (Perdriaux, 2020).

Due to the rapid take-up of electric vehicles markets, the supply of discarded EVBs that could be repurposed is expected to grow significantly. According to one estimate, supply of second-life-batteries suitable for stationary applications could exceed 200 GWh per year at a global scale by 2030 (Engel et al., 2019). In another study for Europe only, the waste stream of lithium-ion batteries from electric vehicles is forecasted to account for 120,000 and 1.8 million batteries in 2030 and 2040 respectively. Repurposed EVB batteries derived from this waste stream can potentially contribute to 8 GWh stationary energy storage capacity in 2030, and 92 GWh in 2040 (Abdelbaky et al., 2020).

3.2 ENVIRONMENTAL, SOCIAL, AND ECONOMIC DESIRABILITY AND CRITICAL RAW MATERIALS PERSPECTIVE OF REPURPOSING EVBS

This section elaborates on the desirability of reusing EVBs from environmental, social, economic, and critical raw materials perspectives. Insights into these aspects are critical in order to be able to evaluate the desirability of repurposing strategies in relation to other circularity strategies, such as recycling.

Environmental aspects

The environmental aspects of repurposing EVBs and reusing them in a second-life application need to be carefully calculated and evaluated in order to conclude if repurposing EVBs would be more desirable than other circularity strategies, such as recycling. Repurposing as a circularity strategy is principally desirable from an environmental viewpoint, as extending the useful lifetime of materials and embedded energy in second-life EVBs would reduce the negative environmental (and social impacts) associated with the production of new batteries

from virgin or recycled materials. These benefits need to be put in context with the environmental impacts from transporting and repurposing EVBs, as well as the energy losses from the charge-discharge cycle in the use phase of second-life batteries.

Recently, a number of studies have been conducted, assessing the life-cycle of second-life batteries (e.g., Bobba, Cusenza, et al., 2018; Bobba, Mathieux, et al., 2018; Casals et al., 2019; Koroma et al., 2021; Kotak et al., 2021; Philippot et al., 2022). Studies show that the repurposing of EVBs for a second life can be beneficial under certain conditions. For example, the study by Tao et al. (2021) suggests that compared to directly recycling LIBs after their EV use, life cycle carbon footprint and CED of LIBs recycled after their second life can be reduced by 8 to 17% and 2 to 6%, respectively, varying across battery chemistries and recycling methods (Tao et al., 2021).

The potential benefits of second-life batteries strongly depend on context-specific boundary conditions, in particular on the source of charging electricity. In tendency, battery repurposing is more favourable in low-carbon electricity systems (Koroma et al., 2021). For example, according to one study, only in countries with an electricity mix below 113 g CO₂eq/kWh, repurposing decreases the impact on climate change, as compared to a recycling scenario (Philippot et al., 2022).

In all, given the multitude of boundary conditions selected (e.g., climate impact of electricity mix) and assumptions made (lifetime of second-life battery, type of battery chemistry) in the life-cycle assessment studies, a generic answer cannot be given at this point whether a repurposing or recycling pathway is more desirable from an environmental viewpoint. There is a significant need to enlarge environmental assessments of second-life EVB scenarios in order to gain a more comprehensive understanding about the potential benefits that this circularity strategy might entail. The results of such assessment need to be benchmarked against scenarios in which EVBs are directly recycled at the end of their first life. It is critical that these assessments consider future trends of boundary conditions in the EU (e.g., increasing share of low-carbon and renewable electricity technologies), as well as development in battery technology (e.g. chemistries, charging efficiency, degradation rates) and user behaviour (e.g. lifetime, accepted capacity degradations).

Social aspects

Along the battery value chain, a variety of social aspects need consideration. Extraction of battery raw materials, such as lithium, manganese, cobalt, and nickel has been associated with a range of social supply chain risks, such as bad labour conditions, conflicts between small-scale and large-scale miners, water scarcity and contamination, and resettlement of local communities (Bobba, Cusenza, et al., 2018). While these aspects in the upstream supply chain need attention irrespective of the downstream circularity strategy, maximizing the value from the sourced raw materials through repurposing and recycling could potentially help to slow down the growth of mining activities for battery raw materials. This might also have implications for the social impacts of these mining activities.

Further downstream, the repurposing of EVBs for stationary energy storage applications presents an opportunity for employment creation in the EU. Transporting, remanufacturing, testing and re-certification of used EVBs requires a highly skilled workforce. A number of specialised firms for battery repurposing have already been established in the EU (Perdriaux,

2020). The scale of employment creation and other social benefits from battery repurposing is, however, not well investigated yet.

Economic aspects

From a business perspective in the stationary energy storage market, repurposed batteries compete with newly manufactured batteries that are subject to rapid technology advancements and price reductions. In particular, a key challenge to the financial viability of repurposing EV batteries for stationary energy storage applications is the falling costs of newly manufactured lithium-ion batteries. Lithium-ion battery pack prices, which were above \$1,200 per kilowatt-hour in 2010, have fallen 89% in real terms to \$132/kWh in 2021 (Bloomberg, 2021). Although recently, the impact of rising commodity prices and increased costs for key materials has put pressure on the industry, the cost reduction potential for new and emerging electricity storage technologies is still significant. The total installed cost of a Li-ion battery could fall by an additional 54-61% by 2030 in stationary applications (Perdriaux, 2020). In addition, continued advancement in technology will significantly increase performance of new battery generations in terms of, amongst others, extended lifetime and improved round-trip charging efficiency levels (Perdriaux, 2020).

The future cost and performance of newly manufactured batteries need to be put into comparison with the cost of refurbishing old EVBs. This involves, amongst others, the cost for collecting, dismantling, and testing used batteries and for building a new battery management system (BMS). The condition of individual batteries, even of the same type, can vary widely and depend on their previous application and user habits. Hence, individual testing of single EVBs is generally recommended, in particular to ensure the safety profile of a repurposed battery. The costs associated with individual testing are a key factor in the economics of repurposing EVBs. In general, the cost differential between repurposed and new batteries is expected to further diminish (Engel et al., 2019).

Critical raw materials

The deployment of many technologies supporting the e-mobility sector will greatly impact the demand for materials in the future. Mobile energy storage will require raw materials such as lithium, nickel, cobalt, copper and graphite, and their demand is expected to continue growing over the next decades. For instance, in 2050, the EU demand for lithium will be 10-50 times higher than the EU 2018 demand in all applications, depending on the considered uptake of EVs (European Commission, 2020b).

The EU is highly dependent on imports of several raw materials that are keys for the development of e-mobility, and some of these materials have a very high and high supply risk (e.g. REEs, PGMs, cobalt and natural graphite). Focusing on the supply chain, the most vulnerable steps are the raw materials and the assembly stages. China, Africa and Latin America provide the majority of raw materials required for the e-mobility sector. China is also the major supplier of batteries components (i.e. cathode, anode, Li-ion cells) (EC, 2020).

A perspective on critical raw materials is relevant for the question whether EVBs should be repurposed or recycled at the end of their first life. Direct recycling would circulate back raw materials to the manufacturing of new EVBs, while lifetime extension through repurposing would delay this material flow. Considerable uncertainties still prevail to what extent materials from battery waste streams could meet the raw material demands for manufacturing of new

EVBs. In one model forecast, results suggest that the annual recycling waste stream in 2040 could cover could meet between 10% and 300% of future raw materials for e-mobility (Abdelbaky et al., 2021). Key factors that determine this wide range are uncertainties about material composition of future EVB generations (including possibly cobalt-free battery technologies), as well as uncertainties about battery lifetime and the take-up of repurposing EVBs for second-life applications (Abdelbaky et al., 2021).

3.3 APPLICATIONS AND MARKET SEGMENTS FOR REPURPOSED EVBS

The main markets for repurposed EVB in a second-life application are traditional energy storage applications, such as utility-scale storage, distributed energy storage, frequency regulation, capacity support, and contingency grid support services (Perdriaux, 2020). Market demand for stationary battery energy storage application is growing, partially driven by the need to store electricity from intermittent renewable energy sources, in combination with the declining costs for battery storage solutions. In 2021, the stationary battery market of the EU27 more than doubled, with annual installations of 2.2 GW / 3.7 GWh. The cumulative installed capacity reached 4.6 GW / 7.7 GWh. The market is expected to further expand significantly over the next decade, reaching 80 GW / 160 GWh of cumulative capacity in the EU by 2030 (Bielewski et al., 2022). EVBs generally have fast-charging capabilities, making them in their repurposed second-life variant a capable choice for many stationary applications that often are less demanding.

3.4 BARRIERS TOWARDS REPURPOSING

Presently, a number technological, financial, market and institutional barriers towards repurposing of EVBs and using them in a (stationary) second-life application still prevail, see Table 3.1. A fundamental challenge is that EVBs are designed and optimized for their first life in an electric vehicle. Battery manufacturers have given limited attention to design for disassembly, repurposing, and recycling.

Preparation of EVBs for repurposing³ requires the repurposer to put the battery thorough a series of costly diagnostics and testing of the cells (or modules depending on the battery). Dismantling is typically required since, since the repurposer does not have access to the first life data. Dismantling is also required when the second-life application requires less modules than the first-life application. The costs for repurposing are exacerbated through lack of scale-economies and resistance from battery OEM to share disclose data from the battery management system.

As elaborated in Section 3.2, the cost advantage of repurposed EVBs is further becoming challenged as the costs for new batteries continue to decline. In the future, an excess in the availability of end-of-life EVBs that exceeds the predicted need for stationary energy storage can potentially further put pressure on prices for second-life batteries, but potentially also allow previously unavailable applications and solutions to emerge (Perdriaux, 2020).

³ Further details about, amongst others, technical aspects and a proposed assessment and testing procedure for repurposing of (industrial) lithium batteries are given in a separate CIRCUSOL report (Mulder et al., 2022).

Presently, due to the early stage of market development, there are still widespread uncertainties about the supply of EVBs to be repurposed, lack of experience about their technical performance and remaining lifetime, as well as issues regarding consumer trust towards refurbished or repurposed batteries.

