FROM LINEAR TO CIRCULAR: Evidence from the UK solar sector

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Contents

Background to this report 3
Authors & Acknowledgements 3
Methodology 3

Executive Summary 4

Introduction – Solar Energy 5

UK Solar Sector - Key Issues and Challenges 6

The Structural Solution: A Circular Solar Energy System 12
The Foundation of a CE 12
Levers of a CE 14

Circular Economy Deep Dive 16
A case for the circular economy: Solar Panels 16

The circular economy in practice 22
Inflow phase: reduce inflow 22
Grafmarine: Designing solar products for the future 22
Re-Solar: Supporting the reconstruction of Ukraine with reused solar panels 23
Application of recovered carbon black in photovoltaic devices 23
In Use phase: asset optimisation 24
Revive Battery BV 24
Re-Solar: Repair 25
Outflow phase: post-use asset recovery/repurpose 25
Flaxres: Modular recycling unit 25
ROSI: Effective recovery of silver 25
Solarcycle: Innovations in PV panel recycling (USA) 25
The Indian Institute of Science: Homes out of decommissioned solar panels, sustainable innovation in India 26
Full System 27
CIRCUSOL project 27
System enablers 28
SecondSol: Solar PV second hand trading platform 28
Regulation: The USA Inflation Reduction Act 28

Identifying challenges to CE adoption of Solar in the UK 29
1. Policy and Regulation 29
2. Lack of visible and legitimate secondary market 31
3. Lack of CE understanding & shortage of recycling facilities 31
4. Logistics challenges 32
5. Externalised cost of panels 32
6. Uncertainty of Economic Lifespan 32
7. Diversity of Products and Lack of Data 33
8. Recommendations (CE Enablers) 33
Conclusion 36

Appendix A 38

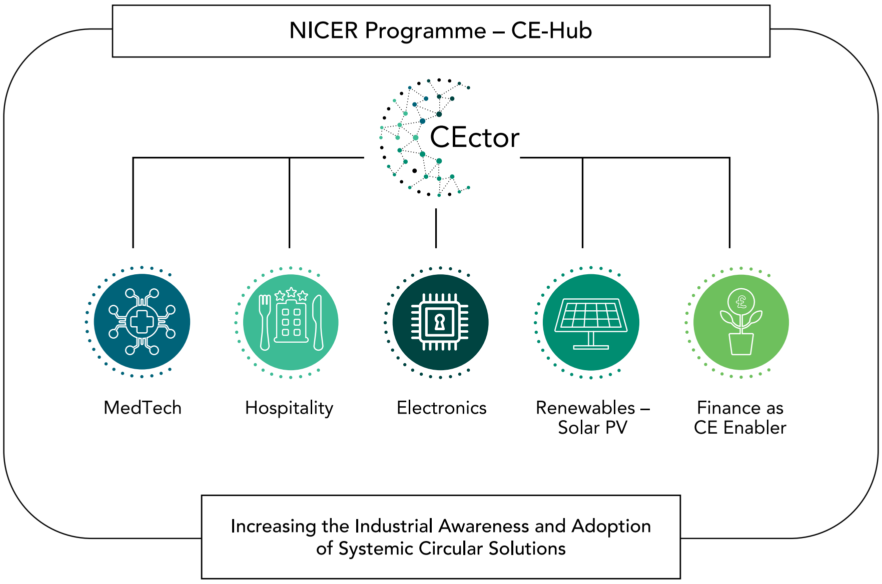
Appendix B 39

References 42

Background to this report

As part of the National Interdisciplinary Circular Economy Research programme (NICER), the CEctor project is a dedicated workstream within the University of Exeter CE Hub. CEctor has the scope to explore five different UK sectors and identify opportunity to accelerate Circular Economy (CE) uptake and implementation. The five sectors are: 1. Medical Technology, 2. Hospitality, 3. Electronics, 4. Renewables-Solar PV, and 5. Finance. The purpose of the project includes engaging with stakeholders, building CE knowledge and understanding, and enabling mechanisms to deliver outcomes and impact. This Spotlight Report draws together academic research and insight from a range of academic and industrial sources providing an evidence base for current and future CE adoption within the Solar PV sector.