Table 3.1 Barriers towards repurposing of EVBs

Design and manufacturing	<p>Manufacturers optimize battery design for first life, not for use thereafter (i.e., design for disassembly, refurbishment, and recycling)</p> <p>Most tests measuring the efficiency and longevity of repurposed LIBs for stationary energy storage have been performed at laboratory or pilot project level only</p>
Repurposing	<p>Transport of used LIBs is costly because it can be considered as hazardous waste; regulations for transporting used EVBs are still a grey area, making certification, logistics and contracting more difficult.</p> <p>Repurposing process of LIBs is demanding as each cell needs to be controlled and the battery management system needs to be set up to fit the battery's new surroundings and application.</p> <p>Uncertainty about ageing performance of second-life batteries.</p> <p>OEMs reluctant to permit repurposers access to the original battery management system.</p>
Market & value chain	<p>Presently, concerns about uncertain supply of sufficient volumes of spent EVBs.</p> <p>With exception of some OEMs having implemented take-back systems, adequate collection systems/plants are lacking.</p> <p>Lack of coordination and collaboration between producers and repurposers.</p> <p>Scattered location of supply of used EVBs, often remote from location of repurposer.</p> <p>Competition from the recycling business model.</p>
Information	<p>Presently, unknowns associated with second life LIBs (e.g., cost, performance, volumes) interfere with the development of innovative value proposition packages for new business models.</p> <p>Due to the low volume of decommissioned PV systems and EV batteries, there is a lack of evidential data on the costs of collecting, dismantling, and recycling both types of systems.</p>
Financial	<p>Cost of newly manufactured batteries expected to continue decreasing, reducing the cost advantage of repurposed batteries.</p>
User acceptance	<p>Customers might perceive refurbished or repurposed products as exhibiting lower performance.</p> <p>Warranties, reliability, and safety concerns of second-life PV LIBs hinder customer trust and product adoption.</p>
Political / Institutional / Legal	<p>Legislation for second-life use of LIBs has yet not been implemented in the EU (as of November 2022)</p>

Compiled from Franco & Groesser (2021) and Pham (2021).

3.5 SERVICE-BASED (PSS) BUSINESS MODELS AS AN ENABLER FOR REPURPOSING OF EVBS

In CIRCUSOL, the use of service-based business models as an enabler for repurposing of EVBs has been successfully demonstrated in the B2B market segment for stationary solar power storage, specifically in the *Cloverleaf* demonstrator. In the B2B sector for urban micro-mobility (*SunCrafter* demonstrator), service-based business model to catalyse repurposing of second-life batteries in solar-powered charging stations for E-Scooters/e-mopeds has been investigated but put on hold for the moment, due to technical reasons. In the B2C segment (*Waasland* demonstrator), the upgrade of the system through a second-life battery, and enabled through a storage-as-a-service business model has been implemented.

The barriers for service-based PSS for repurposed batteries resemble the experiences made for service-based PSS for second-life PV modules, see Section 2.5.

3.6 FUTURE OUTLOOK

Presently, lithium-ion and lithium-iron phosphate dominate the current EV battery landscape. However, LIB technology is facing several challenges, such as diminishing potential for further optimization, concerns about the limited availability and potential price increase of lithium resources, and supply chain challenges and questionable mining practices for cathode materials, such as cobalt (Schmaltz et al., 2022; Tapia-Ruiz et al., 2021). In this context, alternative battery technologies need to be developed. Two key next generation technologies are sodium-ion batteries and solid-state batteries.

Sodium-ion technology (NIBs) is rapidly catching up with the established lithium-ion technology. Techno-economic assessments suggest that NIBs offer significant potential to compete with LIBs in different application scenarios, such as stationary energy storage and low-cost vehicles. NIBs show substantial advantages in safety, compared to LIB chemistries, and have the potential for reduced cost (Tapia-Ruiz et al., 2021). NIBs are relatively close to commercialization, with battery manufacturer CATL aiming for a commercial launch a first generation of NIBs for use in electric mobility and stationary storage for 2023.

Another next generation technology under development are so-called solid-state batteries (SSB). SSBs use solid electrolytes and have the potential to be on par and even outperform state-of-the-art LIBs in several key performance indicators, such as energy density, safety, long-term stability and lifetime. The e-mobility sector is anticipated to be the main application area for SSBs in a mid- and long-term perspective (Schmaltz et al., 2022). It is expected that SSBs, based on oxide and sulfide electrolytes, will be commercialized in larger quantities in the 2025-2030 period.

The emergence and commercialisation of new battery generation technologies is likely to have implications on the circularity strategy of repurposing EVBs after the end of their first life. On one hand, improved long-term stability and extended (first) lifetime of next generation EVBs would undermine the rationale for repurposing, as batteries still would deliver adequate performance in automotive applications for a longer period. On the other hand, the emergence of low-cost NIBs would compete directly with repurposed LIBs in the market for stationary energy storage.

3.7 CONCLUDING REMARKS

Repurposing used EVBs for stationary storage applications has received increasing attention in recent years, as shown by an increasing number of research publication on the topic, as well as the deployment of numerous pilot projects around the world. In line with the experience in other pilot projects, the technical feasibility of repurposing discarded EVBs and deploying them in a second-life application for the stationary storage of solar power has been successfully demonstrated. Demand for stationary battery capacity will increase, due to continued diffusion of non-dispatchable renewable energy sources. Batteries, either new or repurposed, can also provide various grid services such as capacity support, distribution power quality or contingency grid support.

It is still debated under which conditions repurposed batteries will be able to be economically competitive with newly manufactured batteries in the stationary energy storage market. The cost advantage that repurposed batteries presently have over new batteries is expected to shrink, due to the continued learning curve and economies-of-scale in global battery manufacturing. Presently, the costs for repurposing are amplified through the lack of scale-economies and OEMs reluctance to permit repurposers access to the original battery management system.

The environmental benefits of repurposing batteries need to be carefully assessed in order to gain a better understanding under which boundary conditions repurposing could be a desirable circularity strategy. Repurposing of batteries also faces competition from the recycling pathway, which would quicker recirculate battery raw materials into the manufacturing of new EVBs.

Finally, the implication of next generation battery technologies on the availability of batteries suitable for repurposing, as well as on the market competitiveness of repurposed batteries in the stationary energy storage market are not well understood yet.

4. Government interventions and industry initiatives for a circular PV and EVB sector

This chapter provides an overview of the current status of measures taken by public and private entities which are of relevance for a circularity in the PV and EVB sectors. The chapter starts with the government interventions relevant to the circularity of both PV and EVP sectors in the EU (Section 4.1), followed by the product-specific industry and standardization initiatives (Section 4.2 and 4.3).

While the section focuses primarily on the measures taken within the EU or its member states, other measures are also discussed when relevant. The listed measures are by no means exhaustive but rather those which are closely related to our findings as presented in Chapter 2 and 3, which in turn are linked to our suggestions on pathways forward provided in Chapter 5. The description of the respective interventions and initiatives focuses on parts relevant to the circularity of PV and EVB sectors. The authors' view on the potential development of the interventions and initiatives for the further enhancement of circularity of the two sectors are discussed further in Chapter 6.

4.1 CROSS-CUTTING GOVERNMENT INTERVENTIONS

There exist a number of policy measures which are of relevance to the enhancement of circularity of both the PV and EVB sectors in the EU. Developed over the course of the last several decades, these include, among others, the EU Waste Framework Directive, the so-called Basel Convention and corresponding EU law, policies related to critical raw materials, the EU Action Plan for the Circular Economy, the EU Eco-design Directive and green public procurement.

4.1.1 EU Waste Framework Directive

Among the most long-standing EU laws pertaining to closure of material loops include the EU Waste Framework Directive (2008/98/EC), replacing the original Directive from 1975 (Directive 75/442/EEC) and the 2006 Directive (2006/12/EC) that incorporated various changes made to the 1975 Directive.

Article 3(1) of the Directive 2006/12/EC clearly establishes the so-called waste hierarchy with which “the prevention or reduction of waste production and its harmfulness” is put as priority (Article 3(1)(a)). However, despite the priority of prevention being manifested as a guiding principle behind waste management since the late 1980s (Krämer, 2003), its implementation is completely at the discretion of Member States (Krämer, 2007). The 2008 Directive, recognising the necessity of strengthening waste prevention measures (Recital 8), explicitly defines “prevention” (Article 3(12)) and reiterate waste hierarchy (Article 4). The definition of prevention are three folded and includes “measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the reuse of products or the extension of the life span of products ...” (Article 3(12)(a)). The 2008 Directive mandates Member States to put together a national Waste Prevention Programme (Article 29).

The 2008 Directive has been revised several times, with the latest change made in 2018, as laid down in Directive (EU) 2018/851 and incorporating the proposals included in the 2015 Circular Economy Action Plan (see Section 4.1.4). The revision includes the enhancement of prevention-related clauses and lists a number of measures that member states should carry out. Such measures include, among others,

- “encourage the design, manufacturing and use of products that are resource-efficient, durable (including in terms of life span and absence of planned obsolescence), repairable, re-usable and upgradable;
- target products containing critical raw materials to prevent that those materials become waste;
- encourage the re-use of products and the setting up of systems promoting repair and re-use activities, including in particular for electrical and electronic equipment ...;
- encourage ... the availability of spare parts, instruction manuals, technical information, or other instruments, equipment or software enabling the repair and re-use of products without compromising their quality and safety;...” (Article 9(1) (b)-(e)).

The revised Article 11(1) also requires Member States to take measures to encourage preparation for reuse of the items that have come into the waste stream but has the possibility to refurbish and be brought back to market. In the article the provision of access to such waste for reuse and repair networks is mandated.

4.1.2 Basel Convention & EU Waste Shipment Regulation

CIRCUSOL highlights the potential of reuse of PV modules outside of the EU (see Section 2.3). While exportation of reusable products follows the “normal” trade laws, other legislative framework needs to be followed when they become waste.

Law relevant to shipment of waste at the international level is the Basel Convention on the Transboundary Movements of Hazardous Wastes and their Disposal (hereafter Basel Convention), adapted in 1989 and came into force in 1992. Basel Convention sets rules for the shipment of hazardous waste, including certain categories of waste electronics and batteries. In the EU, Basel Convention is integrated in Member States’ legal system as the Waste Shipment Regulation (EC) No 1013/2006 of 2006, replacing an equivalent law from 1993 and is governing the transboundary movement of hazardous and non-hazardous waste, both within and outside the EU.

The 2006 EU Waste Shipment Regulation prohibits the exportation of all waste destined for final disposal to non-EU countries except for EFTA countries (Article 34). In addition, Article 36 of the Regulation *prohibits the exportation of hazardous waste to the non-OECD countries for recovery purpose*.⁴ Many of Waste Electrical and Electronic Equipment (WEEE), as specified in A1180 of Annex V Part 1 List A of the Regulation, as well as waste including cadmium, selenium and tellurium (among the substances used in PV technologies, see European Commission, 2020)) (Annex V Part 1 List A A1030) are considered hazardous. Concerning batteries, except for “waste batteries conforming to a specification, excluding those

⁴ Under the Basel Convention, until the so-called Ban Amendment that was proposed in 1994 got sufficient ratification and came into force in 2019, the transboundary movements of hazardous waste was to be controlled instead of being banned. Since the entry into force of the Ban Amendment, the Basel Convention requires essentially the same as stipulated in the EU Waste Shipment Regulation for countries that ratified the Ban Amendment (Basel Convention, n.d.).

made with lead, cadmium or mercury” (Annex V Part 1 List B B1090),⁵ essentially all the waste batteries are prohibited from exportation to non-OECD countries.