This report outlines the status of the solar sector in the UK and explores how Circular Economy (CE) principles can effectively address its challenges. By showcasing successful CE implementations worldwide and at small scales in the UK, we illustrate the economic, environmental and employment benefits of adopting CE principles. Through stakeholder interviews and discussions, we identify key challenges, enablers, and recommendations for regulators, industry players, and academic partners to facilitate the transition to a Circular Solar sector in the UK.



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- ReSolar
- PVCycle
- Revive Battery B.V

Methodology

The content for this report draws on data, evidence and insights drawn from the following sources:

- A review of the academic and grey literature, including relevant media articles and industry publications.
- Interviews and discussions with expert solar industry stakeholders and wider stakeholders from across the solar PV value chain
- A material flow analysis of UK solar installed capacity and forward projections to 2050.

This report can be referenced as follows: Nidhi, A., Hopkinson, P., Charnley, F., Zils, M., Burnell, M. (2024). From linear to circular: Evidence from the UK solar sector.

Executive Summary

The UK solar industry has experienced substantial growth, reaching 14.65 gigawatts (GW) power capacity by the end of 2022, contributing significantly to national renewable energy targets and supporting a turnover of £3,577million and 11,500 jobs in 2022. However, this success is accompanied by a growing environmental concern: an estimated 152,523 tonnes of aluminium, 8,745 tonnes of copper, and 667,947 tonnes of glass material is already embedded in UK solar installations by end of 2023 which could become a problematic waste stream in the future.

To align with the UK's Net Zero (NZ) strategy and achieve the ambitious target of 70 GW solar capacity by 2035, a transition to a circular economy is imperative. This shift involves rethinking product design, material use, and end-of-life management across the solar value chain.

This report explores the opportunities and challenges associated with implementing circular economy principles across the solar value chain:

- **Inflow Phase:** Focus on sustainable material sourcing, design for circularity, and supply chain transparency.
- **In-Use Phase:** Extend product lifespan through maintenance, repair, and responsible consumption.
- **Outflow Phase:** Prioritise closed-loop recycling, extended producer responsibility, and reverse logistics.

The report also addresses the barriers to circularity, such as lack of end-of-life policies, design limitations, and data gaps. Recommendations for overcoming these challenges include:

- **Design:** Adopt halogen-free and lead-free designs, mandate information, standards and certification on repairability and environmental impact in procurement.
- **Reverse Logistics:** Enhance compliance for producer responsibility schemes, strengthen collection networks, and invest in recycling and re-use infrastructure.
- **Policy and Incentives:** Exclude solar panels from WEEE regulations, introduce eco-modulated EPR and repowering fees, enable products within the Microgeneration Certification Scheme (MCS) to have a second life, and provide financial support for high value recycling and R&D.
- **Data and Transparency:** Mandate data collection and reporting to track material flows and system performance highlighting socio-environmental standards as part of future PC labelling.

By adopting circular economy principles, the UK solar industry can achieve several key benefits. It can enhance resource security and reduce reliance on often volatile global supply chains by prioritising the reuse and recycling of materials within the UK. This approach also improves the resilience of the supply chain, making it less susceptible to disruptions. Moreover, embracing circular practices can significantly reduce waste, with estimates suggesting that up to 1.2mn tonnes of solar waste could be generated by 2050. Applying low, medium or high circular strategies would keep over $2bn aluminium, copper and silver material value in PV use through product life extension and generate between $0.37-£0.46bn from increased recycling rates. Finally, the transition to a circular economy has the potential to stimulate economic growth by creating new jobs and fostering the development of businesses in the repair, refurbishment, and recycling sectors.

The transition to a circular economy requires concerted effort and collaboration across the value chain. By embracing circular principles, the UK solar sector can contribute significantly to a greener and more prosperous future.

Introduction - Solar Energy

Over the past decade, solar energy adoption has grown significantly worldwide, including in the United Kingdom (UK)[a]. By the end of 2022, the UK had a cumulative solar power capacity of approximately 14.65 gigawatts (GW)[1], with 99% of this installed since May 2010[2]. This contributed to the global cumulative capacity of 1062, GW[3], encompassing installations from large-scale solar farms to small rooftop installations.

Several factors have driven this global growth in solar energy adoption. These include the dramatic reduction in solar technology costs (up to 90%), rising energy prices, and increasing environmental awareness among consumers and businesses. Supportive government policies have also played a crucial role. In the UK, for instance, the Feed-in-Tariff (FiT) scheme, which operated from April 2010 to April 2019, significantly boosted solar installations.