Meanwhile, *electrical and electronic assemblies destined for direct re-use*, including repair, refurbishment or upgrading, is listed among items not considered as hazardous waste (Annex V Part 1 List B B1110). This means that while it is not allowed to export PV waste to the non-OECD countries for disposal or recovery, PV modules destined for direct re-use including repair, refurbishment and upgrading. Therefore, in order to enhance the reuse of second-hand PV modules in non-EU, the smooth distinction between PV modules that are fit for reuse or not becomes crucial.

Facing essentially the same issues, Basel Convention established working groups for computers and mobile phones respectively. The working groups have produced various guidelines, providing concrete tips on, among others, the distinction between reusable and non-reusable equipment (Partnership for Action on Computing Equipment (PACE) Working Group, 2013; Mobile Phone Working Group, 2012). As it stands now, no such working group exists for PV modules (see also Section 4.2.1). The European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) carried out projects to enhance the European enforcement of the Basel Convention and the Waste Shipment Regulation (IMPEL 2004, IMPEL 2006). As further described in Section 4.2.1, the Directive on Waste Electrical and Electronic Equipment (WEEE), in its revision in 2012, inserted Annex VI which provides guidance as to how to distinguish between second-hand products and waste. The European Commission meanwhile submitted the proposal for new EU Waste Shipment Regulation in 2021 (COM(2021) 709 final). The proposal acknowledged the necessity of aforementioned distinction between reusable products and wastes from circular economy perspective and seek to empower the European Commission to develop procedure for such distinction.

4.1.3 Policies related to critical raw materials

With the global economic crisis in 2008 and accompanying threat of a steady supply of certain raw materials critical for growing manufacturing industries, many countries and regions around the world started to discuss measures to secure such supply. In the EU, this manifested itself in, among others, the adaption of European Commission’s Communication on raw materials initiatives (COM(2008) 699 final). In addition to securing supply both from the global market and within the EU, the 2008 communication raised capture of secondary raw materials via recycling as one of the three main pathways to secure critical raw materials (CRMs). This highlighted recycling, or closure of material loops as a whole, as a critical component of discourse in not only the environmental but also industrial policy arena (Tojo, 2012), contributing to the development of circular economy strategies (see Section 4.1.4). Obtaining critical raw materials continues to be an integral part of circular economy strategies, as manifested in, for instance, the report on critical raw materials and the circular economy published by the European Commission in 2018 (Bobba, Claudiu, Huygens et al., 2018).

Since the 2008 Communication was published, the European Commission has been periodically reviewing and determining critical raw materials for the EU (European Commission, n.d.b). The latest review from 2020 (COM(2020) 474 final) lists 30 materials.

⁵ There is no further note in the Regulation concerning what “a specification” entails.

The necessity of securing critical raw materials for further development of environmentally friendly technologies has been mentioned as a rationale for securing critical raw materials already in the 2008 Communication by the European Commission. A foresight study analysing the situation surrounding critical raw materials needed for technologies and sectors of strategic importance for the EU include both PV modules/renewables and batteries/e-mobility in such technologies and sectors (European Commission, 2020). Among the 30 materials listed in the latest list published by the European Commission (COM(2020) 474 final), according to the 2020 Commission's foresight study, PV cells contain borate, germanium, indium, gallium and silicon metals, while batteries in e-mobility use lithium, niobium, cobalt, titanium and silicon metal. Bodda and colleagues (2018) also highlights the current limited contribution of recycling to meeting the needs. Meanwhile, it also cites a study from 2010 indicating 95% of recycling of indium, gallium and silicon metals to be economically feasible.

4.1.4 EU action plan for the Circular Economy

While the necessity of the closure of material loop via, among others, reuse and recycling has been discussed for many decades (Section 4.1.1), with the economic and resource crisis in the late 2000s (Section 4.1.3), some material streams coming to their peak and the like there was a revival of recognition on its importance since the early 2010s. In the EU the re-recognition was manifested in the form of the first EU Action Plan for Circular Economy in 2015 (COM(2015) 614 final), which, in addition to closure of material loops from a life-cycle perspective, makes explicit links to other EU priorities, such as creating jobs and growth, industrial innovation and tackling climate change.

Based on the 2015 Action Plan, a number of follow-up activities, including the revision of many of the existing EU laws, have been induced. Such activities include, among others, the better utilisation of the so-called Eco-design Directive as discussed further in Section 4.1.5, revision of a number of waste-related EU laws (see Section 4.1.1, 4.2.1), scrutiny of interlinkages between products, chemicals and waste laws, further actions regarding critical raw materials (see Section 4.1.3) and the like. Actions particularly of relevance to PV modules and EVBs, as found in the European Commission Staff working document summarising the implementation of the 2015 Action Plan, (SWD(2019) 90 final), include:

- Proposal to develop an Implementation Regulation for solar panels and inverters under the Ecodesign Directive (See Section 4.1.5 and 4.2.2);
- Improved communication between manufacturers of electrical and electronic equipment (EEE) and their recyclers via better implementation of requirements under WEEE Directive (See Section 4.2.1);
- Development of European standards for material-efficient recycling of WEEE and waste batteries with the view to enhance recovery of critical raw materials; and
- Pilot projects for optimising e-vehicle battery usage.

The European Commission published a new Action Plan in 2020 (COM(2020) 98 final), which include both electrical and electronic equipment (EEE) which include PV modules in some laws (e.g. WEEE Directive, see Section 4.2.1) and batteries as key product value chains. The 2020 Plan proposed the development of a new law replacing the existing Battery Directive from 2006 (see Section 4.3.1), and explicitly included the facilitation of reuse and repurposing in the outline. The new plan also refers to the development of sustainable product regulation enhancing and replacing the Ecodesign Directive, whose proposal appeared in 2022 (see Section 4.1.5), as well as establishing “right to repair.”

4.1.5 EU Ecodesign Directive

The so-called EU Ecodesign Directive was originally introduced in 2005 to serve as a framework for setting ecodesign requirements for energy-using products (Directive 2005/32/EC). The 2005 Directive was replaced four years later by the Directive 2009/125/EC, expanding its scope from energy-using products to energy-related products.

The Ecodesign Directive sets the minimum requirements for the products to be put on the EU market. As of November 2022, the European Commission put together the ecodesign requirements for a total of 27 product groups (European Commission, n.d.g). While the requirements set in the implementing regulations focused predominantly on use phase energy efficiency, the potential inclusion of resource efficiency-oriented requirements has been explored (Ardente et al., 2012; Dalhammar et al., 2014). Urged also by the discourse of circular economy discussed in Section 4.1.4, some of the new requirements stipulated by the European Commission, such as the one for enterprise servers, started to include resource efficiency aspects (Mathieux et al., 2020, Peiró et al., 2020). While there is no ecodesign requirements for PV modules or batteries at the moment, the Joint Research Centre of the European Commission assessed the feasibility of applying, among others, the Eco-design implementing regulation for PV modules, along with three other instruments - Energy label, so-called ISO Type I Eco-label and Green Public Procurement (Dodd et al., 2020). As of November 2022, the assessment is open for public review and comments (European Commission, n.d.c). The content of the assessment will be further discussed under Section 4.2.2.

As of March 2022, in line with the new Action Plan for Circular Economy published in 2020, the European Commission published a proposal on the regulation on sustainable products replacing the Eco-design Directive (COM(2022) 142 final). The proposed Regulation clearly put more emphasis on circular aspects of products. Among the aspects related to reuse include product reusability, upgradability, reparability, maintenance and refurbishment, and those related to recycling include, for instance, presence of substances of concern in products, product remanufacturing and recycling (Article 1(1)). The scope does no longer put boundary to energy-using products (Article 1(2)). Moreover, the proposed Regulation introduces a digital product passport (Article 1(1), Article 8-10) to enhance information sharing among actors across the value chain. The proposal also encompasses inclusion of mandatory green public procurement in public procurement activities (Article 1(1), see Section 4.1.7).

The aforementioned Report on Critical Raw Materials by the Bodda et al. (2018) suggests potential inclusion of requirement on easier extraction at end-of-life of key components containing CRMs as well as the declaration on the content of CRMs as a potential role of Ecodesign Directive. Interestingly, the proposed Regulation on sustainable products which is meant to replace the Ecodesign Directive hardly mentioned of critical raw materials per se. This could come as part of the ecodesign requirements related to, for example, recycling, or under the specification of product passport, however.

4.1.6 ISO Type I eco-labels

There exist a number of labels that seek to indicate the superiority of a product from environmental perspective. Given the great variety of such labels, the International Organization for Standardization (ISO) introduced three typologies of these so-called eco-labels.⁶ Among them, Type I eco-labels are those “A voluntary, multiple-criteria based, third party program that awards a license which authorizes the use of environmental labels on products indicating overall environmental preferability of a product within a particular product category based on life-cycle considerations” (Global Ecolabelling Network, 2022). Originated as early as in the late 1970s, Type I labels have been introduced in some 60 countries and regions and has been governed by a government as well as an independent third party, including EU.

Originally introduced in 1992, the ISO Type I EU Eco-labelling scheme is currently governed by Regulation (EC) No 66/2010, based on which criteria has been set for 22 product groups ranging from detergents, paints to textiles and furniture (European Commission, n.d.h). The EU currently has no eco-labelling scheme for PV modules, but it is under discussion based on the study conducted by the Joint Research Centre (See Section 0 and 4.2.2).

4.1.7 Green public procurement

Green Public Procurement (GPP), as understood as “a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured.” (COM2008) 400 final, p4), has been promoted as an important policy instrument to enlarge greener products and services in the EU and elsewhere. Public entities, by utilizing their big purchasing power amounts to 14% of the GDP in the case of EU (COM(2022) 142 final), could send a clear market signal to the market by incorporating environmental-oriented criteria in their technical specifications.

Similarly to other aspects of sustainability, the use of GPP has been promoted as a way of enhancing products that are designed to be more circular, as well as business models that take circularity aspects into consideration (COM(2015) 614 final). As a support for public authorities, in addition to general guidelines for GPP, the European Commission published a guideline for circular public procurement in 2017 (ICLEI, 2017), and provides examples of best practices (European Commission, n.d.e). In order to ease the integration of green criteria in the public procurement officers of various levels of governments in the EU, the EU has also developed a set of “model” Green Public Procurement criteria for 21 products (European Commission n.d.d). As it stands now, cases regarding the integration of criteria to enhance circularity of PV modules or repurposing of batteries are not found, and no model criteria has developed for PV modules or EV batteries. However, the development of such criteria for PV modules have been proposed by the Joint Research Centre of the European Commission and is currently receiving public comments (See Section 0 and 4.2.2).

While some countries such as Japan have mandated public entities to conduct GPP and implementation of GPP became mandatory for some sectors in the EU (European Commission, 2016), uptake of GPP is essentially voluntary for public entities in the EU. This means that whether, and what concrete green criteria to include in technical specifications, as well as level

⁶ It should be noted, however, that there exist many types of eco-labels that do not fall under any of the ISO typologies, such as organic food labels, energy efficiency labels and the like.

of stringency, are left in the hands of public entities. The limitation of GPP as an instrument to promote circularity due to its voluntary nature has been recognized in the 2020 EU Circular Economy Action Plan (COM(2020) 98 final). The aforementioned proposal on regulations for sustainable products includes mandatory GPP (COM (2022) 142 final), but its final formulation and implementation are yet to be seen.

4.2 GOVERNMENT INTERVENTIONS AND INDUSTRY INITIATIVES FOR PV MODULES

This section starts with government interventions that are of particular relevance to the enhancement of circularity of the PV sector in Europe (Section 4.2.1 - 4.2.2), followed by examples of industry and standardization initiatives (Section 4.2.3 – 4.2.4).

4.2.1 Waste Electrical and Electronic Equipment (WEEE) Directive

The EU Directive on Waste from Electrical and Electronic Equipment (WEEE Directive) from 2012 (2012/19/EU), replacing the original WEEE Directive from 2002 (2002/96/EC) included PV modules under its scope. Based on the concept of extended producer responsibility (EPR), the WEEE Directive stipulates various obligation related to end-of-life management of diverse types of electronics, including PV panels (Article 2, Annex II and IV) to producers and other actors, with the intention to also incentivise producers to enhance design for repair, upgrade, reuse, disassembly and recycling (Recital 12).

In the context of the Directive, producers refer to 1) manufacturers who design, manufacture and market products under their name, 2) resellers who sell products manufactured by other actors under their name, 3) professional importers, and 4) distant sellers (Article 3(1)(f)) – a commercial actor who places a product in the market of one of the EU Member State. While transposition of the WEEE Directive into the national legislation varies (Sander et al., 2007), concrete responsibilities given to producers of PV panels or third parties acting on their behalf according to the Directive, especially relevant to reuse of PV panels, include:

- Establishment of collection mechanisms for WEEE from organisational users (Article 5(5))
- Establishment of systems for recycling and proper treatment of WEEE (Article 8)
- Achievement of recovery targets (85% of what is collected, by weight) and preparation for reuse and recycling targets (80% of what is collected, by weight) (Article 11, Annex V),
- Financing of WEEE management from private households (Article 12 and 13)
- Provision of information to facilitate preparation for reuse and environmentally sound treatment (Article 15)

As seen above, despite the introduction of the target related to the preparation for reuse in the 2012 Directive, the target is set together with recycling and does not detail the target for each one of the circular strategies. Furthermore, the weight-based targets do not incentivise the capture of high-value materials (Richter, 2019).

Regarding the information provision to actors engaged in repair, refurbishment and recycling, industry associations for home appliances and for digital transforming industry together created “I4R Platform” to enhance transparency and information flow (I4R Platform, 2022).

The Directive further requires Member States to ensure the achievement of a minimum collection rate, which from 2019 is 65% of the average weight of EEE placed on the market in the three preceding years, or 85% of WEEE generated (Article 7). WEEE Forum, one of the associations of producer responsibility organisations (PROs) carrying out responsibilities of producers on their behalf for WEEE in Europe, in their report on 2021 questions the reasonableness of these collection targets for PV panels, given their long lifetime and relatively short use periods of the panels so far (WEEE Forum, 2021).

Given the challenges of distinguishing between reusable products and waste destined for recycle or disposal in the context of shipment of such, as discussed under Section 0, the revised WEEE Directive from 2012 articulates the Member States’ concrete responsibility regarding, among others, inspections to shipment of reusable products/waste abroad (Article 23). The 2012 Directive further introduced Annex VI which outlines minimum requirements for shipments to distinguish between reusable EEE and WEEE. IMPEL (the network of implementation and enforcement of environmental law in the EU) also reviewed the implementation of Annex VI by the Member States and developed a guideline (IMPEL, 2018). The guideline contains, among others, how to test the functionality of six EEE most commonly found exported. As discussed in Section 0, however, the enforcement continued to be insufficient and led to the further measures discussed in the proposal of revised EU Waste Shipment Regulation.

Van der Heide et al. (2021) argue that the existing requirements and guideline to distinguish between WEEE and a reusable EEE have been designed with only energy consuming devices in mind. For a PV module, unlike energy consuming products whose functionality test means, in essence, whether it still works or not, this is not the case. Since its power output will gradually decrease, it is necessary to set a minimum limit for the proportion of the original power to be able to distinguish between a reusable product and waste and such testing requires special equipment to measure the remaining power output.

Recently, a call to recast EU legislation for Waste Electrical and Electronic Equipment (WEEE) has been put forward by Deutsche Umwelthilfe, ecos Environmental Coalition of Standards, European Environmental Bureau, and RREUSE (Deutsche Umwelthilfe et al., 2022). The call contains a number of proposals that are of relevance for a circular PV sector. This includes, amongst others, the (1) promotion of horizontal design and information requirements, (2) introduction of the right to repair, (3) promotion of re-use through stricter requirement for collection operations and dedicated incentive mechanisms. In October 2022, the European Commission also launched a call for evidence for the evaluation of the 2012 WEEE Directive, inviting comments from various stakeholders.

4.2.2 Preparatory studies by European Commission’s Joint Research Centre

Between 2017 and 2020, the Joint Research Centre (JRC) of the European Commission supported the Directorate General Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) in the development of the “Preparatory study for the product group ‘solar photovoltaic modules, inverters and systems’ (Photovoltaic Panels)” (Dodd et al., 2020). The study analysed the impacts of the introduction of four interventions, namely introduction of implementing regulation under the Eco-design Directive, Energy Labelling, Eco-labelling, and Green Public

Procurement. Results of modelling policy scenarios showed that a combination of the mandatory instruments (i.e. Implementing Regulation under the Ecodesign Directive and Energy Label) with voluntary Green Public procurement would be most preferable, from the perspective of increasing photovoltaic yield (Dodd et al., 2020).

The product scope of the instruments analysed in the JRC study was new products (modules and inverters) intended for use in PV systems for grid-connected electricity generation. The study proposes a number of criteria on information requirements, durability and quality, as well as installation, operation, maintenance and repairability. These criteria are relevant to different circular economy strategies, such as life-time extension, reuse, and recycling. For the instruments of Eco-design Directive, ecolabeling, and green public procurement, Tables 4.1 – 4.3 provide an overview of selected proposed criteria and requirements for PV modules that are relevant from a circularity perspective.

Table 4.1 Implementing regulation under the EU Ecodesign Directive: proposed requirements for modules (selection of criteria with regard to circularity), adopted from Dodd (2020)

Performance aspect	Detailed proposed requirements
Information requirements	
2.2.3 Repairability	<p>The manufacturer shall report on:</p> <ul style="list-style-type: none"> the possibility to access and replace the bypass diodes in the junction box, the possibility to replace the whole junction box of the module <p>Note: the possibility exists to prescribe reparability, or to include a semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for reparability prEN 45554.</p>
2.2.4 Dismantleability	<p>The manufacturers shall report on the potential to separate and recover the semi-conductor from the frame, glass, encapsulants and backsheet. Design measures to prevent breakage and enable a clean separation of the glass, contacts and internal layers during the operations shall be detailed.</p> <p>Note: the possibility exists to prescribe that full material dismantleability is ensured, or to include a semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for recyclability prEN 45555.</p>
2.2.5 Material disclosure	<p>The manufacturer shall declare the content in grams of the following materials in the product: Antimony; Cadmium; Gallium; Indium; Lead; Silicon metal; Silver; Tellurium</p> <p>For the encapsulant and backsheet the manufacturer shall also declare the type of polymers used (including if it is fluorinated or contains fluorinated additives) and the content in grams.</p>

Table 4.2 Preferred EU Ecolabel criteria set for modules, inverters and services (selection of criteria with regard to circularity), adopted from Dodd (2020)

Performance aspect	Detailed requirements
4.3. Circular economy criterion	
4.3.1 Module durability and quality	Design type approval proposed as an Ecodesign requirement shall be implemented by an audited factory quality control system in accordance with IEC TS 62941 and IECRE OD 405 series.
4.3.2 Module degradation rate	Declaration of the rate shall be validated by the Transitional Method for Ecodesign and demonstrate an average performance degradation rate over a 30-year time period of 0.6%
4.3.3 Module design for recycling	The manufacturer shall document and report the sequence of steps and tools required to dismantle the module and recover the solar cells or semi-conductor material.
4.3.4 Inverter on-site repair service	The installer shall ensure that a responsive repair service is provided for inverters, with on-site replacement of the main circuit boards forming part of the service.
4.3.5 Repairability requirements for inverters	<30 kW: The manufacturer shall ensure that the power, filter and communications circuit boards as well as firmware updates shall be made available for a minimum period of 7 years. >30 kW: Manufacturers shall ensure that replacement parts and firmware
4.5 System service criteria	
4.5.2 Handling and installation protocols	The contractors used to install the system shall follow a protocol designed to minimise any breakages to modules during transport to and handling on site.
4.5.3 Monitoring and maintenance	The service shall include, for a minimum of 10 years, the monitoring of the system for faults and a responsive repair and maintenance service designed to optimise performance. This shall include, as a minimum (1) fault diagnosis, (2) repair and replacement cycles for major components, and (3) cleaning of the modules.