The solar energy market in the UK is expected to continue its growth trajectory in the coming years. The UK government has recently expressed an ambition of a five-fold increase in solar capacity by 2035, which would equate to roughly 70GW of total generation capacity[4]. Solar is therefore fundamental to enabling the UK government to meet its legally binding NZ targets by 2050. In 2020, the solar industry supported 11,500 jobs across the UK, most of them highly skilled, a figure that is expected to rise further[5]. The solar industry contributed £934mn[6] in 2021 to the UK economy and by 2022, had a turnover of £3,577mn[7]. Despite this growth and widespread consumer adoption, the UK solar sector faces many challenges. Many of these are driven by the reliance on an underlying linear take-make-dispose economic model. A circular economy (CE) offers a different type of economy, and a proven, practical way to preserve product, material, energy and information resources through multiple use cycles, displacing energy-intensive products and wasteful practices. There are established CE approaches to reduce material demand, increase product utilisation and preserve their economic and material value for longer or alternative use.

To achieve this across the UK solar sector and make CE the new norm, many issues need to be addressed. However, these are not insurmountable and there are many existing examples of innovative CE initiatives to increase utilisation and resource recovery across global energy systems. These activities are currently prevalent in the USA and Europe. Within the UK, there are a small number of emerging, innovative CE case examples with high impact and scalability potential, some of which are covered in this report.

In this report we set out to explore how and where CE can be effectively applied in the UK solar sector and the current challenges to the large scale CE adoption. Through case examples, we show that CE is already realising economic benefits, and carbon and waste reductions which can be further scaled up. Through stakeholder interviews, we have defined the challenges to be overcome along with the enablers to initiate, implement and scale up a Circular Solar system fit for the future.

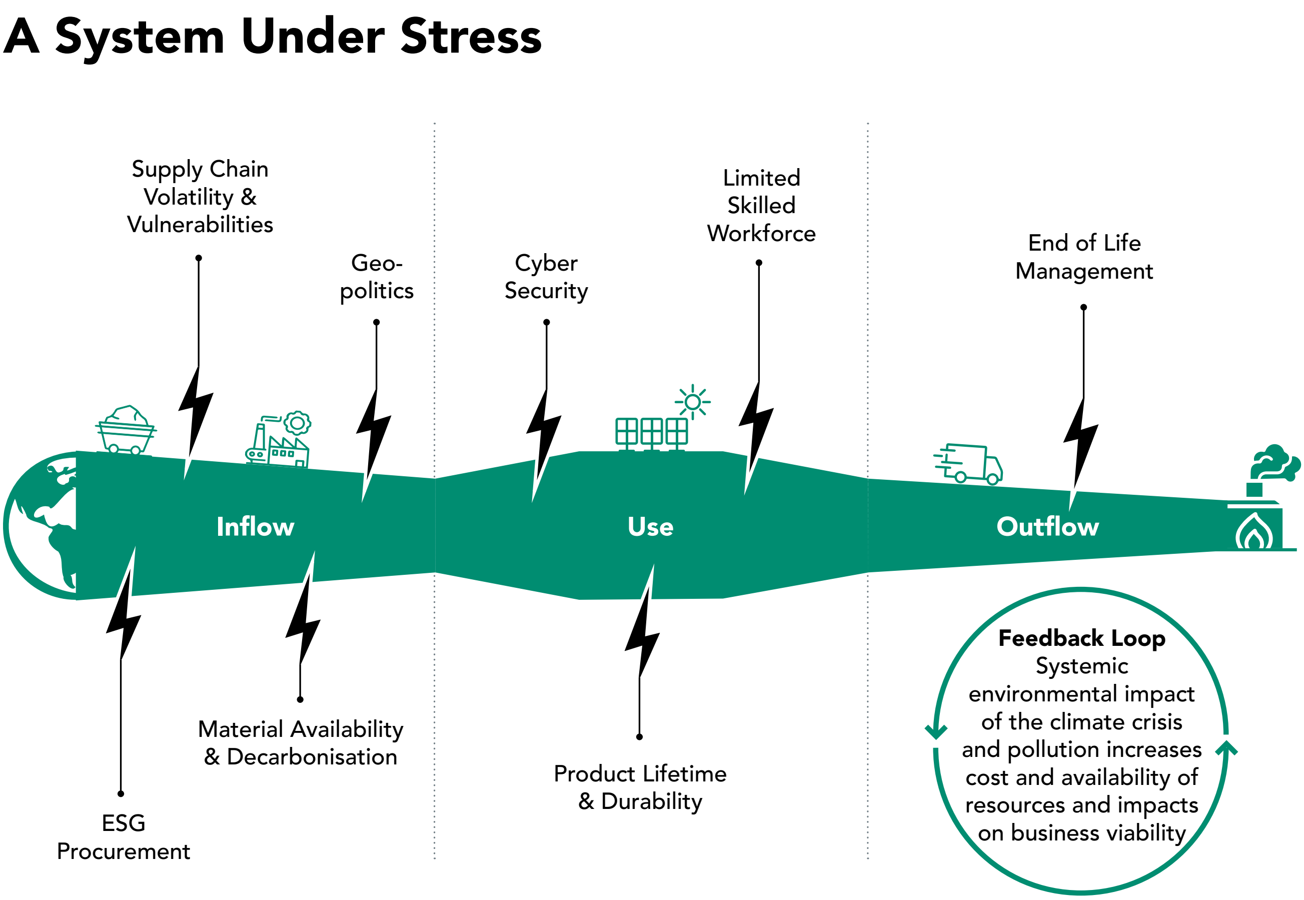
To make this a reality, we identify recommendations for key stakeholders across the UK solar value chain: regulators and policymakers, industry and supply chain, academics and research partners.

[a] Solar Photovoltaics (PV) has been a fast-growing market with the Compound Annual Growth Rate (CAGR) of cumulative PV installed capacity between year 2011 to 2021 being approximately 30%.

UK Solar Sector - Key Issues and Challenges

From extensive academic research and interviews with industry stakeholders, the key issues and challenges currently facing the UK solar sector were identified (Figure 1). These challenges include, but are not limited to the following:

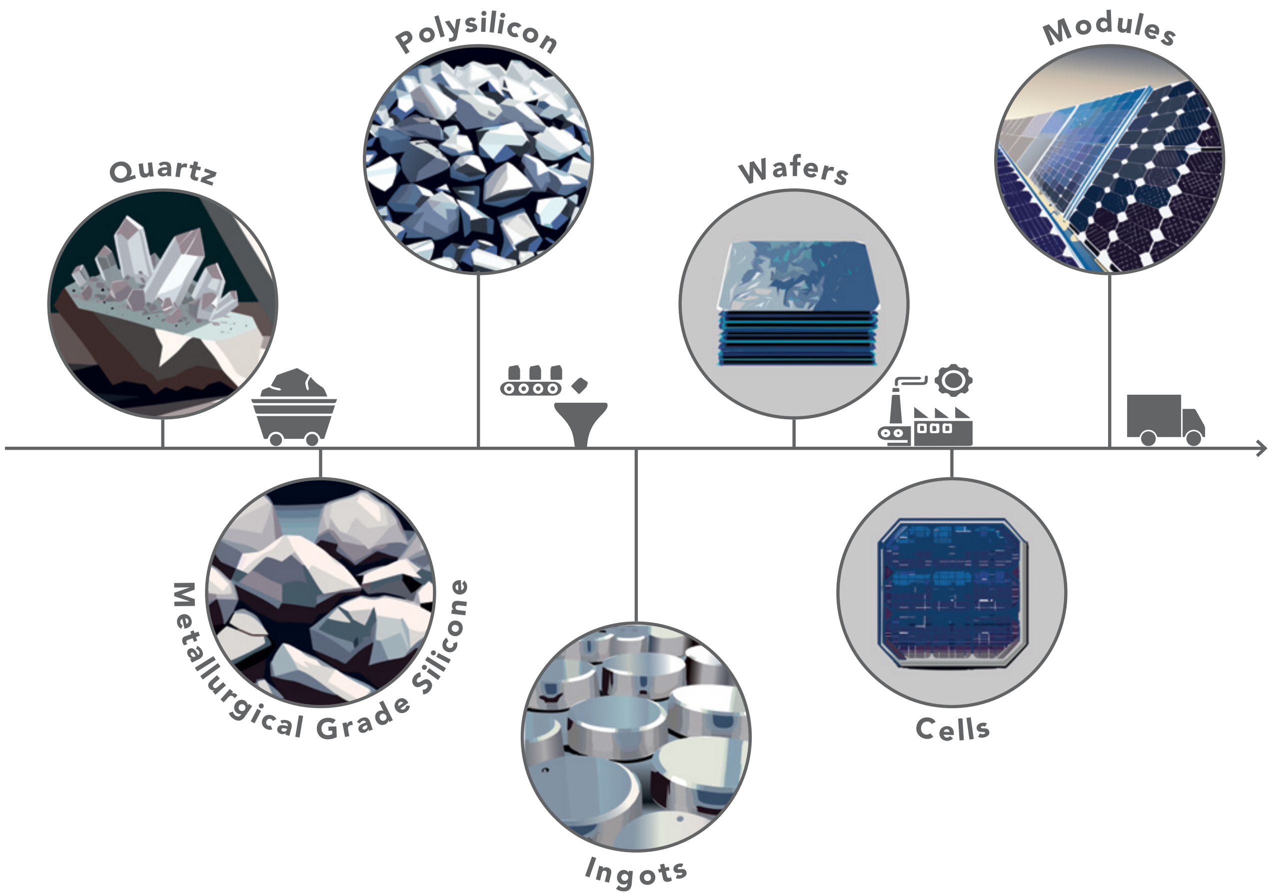
Figure 1: Systemic stresses in the UK solar value chain