Table 4.3 GPP criteria set for PV system procurement (selection of criteria with regard to circularity), adopted from Dodd (2020)

Performance aspect	Detailed proposed requirements
Installation / construction	
5.1.5 Handling and installation protocols	<p><i>Selection Criteria evidencing the use of such protocols and/or Technical Specification requiring specific actions within a protocol.</i></p> <p>The tenderers for installation of the system shall follow a protocol designed to minimise any breakages to modules during transport to and handling on site.</p>
5.1.6 Commissioning test	<p><i>Contract performance clause based on the target plant Performance Ratio</i></p> <p>A commissioning test shall be carried out according to IEC 61724 in order to evaluate the Performance Ratio of the system. The commissioning PR shall be compared with the target plant Performance Ratio declared at bid stage.</p>
Operation & maintenance	
5.1.7 Inverter preventative repair cycle	<p><i>Technical Specification based on planning to respond to inverter manufacturers recommended repair cycle</i></p> <p>In order to use a longer inverter lifetime than the default for the life cycle GWP calculation tenderers shall provide a recommended preventative maintenance cycle. This shall include a list of parts recommended to be replaced and preventative measures to achieve an intended design technical lifetime.</p>
5.1.8 Monitoring	<p><i>Technical Specification/Award Criteria for the granularity of monitoring system</i></p> <p>The tenderers shall ensure that the system design supports class C data monitoring according to IEC 61724-1.</p> <p>The system shall have physical and/or wireless connectivity capable of communicating with remote monitoring systems using a recognised data transfer protocol.</p>
5.1.9 Maintenance	<p><i>Technical Specification/Award Criteria for the provision of aftercare services</i></p> <p>The service shall include, for a minimum of [award] years, a repair and maintenance service designed to optimise performance. This service shall include, as a minimum (1) fault diagnosis, (2) responsive repair and planned replacement cycles for major components, and (3) cleaning of the modules.</p>

4.2.3 Labelling and certification protocols for second-life PV

One key objective of the CIRCUSOL project has been to develop labelling and (re)certification protocols for second-life PV modules. This involved the development of procedures for the decommissioning of PV installations, and the quality inspections and repairs that have to be done before the decommissioned modules can be re-used again. The recommendations have been summarized in CIRCUSOL report D3.2 (van der Heide, 2022). The guidelines, as developed in the CIRCUSOL task group, address the following aspects:

- Evaluation of module re-use before PV plant decommissioning
- Visual inspection & test methods for decommissioned modules
- Repair options for decommissioned modules
- Testing and sorting of decommissioned PV modules
- Labelling of decommissioned modules

To standardize the preparation of PV modules for reuse, the CIRCUSOL task group proposes (1) to impose minimal testing requirements on visual inspection, electrical performance and safety tests (with clear protocols to follow), (2) to set clear quantitative criteria for PV module quality selection, e.g. PV modules >80% initial performance and without safety concerns can be retained, and (3) to provide product warranty of 1-2 years, and (4) to include labelling & documentation requirements (van der Heide, 2022).

The CIRCUSOL task group has delivered a presentation IEC technical committee TC82 “*Solar photovoltaic energy systems*”, working group 2, in April 2021. The objective is to start a project group that will use the CIRCUSOL recommendations concerning quality tests for module reuse in order to make adaptations to existing international standards on PV modules and PV systems, and introduce a new standard if necessary. It is estimated that the whole process of standardisation will take 3-4 years. The next step will be the formation of a project group and the writing of a technical report which will serve as a basis for adaptations in standardisation.

4.2.4 Ecolabelling for PV modules

The Global Electronics Council (GEC) owns and operates EPEAT⁷, a voluntary sustainability ecolabel. GEC launched a new EPEAT category for PV Modules and Inverters (PVMI) in October 2020. The criteria for this product category are based on NSF/ANSI 457 – 2019 Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters (NSF/ANSI, 2019), addressing several attributes and environmental performance categories, such as management of substances, use of preferable materials, energy efficiency, water use, responsible end-of-life management, design for recycling, product packaging, and corporate responsibility. With regard to circularity, EPEAT criteria include specifications for recycled content and design for recycling. Manufacturers are also encouraged to consider reuse as an option in the hierarchy of management of used products. However, EPEAT criteria do include more specific requirements, specifications or targets with regard to reuse of PV modules and inverters. As of December 2022, only PV modules of the cadmium tellurite (CdTe) type from one manufacturer are registered in the EPEAT database.

In 2021, a novel Environmental Impact Index for PV modules has been proposed in a position paper by a consortium composed of the PV European Technology & Innovation Platform

⁷ <https://www.epeat.net>

(ETIP-PV), SolarPower Europe, PVthin, European Solar Manufacturing Council, and IECRE (Wade et al., 2021). The aim of this initiative is to translate the complexity of an environmental assessment into an abbreviated form, e.g. a scoring system. The proposed score is based on the holistic evaluation of sustainability performance through an Environmental Impact Index (EII). The sustainability criteria of the proposed index include (1) life-cycle global warming potential / embodied carbon footprint, (2) life-cycle primary energy use / energy payback time, (3) hazardous substances, (4) recycled content, (5) recyclability & repairability, and (6) quality. With regard to circularity project, the criteria in relation to recyclability, repairability and quality are particularly relevant. It is noteworthy that a detailed standard methodology for the determination of the repair- and recyclability for photovoltaic modules and inverters still has not been defined. The initiative proposes to develop those vertical product group standards in conjunction with the existing horizontal standards for electronic products IEC 45552 through IEC 45559.

4.3 GOVERNMENT INTERVENTIONS AND INDUSTRY INITIATIVES FOR ELECTRIC VEHICLE BATTERIES

Following the sections on PV, this section starts with government interventions that are of particular relevance to the enhancement of circularity of the EVB sector in Europe (Section 4.3.1 - 4.3.2), followed by examples of industry and standardization initiatives (Section 4.3.3 – 4.3.7).

4.3.1 Batteries Directive

The existing EU law concerning the circularity of batteries, as of November 2022, is Directive 2006/66/EC, replacing the previous Directive 91/157/EEC. The Directive prohibits the use of certain heavy metals in batteries while setting requirements for collection, recycling and treatment of batteries sold in the European Union with the overall aim of improving the environmental performance of batteries and accumulators (Article 1). The 2006 Directive covers all types of primary and secondary batteries (accumulators) except for those used for defense purposes (Article 2), and divide them into three categories: portable, vehicle and industrial. The latter includes all batteries designed exclusively for professional and industrial applications, or for electric vehicles (EVs) (Article 3(6)). The vehicle battery category instead refers to the starter battery in cars (Article 3(5)).

The Directive 2006/66/EC considers actors who put batteries or accumulators (including those which are in other products) on the market of one of the EU Member States for the first time (Article 3(12)). Requirements stipulated in the Directive that are relevant to producers of EV batteries include:

- Prohibition of the use of mercury and cadmium (Article 4(1));
- Acceptance of waste batteries from end-users regardless of chemical composition and origin (Article 8(3));
- Achieve recycle rate of 50% by weight (Article 12, Annex III Part B (c)) and treat the waste batteries as specified in Annex III Part A; and
- Financing of collection, treatment and recycling unless otherwise agreed with users (Article 16(1)(b) and 16 (5)).

The terms “second-use”, “second-life” or “repurpose” are not used in the text of the existing 2006 Directive even after its latest amendment in 2018.

In April 2019, the European Commission published a report on the implementation, the impact on the environment and the internal market functioning resulting from the Batteries Directive (European Commission, 2019). While the report highlighted various strengths and achievements of the Directive, it also highlighted areas of improvement both in terms of the Directive’s as well as its implementation. Highlighted issues of particular relevance to the circularity of EV batteries include:

- Strong focus on end-of-life phase: while the 2006 Directive has contributed to circular economy through its focus on the environmental impacts of end-of-life phase of batteries, it lacks though a life-cycle and broader circular economy perspective, such as enhancement of reuse.
- Lack of mentioning of second-life of batteries: in relation to this, the Directive has not considered second-life of batteries, which was unexpected when the Directive was

developed. This creates legal uncertainty as to e.g. whether second-life batteries are waste or not, the end point of the responsibility of original battery producers, and the like.

- Insufficient provision on material recovery: except for lead-acid and nickel-cadmium batteries, recycling efficiency targets for all other batteries, including lithium-based ones, is 50% by weight. The Directive does not set any quality-based requirement for recycled materials, nor does it set any requirement specific to materials. This does not assure the capture of materials such as lithium and cobalt which are considered critical.
- Limited producer responsibility for collection: Unlike other types of batteries, the 2006 Directive does not require producers of industrial batteries, including those used in EV, to set up collection infrastructure. Nor there is any requirement for meeting a certain collection rate. These would make the collection of such batteries ineffective, which further reduce the capture of materials. Life-cycle analyses do indicate that repurposing batteries for stationary energy storage results in more efficient use and a longer depreciation of the used raw materials (Bobba, Mathieux, et al., 2018).

4.3.2 The New Batteries Regulation Proposal

Following the evaluation of the Batteries Directive 2006/66/EC, and as part of the Circular Economy Action Plan (Section 4.1), in December 2020 the European Commission published a proposal for a new batteries regulation which is to replace the 2006 Batteries Directive (COM(2020) 789 final). As of 9 December 2022, the European Parliament and the Council comes to the provisional agreement of the legal text (European Commission, n.d.).

The objective of the New Batteries Regulation Proposal is to enhance the functioning of the EU's internal market with a set of common rules across Europe, promote circular economy, and alleviate social and environmental impact from life-cycle perspective (COM(2020) 789 final). Given the rapid and wider spread of electric vehicles and its importance in relation to EU's climate goals, as well as lack of provisions specific to EV batteries in the 2006 Directive and its negative implications, the proposal separate EV batteries from industrial batteries (Article 1(2), Article 2(12)). Moreover, a number of provisions related to second-life and repurposing of EV batteries are introduced.

These include, amongst others:

- Requirements related to EVB's performance and durability (Article 10).
- Requirements of incorporating in EVBs a "battery management system" containing data related to state of health and expected lifetime of batteries (Article 14(1), Annex VII).
- Guarantee non-discriminatory access to the battery management systems of batteries to the legal or natural person who has legally purchased the battery or any third party acting on their behalf at any time in order to facilitate reuse and second-life use of batteries in various ways (Article 14(2)).
- Establishment of an electronic exchange system, which stores characteristic information and data of each EVB's type and model. Such information and data "shall be sortable and searchable, respecting open standards for third party use" (Article 64(2)).

- Introduction of an electronic record called “battery passport” (Article 65), which is expected to, among others, provide second-life EVB operators with a better knowledge base. The battery passport will be linked to the data and information stored in the electronic exchange system as articulated in Article 64.

In addition, the proposal includes a number of provisions that directly or indirectly enhance recycling and recovery of specific materials, thereby closing the material loops, reducing supply risks and reducing environmental and social impacts arising from mining of such materials. Examples of such provisions include minimum recycled material content requirements for cobalt, lead, lithium and nickel (Article 8(2)(3)), information provision of the actual content of these materials (Article 13(5)(h)), obligation to establish supply due diligence policies (Article 39), establishment of extended producer responsibility system, which includes organisation of separate collection system (Article 47) and free take back requirement from end users (Article 49).

4.3.3 ANSI/CAN/UL 1974 Standard for evaluation for repurposing batteries

In October 2018, ANSI/CAN/UL 1974 was published as the first dedicated standard for evaluation for repurposing batteries. UL1974 covers the sorting and grading process of battery packs, modules and cells that were originally configured and used for other purposes, such as electric vehicle propulsion, and that are intended for a repurposed use application, such as for use in stationary energy storage and other applications. It applies to all battery chemistries (Lion and others) and also to electrochemical capacitors. UL1974 proposes a list of essential guidelines and requirements to be followed by manufacturers, starting from the collection of batteries that were originally used for other purposes, up to the repurposed product to be used in other application. The standard addresses aspects of (1) construction, (2) quality control and safety of facilities for repurposing, (3) examination of incoming samples, and (4) performance. The requirements for packing and shipment, quality control and safety of facilities are similar to battery standards requirements for first-use batteries (Mulder et al., 2022).

4.3.4 IEC 63330 Requirements for repurposing of secondary batteries

In CIRCUSOL, a key objective has been to develop labelling and (re)certification protocols for second-life batteries. In parallel, work has started at the international level (IEC) towards the development of second-life battery standards. Two working groups, with CIRCUSOL partners CEA and VITO being actively taking part in, have been started at the International Electrotechnical Commission (IEC), Technical Committee (TC) 21 (Secondary cells and batteries),

TC 21 is presently developing standard *IEC 63330 Requirements for repurposing of secondary batteries*, with its publication foreseen by about the end of 2023 (IEC, 2022). The standard mainly focuses on lithium batteries, but is not limited to them (Mulder et al., 2022). The standard provides a classification for the repurposing of batteries, taking into account their residual performance and useful life. The classes range from A1 to C3, see Figure 4.1. The classes are related to hard criteria for classification, which have been developed as part of the battery assessment procedure, developed within the respective task group of the CIRCUSOL project (see Section 4.3.7).

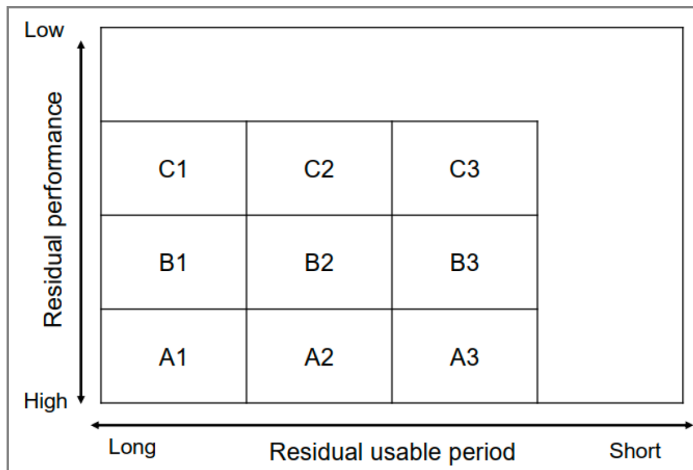


Figure 4.1 Repurposing classification as a function of remaining performance and period of use (Mulder et al., 2022)

Furthermore, the standard prescribes whether or not to perform safety tests for repurposed batteries. If the battery is used within the estimated useful life of its primary use, and within the same operating range and operating environment, e.g. ambient temperature, humidity, dust, vibration, with a lower load than original, then the original design of safety and performance remains valid. If the design (connections, cooling, battery management system, contactors, etc.) of the repurposed battery is changed then the original safety design no longer applies. In this case, safety must be proved by an evaluation of the new safety design required for the new use (Mulder et al., 2022).

4.3.5 IEC 63338 General guidance for reuse of secondary cells and batteries

In parallel to the development of IEC 63330, subcommittee 21A initiated a request called “General guidance for reuse of secondary cells and batteries” (IEC 63338), with a focus on lithium-ion and nickel-metal-hydride. The standard is intended to assist in refurbishing and repurposing of these battery types. Cell-based reuse is not recommended because the desired conditions of use, especially with regard to functional safety, cannot be guaranteed (Mulder et al., 2022).

The standard provides guidance on a range of aspects, ranging from data tracing and exchange, environmental aspects, risk and safety, and requirements on the type of information to provide to users of second-life batteries. Specifically, the standard provides recommendations on the type of data to be stored in the Battery Management System (BMS) during the battery’s first life. This data includes the histories of overcharge, over-discharge, overcurrent, external short circuit, the insulation value and/or insulation faults, excessive shock and vibration, results of the BMS self-diagnosis, as well as error history concerns BMS communication with the application side (Mulder et al., 2022). Furthermore, the standard places emphasis on additional battery lifetime traceability data, such as data on accidents and storage conditions (Mulder et al., 2022).

In addition, the standard gives guidance on destructive safety tests. It also gives guidance on what type of information to provide to users of reused batteries, including information on the operating range (such as voltage and temperature), potential hazards at the end of a battery's

life, and responsibilities of the OEM to communicate the principal suitability of a battery for reuse (Mulder et al., 2022). The intended date of publication of IEC 63338 is December 2023.

4.3.6 CEN-CENELEC

In the context of the EU Strategic Action Plan on Batteries, the European standardisation body CEN-CENELEC are developing standards concerning the performance and durability aspects of portable rechargeable and non-rechargeable batteries and their re-use and repurposing. Technical committee CLC/TC 21X ‘Secondary cells and batteries’ supports the International Electrotechnical Commission activities by working with IEC counterpart IEC/TC 21 and implementing IEC documents into CENELEC standards. In alignment with IEC, the committee presently works on the development of standard *EN IEC 63338 General guidance for reuse of secondary cells and batteries* (CEN-CENELEC, 2022a). Implementation of IEC 63300 into CENELEC standard *EN IEC 63300 Requirements for reuse of secondary batteries* is currently in the enquiry stage (CEN-CENELEC, 2022b)

4.3.7 CIRCUSOL battery assessment procedure

The development of labelling and (re)certification protocols for second-life batteries have been one key objective of the CIRCUSOL project. The proposed assessment procedure and diagnosis methods, as developed by the respective task group, are summarized in CIRCUSOL report D3.4. Given the time, risks and costs associated with dismantling and reassembling batteries into new packs, direct repurposing is preferred. Reuse through dismantling is more complicated, and detaching individual cells is practically only feasible if they are mechanically assembled, which is rarely the case (Mulder et al., 2022).

In the proposed test procedure, the repurposing of the batteries is divided into two parts: (1) a preliminary stage when selecting incoming batteries, and (2) the actual repurposing process. The underlying idea of this two-step procedure is to carry out time-consuming tests as much as possible only at the point when most unsuitable batteries have already been removed. Figure 4.2 gives an overview of the key steps of the repurposing process, which are described in detail in Mulder et al. (2022).

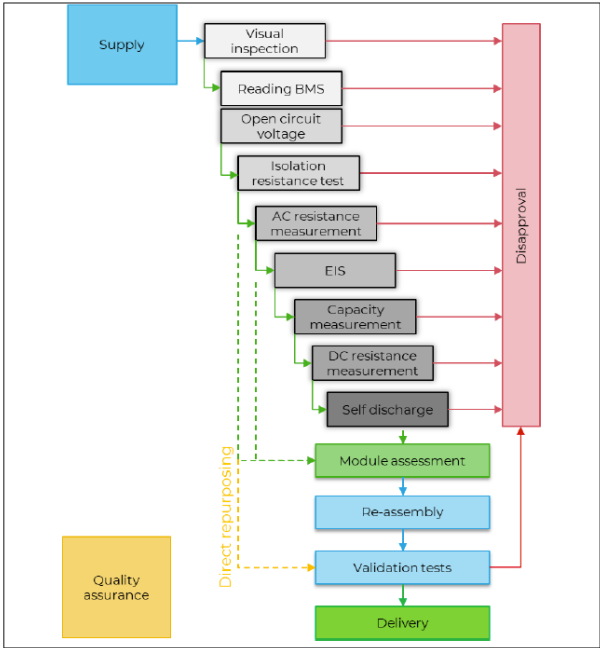


Figure 4.2 Course of the repurposing process (Mulder et al., 2022)

Incoming batteries have different quality, and this test procedure provides the basis for sorting batteries, depending on their residual performance and their residual lifetime, see Figure 4.1. This screening allows determining to which kind of second-life applications individual batteries are suitable, enabling the repurposer to use a larger part of the supply.

In the preliminary phase, a number of criteria can be used, including (1) actual capacity, (2) internal resistance, (3) maximum and minimum open circuit voltage (OCV), (4) spread of the open circuit voltage between cells in a module or over the entire pack, (5) insulation resistance, amongst others. Measurement results are benchmarked against application-specific reference values, which will then determine into which selection bin an individual battery will be sorted into. Table 4.4 shows an example of how the sorting bins can be formed.

Table 4.4 Example from sorting method to application and quality. The worst feature determines the category: a battery with 92% capacity and 130% resistance ends up in bin A2 (Mulder et al., 2022)

Criteria			Bin	
Actual capacity	Internal resistance	Spread in OCV	Application	Quality
95-90%	100-120%	0-5 mV	A	1
90-85%	120-150%	5-10 mV	A	2
85-80%	150-200%	10-15 mV	B	1
80-75%	„	„	B	2
75-70%	„	„	B	3
<70%	> 200%	> 15 mV	Recycling	–

5. Discussion on potential pathways forward

This chapter offers ideas and suggestions on potential pathways forward. They are based on the findings of the CIRCUSOL project and on the literature of barriers towards a more circular PV and EVB sectors, as summarized in Chapter 2 and 3 of this document. In the discussion we also reflect upon the existing and emerging landscape of government interventions, industry and standardization initiatives, as well as ongoing R&D projects, as described in Chapter 4, and propose some additional action points. The 10 potential pathways forward discussed in this chapter are:

- Address premature defects and decommissioning
- Enhance design for circularity & recovery of CRMs
- Advance preparation for reuse
- Establish data collection and sharing procedures
- Address legal-administrative barriers for service-based business models
- Investigate feasibility of reuse in underexplored EU market segments
- Investigate feasibility of reuse and address end-of-life management in non-EU countries
- Actualise and implement EU battery regulation proposal and standardization for reuse of EVBs
- Strengthen public perception of circular PV and EVBs
- A research agenda for a circular PV and EVB sector

5.1 ADDRESS PREMATURE DEFECTS AND DECOMMISSIONING

Background & problem

PV modules suitable for reuse in a 2nd life application primarily descend from early-and mid-life failures, damage from extreme weather events, other insurance claims, and early repowering. However, from a societal viewpoint, and unless (roof-)space is a limiting factor, reaching a 30-years service in the 1st-life application would be desirable from an environmental perspective. Hence, reducing the rate of early-and mid-life failures would be desirable (Section 2.2 and 2.3).

Potential pathways forward

Reducing the rate of early- and mid-life failures in first-life PV applications could be achieved through the continued development of life-cycle quality management, including good operation and maintenance practices, all of which would contribute to ensure that solar power systems reach a long lifetime. Many of the green public procurement criteria as well as criteria on Type I eco-labels, as proposed in the preparatory study by European Commission's Joint Research Centre (Table 4.2 and 4.3), would encourage such practices. Thus, uptake of such criteria by the public sector when purchasing PV systems and/or services, as well as industry's uptake on eco-labels, would help spread the practices. Information sharing of good practices via, e.g. workshops for operators who are engaged in the maintenance of PV modules, would serve as another example of concrete action.

In addition, in order to avoid early repowering, we also propose to introduce routines and incentive schemes to prevent early decommissioning, and to enable viable operation of solar power systems for the time when the initial support scheme (e.g. a feed-in-tariff scheme) has expired. The application of aforementioned green public procurement criteria would also address early decommissioning. Mandating the PV system actors engaged in actual installation of the PV panels to (1) keep records of the operational duration of PV modules they install, and (2) provide periodical inspection and maintenance services, could be also considered. Alternatively, inclusion of such information could be mandated as part of the data contained in battery passport in the upcoming Batteries Regulation (Section 4.3.2).