1. Supply chain volatility & vulnerabilities

China's dominance in the global solar PV market is pronounced, commanding a market share exceeding 80% across all phases of PV panel manufacturing, encompassing polysilicon, ingots, wafers, cells, and modules (Figure 2). Some projections indicate that its share in the initial three stages of production is poised to reach 95% by the year 2025[8]. Furthermore, the production and processing of raw materials essential for PV manufacturing, such as aluminium, copper, and silver, is heavily concentrated in a select few countries, notably China and Russia for some metals and the top three producers collectively control more than 50% of the global supply[9]. This concentration raises concerns over supply chain vulnerability; particularly as certain nations face escalating trade sanctions[10].

Fig 2: Silicon processing value chain to make crystalline silicon solar panels



The concentration of supply chains and the limited substitutability of critical materials present material risks to future solar technology availability, deployment and investment. For example, there was a tripling of polysilicon prices between 2020 and 2021, triggered by disruptions from flooding and industrial fires in 4 separate Chinese plants, resulting in a 20-25% decline in global production[11] and creating a supply bottleneck. COVID-19 lockdowns in China also had a big impact with PV module prices increasing by an average of 14% from 2019 to 2023[12] (as high as 30% in 2022) leading to project delays worldwide[13] and financial unviability for investors[14]. The prices plummeted by 40% from 2023 onwards due to overproduction in China[15] and panels are currently selling at their historic low prices[b].

This rapidly changing market landscape has placed solar panel manufacturers in the United States and the European Union at imminent risk of bankruptcy. These manufacturers were previously encouraged by major PV importers' "China+1" strategy[c], which aimed to insulate them against supply chain shocks. Now governments are seeking to take emergency action[16] to support domestic manufacturing.

In parallel the prices of ancillary components integral to solar plant infrastructure, including cables, inverters, and module mounting structures, also experienced notable escalations from 2019 to 2023[17]. This was due to an increase in material prices for copper and steel, which inflated by 34% and 27% respectively during the period, eventually stabilising at elevated levels[18].

[b] In 2022, the global PV module market experienced an unprecedented growth to 295 GW installed capacity worldwide with the production capacity by the end of the year increased to 600 GWp resulting in an oversupply of PV modules and anti-dumping investigations being launched in different parts of the world.

[c] Business approach where companies diversify their investments by establishing operations in countries outside of China to reduce dependency on a single market. Countries like Vietnam, India, and Thailand are popular alternatives.

2. Procurement

The UK solar sector faces various procurement challenges including Environment, Society and Governance (ESG) issues and workforce availability.