5.2 ENHANCE DESIGN FOR CIRCULARITY & RECOVERY OF CRM

Background & problem

In general, PV modules and EV batteries have not been designed for repair, recycling and recovery of various components and materials, including critical raw materials. This in turn pose challenges to various operations to enhance circularity – repair and repurposing of these products, as well as recycling and recovery of components and raw materials (Section 2.4 and 3.4).

Potential pathways forward

Similar to the actions taken by a number of producers when facing EPR-based laws (see for instance, Tojo (2004), van Rossem (2008)), producers of PV modules and EV batteries should incorporate consideration on circularity at the design stage of their products. This could be done by, for example, including aspects that enhance circularity – anything from reducing the number of parts, using reduced number of materials and components, to provision of information – in their design manuals. Cross-sector learning could be enhanced by, for example, engaging design personnel from cars and electronics industries in providing trainings for PV modules and EV battery industries.

For PV modules, proposals in the preparatory study of eco-design implementing regulation, as well as that of EU Type I eco-labels (Section 4.2.2) contains relevant design specifications, thus it would be useful when these proposals come into reality. Similar to the proposed Battery Regulation (Section 4.3.2), revising the existing WEEE directive (Section 4.2.1) and stipulating specific recovery targets for critical raw materials or the use of recycled content, could also be considered. The use of a digital product passport, as found in the proposal for sustainable product regulation replacing the existing Ecodesign Directive (Section 4.1.5), would also enhance communication between actors in the value chain. CIRCUSOL has already developed a prototype of an asset database that could serve as the host for such a digital product passport.

Concerning EV batteries, as discussed in Section 4.3.2, the proposed new Batteries Regulation contains a number of provisions, such as minimum recycled material content requirements for selected metals, mandatory information provision of the actual content of these materials, as well as obligation to establish supply due diligence policies, which relate to enhancement of quality recycling and recovery of critical raw materials.

5.3 ADVANCE PREPARATION FOR REUSE AND REPURPOSING

Background & problem

To date, guidelines and standards for preparation of reuse of PV panels have been lacking, and those for repurposing of EV batteries for second-life is at its infant stage. CIRCUSOL has made key contributions to the development of guidelines and standards for preparation of reuse of PV panels, as well as repurposing of EV batteries (Section 4.2.3, 4.3.4, 4.3.5).

Potential pathways forward

The third pathway we suggest is to advance preparation for reuse via establishment of various supporting measures. Various contributions on guidelines and standards for preparation of reuse of solar panels, as well as repurposing of EV batteries, such as those developed through CIRCUSOL, should be further adopted and mainstreamed.

To date, the volume of PV modules that are decommissioned and are potentially suitable for reuse has been rather modest, due to the generally long lifetime of the technology as such.⁸ As described in Chapter 1, waste volumes are expected to increase significantly in the future. Providing refurbishers with access to solar panels suitable for refurbishment and resale will be a key issue then. This has been considered as among the key challenges facing refurbishers in the implementation of the WEEE Directive for other products. As found in, for examples, the Finnish transposition of the WEEE Directive, requiring the so-called producer responsibility organisation to provide refurbishers with access to refurbishable products could be mandated at the EU level.

Another issue is that the cost of preparation for reuse currently accounts for a significant part of the retail price of second-life panels, due to the relatively high level of labour involved. A potential solution would be to stimulate the development and adoption of further automation techniques for these processes to bring down the costs for testing and re-certification. Policy makers could facilitate this by supporting R&D in this area.

A third issue is that currently routines and workers' vocational skills are lacking on how to disassemble solar modules without damaging them. Development of guidelines for the dismantling of solar installations as well as for the transport and handling of modules should be developed, to ensure the quality and integrity of decommissioned modules that are suitable for reuse. Such guidelines could be integrated into existing handbooks on good operation and maintenance (e.g., IRENA, 2017; Solar Power Europe, 2021). In addition, provision of hands-on training in this area could be of great use.

⁸ Simulations carried by CIRCUSOL provide projections until 2050 of the volumes of PV modules available for reuse and recycling (Franco & Groesser, 2022).

5.4 ESTABLISH DATA COLLECTION AND SHARING PROCEDURES

Background & problem

A key challenge facing the advancement of more effective recycling processes, repair, and re-use activities, as well as estimation of “active” installed PV capacity and track waste, and re-use volumes, is lack of reliable information (Section 2.4).

Potential pathways forward

To address this challenge, establishing data collection and sharing procedures would provide firms across the value chain with relevant data to enable more effective reuse and recycling activities. In the CIRCUSOL project, a database facilitating the collection and sharing of relevant information was developed as a pilot platform. But this also requires manufacturers to disclose information and enable sharing through e.g. QR codes, RFID tags, or other technologies.

Article 15 of the 2012 WEEE Directive mandates the provision of information to manufacturers regarding the properties of products relevant for reuse and recycling, and there is an on-going initiative to enhance the exchange of such information (Section 4.2.1) However, even when the information on properties of products that actually reach actors engaged in reuse, refurbishing and recycling activities, it does not help in identifying and distinguishing the fate of used products (e.g. which products/components are suitable for reuse), as well as their whereabouts. The utilisation of digital product passport, as discussed in the proposed sustainable product regulation (Section 4.1.5) and batteries regulation (Section 4.3.2), could provide a good solution for the determination of fate. Moreover, mandatory record keeping and data sharing on the panels that are actually installed, as suggested in Section 5.1 would also help enhance data tracking.

On top of this, there is a need for R&D to understand the impact of different databases, information-sharing practices, and digital technologies towards recyclability, reparability, and other circular strategies.

5.5 ADDRESS LEGAL-ADMINISTRATIVE BARRIERS FOR SERVICE-BASED BUSINESS MODELS

Background & problem

In the CIRCUSOL project, demonstrator projects have experienced various types of legal-administrative challenges in the implementation of PSS / service-based business models (Section 2.5). One example experienced by CIRCUSOL solar firms in both Belgium and Switzerland is the high costs and administrative effort involved for solar service firms to secure ownership rights of service-based PV systems in the cadastre registry. Such registration is important for providers of service-based solar power offers in order to safeguard the firm’s right of ownership to PV systems that are deployed on the property of their clients. The high cost for the cadastre registry, however, poses an economic barrier to the financial viability of service-

based solar power business models. Solar firms in the CIRCUSOL consortium have highlighted the need for an efficient and low-cost registration system for solar-as-a-service models.

Potential pathways forward

A potential alternative and solution to this present practice of costly and time-consuming entries in public cadastres would be the establishment of a dedicated European-wide registration system for PSS installations. In this registration system, solar firms would record PSS-enabled PV systems that are installed on users' premises but remain under the firm's ownership. Upon any real estate sale, notaries would be obliged to verify the ownership of certain technical installations, such as PV systems, that are installed on the property. This approach would safeguard the firm's right of ownership to the PV system at presumably much lower transactions costs than the current practice.

The scope of the database should not only comprise PV and battery storage systems, but should extend to a range of energy and space conditioning technologies (e.g. heating, ventilation, lighting, air conditioning, etc.) for which PSS models could be an important catalyst for roll-out. With the aim to facilitate the accelerated diffusion of PSS-enabled low-carbon end-user technologies, including service-based circular solar power and battery systems, we therefore recommend to European legislators to mandate the establishment of a PSS registration system. Unlike the fragmented system of local and national cadastre registries, a European-wide PSS registration system would furthermore facilitate the uptake of successful PSS models across Europe.

Another type of legal-administrative barriers found are rooted in specific legislation, the Electricity Tax Implementing Ordinance in Germany, leading to excessive bureaucratic efforts for a firm engaging in off-grid solar-powered charging services for micro-mobility providers (Section 2.5). Such type of barriers to novel service-based business models can be very context specific, and depending on the issue, will have to be addressed by making amendments in specific national and subnational legislation.

5.6 INVESTIGATE FEASIBILITY OF REUSE IN UNDEREXPLORED EU MARKET SEGMENTS

Background & problem

In developed, high-incomes economies (such as the locations of the CIRCUSOL demonstrator sites), PV systems with new components remain the preferred choice, as consumers rely heavily on high efficiency, aesthetics, and warranties. In addition, low-financing costs and good availability of capital, particularly in the market segment of home owners, enable user to purchase new PV systems. There is also still a prevailing mentality for ownership among these user groups. As such, user interest in second-life PV and service-based business models has been found modest (Sections 2.2 and 2.3).

Potential pathways forward

The sixth pathway would therefore be to investigate the feasibility of reuse in underexplored EU market segments. Currently, user interest in second-life solar and service-based business models has been found rather modest. However, these barriers may be less relevant in other

market segments such as the commercial and public sector. One concrete policy measure to enhance demand in this area is to enhance the uptake of green public procurement (Section 4.1.7) that incorporate the use of second-life PV panels and/or service business models as part of the awarding criteria. The green public procurement criteria proposed in the preparatory study of the European Commission Joint Research Centre (Section 4.2.2) does not refer to such inclusion, but it could be included as an option for public authorities to consider as part of the GPP criteria. Uptake of second-life PV modules by the public sector and its visibility would most likely have a positive effect on the perception of citizens in their own usage of second-life PV modules, as discussed further in Section 0.

In addition, we propose further investigation of the market viability of second-life solar panels for novel applications such as agrivoltaics, floating PV, and off-grid solutions, as well as European countries with middle income levels, where reused panels potentially could play out their cost advantage.

5.7 INVESTIGATE FEASIBILITY OF REUSE IN NON-EU COUNTRIES

Background & problem

As mentioned in Section 5.6, in developed, high-incomes economies PV systems with new components remain the preferred choice, limiting the market for second-life PV systems. Presently, export of used, functional PV panels to non-EU countries is not well regulated. Existing export regulation is poorly enforced. In many non-EU countries, there are risks with uncontrolled end-of-life management of PV components, entailing environmental risks (e.g. leaching of metals (e.g. lead)), social and health risks in uncontrolled landfilling, loss of (critical) raw materials, and reputational risks for the PV industry as a whole. Despite these challenges, the use of second-life PV systems in many of the non-EU, low-income countries have great potential in providing electricity, especially in areas not connected with the electricity grid.

Potential pathways forward

Given the background mentioned above, we consider it meaningful to explore opportunities for the responsible deployment of second-life solar panels in low-income countries that are characterized by lacking access to grid electricity / energy poverty, but often have good solar irradiation potential. This should come with the ensurance that only functional modules of good quality are being exported outside the EU. On this note, the guidelines that the Basel Secretariat has developed for the distinction of reusable mobile phones and computers from their waste counterparts (Section 4.1.2), as well as the provision within the WEEE Directive and guideline developed by IMPEL on the distinction of several other second-life products from their waste (Section 4.2.1) could serve as an inspiration. The EU could perhaps collaborate or support the Basel Secretariat to develop such a guideline for PV modules, taken into consideration the specific characteristics of energy producing products. The guidelines developed under the CIRCUSOL project as described in Section 4.2.3 could serve as a good starting point.

Furthermore, measures should be taken so that facilities for the treatment of solar waste should be developed locally in low-income countries to avoid uncontrolled landfilling at the end-of-life stage. In this area, policy approaches taken to tackle illegal harvesting of timbers in countries outside of their jurisdiction might provide an inspiration. Namely, in addition to the

demand-side policy (the so-called EU Timber Regulation ((EU) No 995/2010)), the EU has been seeking to conclude so-called Voluntary Partnership Agreements (VPAs) with timber harvesting nations to ensure that EU only imports legally harvested timber products (European Commission, n.d.a). The approach of the latter could be adapted to support the sound development of infrastructure for management of PV modules which eventually become waste.

5.8 ACTUALISE AND IMPLEMENT EU BATTERY REGULATION PROPOSAL & STANDARDIZATION FOR REPURPOSING OF EVBS

Background & problem

To date, the lack of dedicated policies, legislation and standards to support repurposing of used EVB batteries has hindered development of the market for second-life batteries.

Potential pathways forward

Our eight pathway is to support the adoption and implementation of the new battery regulation proposal and related standards. As described in detail in Section 4.3.2, once adopted, the new battery regulation proposal is anticipated to support repurposing and market development of second-life batteries. Adoption of the law would also enhance circularity by, among others, mandating the use of secondary raw materials.

Needless to say, whether the proposed regulation provides various effects as anticipated depends critically on its implementation. The proposal includes many innovative elements (e.g. mandatory inclusion of secondary raw materials, digital product passport), and its implementation undoubtedly require careful observation and evaluation. Regarding the due diligence requirements, experiences from existing laws utilising the similar approach – the aforementioned EU Timber Regulation ((EU) No 995/2010) as well as so-called Conflict Mineral Regulation ((EU) 2017/821) – could be looked into. The Conflict Mineral Regulation came into force only in 2021 and its implementation is limited. However, due diligence system for minerals has been discussed by the OECD since the early 2010s with several guidelines developed, and US introduced its own law in 2011 using a similar approach.

Furthermore, the adoption of the standards IEC 63330: Requirements for reuse of secondary batteries (Section 4.3.4) and IEC 63338: General guidance for reuse of secondary cells and batteries (Section 4.3.5) will complement the implementation of the new battery regulation.

5.9 STRENGTHEN PUBLIC PERCEPTION OF CIRCULAR PV & EVBS

Background & problem

Currently, further uptake of second-life PVs and EV batteries faces challenges of not-well developed public and consumer perception (Section 2.4 and 3.4).

Potential pathways forward

The ninth pathway we consider crucial is to strengthen public perception and awareness about circularity in the solar power and battery sectors. In addition to low level of education and communication about the benefits of circular economy strategies and about waste as a resource, lack of trust on the functioning of second-life PV modules and batteries remains a critical issue to address.

While sustainability issues have been increasingly addressed already at the primary (or even, pre-primary) school level as part of the school curricula, the awareness raised might not be necessarily connected to concrete behavioural changes, especially when it is connected to purchase of technical devices that average consumers do not have expert knowledge on. Here, the guidelines and certification schemes, for which the CIRCUSOL project made important contributions (Section 4.2.3, 4.2.4, 4.3.5), can play a crucial role. These certification schemes could also help the installers in offering to their customers second-life solar panels and batteries with confidence. As also suggested in Section 5.6, inclusion of second-life PV modules as part of the criteria for green public procurement would help in enhancing the uptake, as well as increasing experiences in this area. If the public sector makes the use of second-hand PV modules visible by, for example, setting up a poster and talking about it, citizens might feel more comfortable in daring to use the second-life PV modules and batteries.

5.10 A RESEARCH AGENDA FOR A CIRCULAR PV AND EVB SECTOR

Last but not least, we propose to develop a research agenda for a circular solar and EVB sector. The CIRCUSOL project has identified a range of avenues for future research.

Firstly, CIRCUSOL has identified a lack of statistical data and knowledge on the actual flow of solar panels and EVBs that might be suitable for reuse (and recycling). The development and calibration of models to better forecast resource and product flows, and the identification of factors that influence these flows, would enable the industry to align and finetune their strategies and investment roadmaps. In this context, it would also be particularly valuable to assess the impacts of raw material scarcity and price fluctuations on high-value material recovery activities at the end-of-life stage of PV modules and EVBs. The development of economic models would enable the industry to evaluate the opportunities and risks of different circulatory strategies, such as recycling.

Secondly, CIRCUSOL has focussed in its activities on those solar and EV battery technologies that are presently well established in the market and are expected to reach the end of their first life in the near-term future. However, both solar and battery technologies continue to evolve and it will be critical to understand which solar technologies and which battery chemistries will gain significant market shares in a medium and long-term perspective, and what this would mean in regard to different circularity strategies. Furthermore, a fully circular solar sector should not be limited to modules and batteries, but include all components, such as inverters,

mounting systems, and building integration, etc. Hence, any type of technology assessment should take a holistic approach in its scope of products to be covered.

Thirdly, we believe it is important to assess the socio-economic and environmental benefits of different circularity strategies. Such research would help to gain a better understanding on the implications of a more circular solar power and battery sector on e.g. entrepreneurship and new forms of organisational collaboration in a circular value chain, the opportunities for employment generation, and more in-depth insights about benefits to consumers through competitive second-life solar and battery solutions. Given the dynamics in the technology trajectories of the solar power and battery sectors, the environmental pros and cons of different circularity strategies should be carefully assessed through life-cycle assessment (LCA) in order to guide policy makers towards those strategies that bring about the highest value from a resource-efficiency and climate perspective.

Finally, as illustrated in Chapter 4, a number of new government interventions are currently in their pipeline. Once they come into force, in addition to their content, it would be crucial to critically analyse the actual implementation and their effectiveness in addressing what the respective interventions seek to address. Such research should further identify gaps and explore what other measures, be it in public or private sector, need to be introduced.

6. Conclusions

CIRCUSOL sought to address the circularity side of sustainability of two dynamic industries – photovoltaic modules and electric vehicle batteries – that have been rapidly expanding over the last decade, and are expected to show continued strong growth in coming years. As summarized in Chapter 2 and 3, the technologies, materials used, and performance of PV modules and EVBs continuously. In order to avoid the situation where the enhancement of climate actions do not lead to the depletion of resources and environmental degradation, CIRCUSOL sought to understand whether, and how, alternative business models based on product-service-systems (PSS) might help in enhancing the reuse and repurposing of PV modules and EVBs in second-life applications.

Regarding PV modules, our main findings was that, despite various attempts on the ground, service-based business models to deploy second-life PV panels has faced various challenges on several fronts, such as competition with new and less expensive PV modules, customer acceptance in high-income countries in the EU currently limited to few specific cases, and preferences among many users for ownership. Various stumbling blocks were also identified at the local level where existing laws and administrative procedures create barriers to emerging service-based business models. Economic viability and demand for second-hand exists outside Europe, and particularly in low-income regions with insufficient access to modern energy services. However, lack of clear mechanisms to distinguish reusable PV modules from PV waste makes it problematic to simply encouraging exportation of potential second-life PV modules to non-EU, low-income countries. Furthermore, lack of appropriate local EOL treatment facilities in these regions can compromise the environmental benefits.

Concerning EVBs, is still debated under which conditions repurposed batteries will be able to be economically competitive with newly manufactured batteries in the stationary energy storage market. The cost advantage that repurposed batteries presently have over new batteries is expected to shrink, due to the continued learning curve and economies-of-scale in global battery manufacturing. Presently, the costs for repurposing are amplified through the lack of scale-economies and OEMs reluctance to permit repurposers access to the original battery management system. Among the largest challenge for repurposing of EVBs has been lack of specific provisions tailored to the emerging initiatives of repurposing in the existing EU law.

Thankfully, the policy landscape at the EU level is rapidly evolving on various ends. A number of proposals – ecodesign standards, green public procurement criteria and Type I eco-labels for PV modules, Batteries Regulation, Sustainable Product Regulation, revision of Waste Shipment Regulation – addresses many of the issues identified in the project. Specifically, the standards and criteria suggested for three government interventions in the preparatory study of PV modules contain various elements that support the prolongation of PV modules' first usage. The new Batteries Regulation proposal has several provisions promoting and supporting the repurposing of used EVBs, as well as to enhance higher quality recycling and material recovery. The stipulations on data sharing are intended to facilitate the information flow better for purpose of remanufacturing and reuse. Linking a battery passport with a data exchange platform is anticipated to enhance data transparency on the design, materials, carbon footprint, recyclability and performance of EVBs. The requirement to use certain percentage of recycled materials as well as material-specific recycling requirements would help in capturing critical raw materials. Also, the content of recycled battery raw materials will be stored, for which minimum requirements will be set in the future.

What these regulatory initiatives could actually achieve depends on the final legal text that would be agreed upon as well as their implementation, and it requires careful observation. Furthermore, as discussed in Chapter 5, these proposals could be strengthened even more to support further usage of second-life PV modules and batteries. Such finetuning include incorporation of the use of second-life PV modules as potential green public procurement criteria, as well as requiring the inclusion of data on the actual instalment of PV modules and their usage in product passport. In addition, elements of the proposed Batteries Regulation and Sustainable Product Regulation could inspire upgrading of existing interventions such as WEEE Directive. Further work could be done also in the area of developing concrete criteria to distinguish PV modules fitted for reuse from PV module wastes, taking into consideration the specific characteristics of energy-producing devices.

In order to address the presently high costs and administrative effort involved for solar service firms to secure ownership rights of service-based PV and battery systems in the cadastre registry, we furthermore propose the introduction of a European-wide digital registration system for clean and low-carbon technologies that are deployed through service-based business models. Such a registration system would safeguard service providers' right of ownership of their user-sited "green" assets at much (or zero) costs than the current practice.

In addition to the findings from the demonstrator projects, CIRCUSOL produced tangible contributions in relation to standardisation and labelling of both PV modules and EVBs. They are both critical in addressing many of the concerns (operators' certainty, consumer's confidence, enhancement possibility for export to countries where second-life PV modules can be of great use) identified during the project.

It is our sincere hope that these inputs help in bringing forward the multiple goals of sustainability - climate change and circularity, resource security and reducing environmental impacts from mining - in a balanced yet rigorous way.

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The logo features a stylized orange letter 'C' that incorporates a white silhouette of an umbrella. The background of the entire image is a light gray, textured pattern resembling a leaf's vein structure.

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