ESG & Antislavery Compliance

Despite the solar industry's supply chain being concentrated in China, increased international scrutiny has made upstream segments of the supply chain increasingly opaque[19]. Over one-third of global polysilicon and metallurgical grade silicon production, crucial for solar panel manufacturing, occurs in the Xinjiang Uyghur Autonomous Region (XUAR), often powered by cheap coal and alleged forced labour[20]. Consequently, over 90% of global wafer manufacturing is conducted in China, amplifying the risk of forced labour exposure. Additionally, materials like silver paste, used in panel connectors, often transit through countries with heightened labour risks[21].

Even though the UK's Modern Slavery Act has been in place since 2015, many British organisations recently faced reputational risks for sourcing solar equipment from the XUAR region[22]. The USA enacted the Uyghur Forced Labor Prevention Act in 2021, prompting similar restrictions worldwide in other developed nations. This prompted the creation of dedicated "bifurcated" supply chains believed to be free from inputs sourced from the XUAR and the mandating of the "China+1" policy. However, these separate supply chains, which account for only 7-14% of Chinese companies' global production capacity, are challenging to verify for purity[23]. This "bifurcation" of supply chain moreover introduces governance complications and poses challenges to governments, developers, and retail consumers. Efforts to simplify due diligence and ESG compliance are underway by industry associations and assurance schemes like the Solar Stewardship Initiative[24], and thought leaders like Action Sustainability with their procurement guidance[25]. However comprehensive adoption of best practices and reshoring the bulk of upstream (polysilicon/ingot/wafer) manufacturing to less risky countries (such as US, EU region) will take considerable time as manufacturing facilities need to be set-up from scratch[26] and there remains the challenge of procuring raw materials from responsible sources.

Workforce Availability

Labour procurement is another significant challenge due to increasing competition across the supply chain and the impacts of Brexit. The UK plans to expand its solar capacity to 70GW by 2035, but there is a shortage of skilled labour to meet this target with an additional 13000 skilled workers needed[27]. According to panellists at a recent UK Solar Summit[28], the UK's departure from the EU has made it difficult to attract European engineering companies, with many opting for projects in other EU countries due to visa issues and bureaucratic hurdles. Additionally, the UK's solar industry competes with other infrastructure projects, such as housing and rail expansions, further straining the availability of skilled workers. This has transformed the labour market into a "seller's market,"[29] where contractors can choose their projects, forcing developers to build strong relationships and maintain a steady pipeline to secure the necessary workforce.

3. Geopolitics, material availability & decarbonisation

The UK solar PV industry is facing significant and interconnected challenges in geopolitics, material availability, and supply chain decarbonisation, all of which are critical for its sustainable growth.

Geopolitics

China's 94%[30] share of global crystalline silicon (c-Si) PV module production gives it significant control over solar PV prices and supply chains. This centralisation, especially in regions reliant on coal, creates vulnerabilities[31] for countries like the UK, risking supply disruptions due to political or economic tensions. Efforts by the USA, Europe and India to diversify their supply chains face substantial challenges[32] due to China's entrenched market position.

Material Availability

The solar PV industry faces critical material availability challenges due to the rising demand for resources to support the clean energy transition and the unique requirements of various solar technologies. Technological advancements have reduced silicon consumption, but the rapid expansion of manufacturing strains global supplies. For example, by 2030, the demand for silver in solar PV manufacturing could exceed 30% of 2020's global production, risking shortages and cost increases[33]. Thin-film technologies place supply pressure on metals such as cadmium and indium, while crystalline silicon technologies consume significant amounts of aluminium, copper, and silver. By 2050, the demand for materials like silver and gallium could surpass 2020's global production levels[34], highlighting the need for diversified technologies to mitigate resource risks including that of significant material intensity surges. Even scenarios where China alone accounts for just 50% or 80% of global PV panel production, the material intensity surges to 800% and 1400% respectively[35], which would strain material supplies for critical resources.

Supply chain Decarbonisation

The decarbonisation of the solar module supply chain faces significant hurdles, especially in the energy-intensive production of metallurgical grade silicon and polysilicon. Globally, coal powers 62% of the electricity used in solar PV manufacturing, much higher than its 36% share in global power generation[36] due to production being concentrated in China. All polysilicon plants in the Chinese Xinjiang region are solely coal-powered[37], resulting in a high carbon footprint for panels produced there. For instance, a polysilicon-based panel made with coal energy has a CO2 payback time nearly four times longer than one made using renewable energy sources[38]. Despite progress in reducing emissions intensity through efficiency gains, global CO2 emissions from solar PV manufacturing have nearly quadrupled since 2011[39], reaching over 51,900 kilotonnes (Kt) in 2021. Since 2015, emissions have spiked due to increased demand for monocrystalline wafers. These wafers are three times more energy-intensive to produce than multicrystalline wafers[40].

4. Cybersecurity

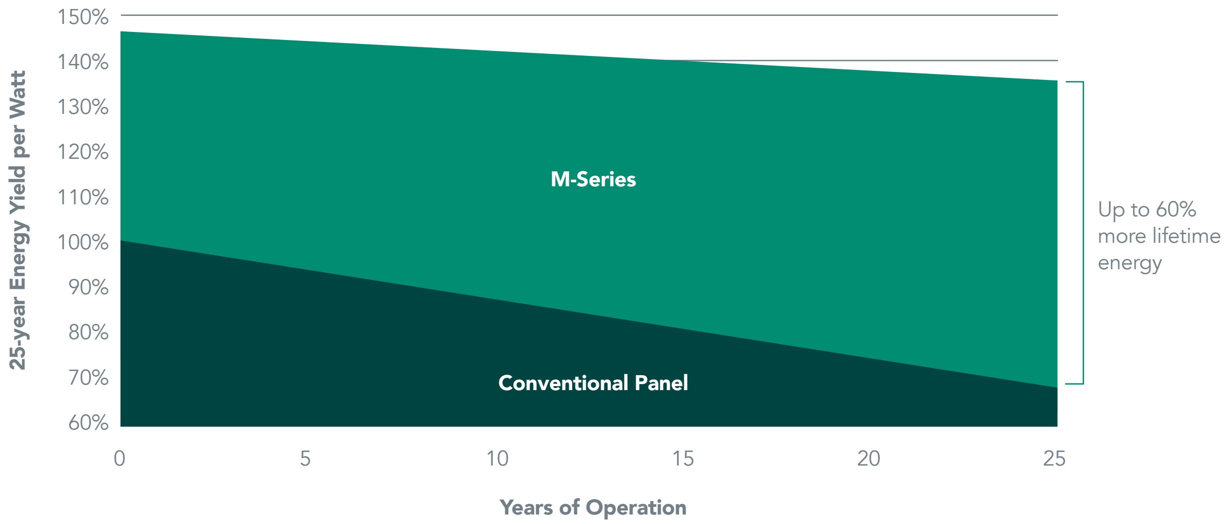
Solar panels are vulnerable to cybersecurity risks due to their integration into smart grids and reliance on the Internet of Things (IoT)[41]. These systems use communication networks to monitor and manage energy production and distribution, exposing them to potential cyberattacks. Research has highlighted how weak security protocols in solar panel firmware could be exploited, allowing hackers to manipulate energy output or shut down systems entirely and manipulate user data[42]. This could lead to large-scale power outages causing significant financial losses or even be used as leverage in geopolitical conflicts.

One major concern for solar energy systems is the vulnerability of inverters, which convert solar power into usable electricity. These devices often have outdated software and weak security, making them prime targets for cyberattacks. Their decentralised nature adds complexity to securing these systems, necessitating continuous cybersecurity measures. Recent studies[43] and incidents, such as the first known cyberattack on U.S. solar and wind assets[44], have highlighted these vulnerabilities. The rapid growth of solar installations, coupled with varying cybersecurity awareness among manufacturers and other stakeholders, exacerbates this issue. Prioritising robust cybersecurity is essential to protect the integrity and reliability of renewable energy sources.

5. Product lifetime and durability

Solar panels typically have a designed lifespan of 25-30 years, during which their performance gradually declines to 70-90% of their original capacity following a linear degradation pattern as shown in Figure 4. However, in practice, panels are retired prematurely, nearly at a third of their lifespan primarily due to shifts in economic feasibility, technological advancements, and operational factors, in a phenomenon known as "repowering"[45] Advancements in solar panel efficiencies have been remarkable over the past 15 years, driven by technological and manufacturing improvements resulting in 0.3-0.4% increase every year for the last decade. Initially, panels had efficiencies of around 10-15%, but newer generations have achieved efficiencies exceeding 20%, with cutting-edge designs reaching beyond 25%[46]. At the same time, panel prices have fallen over 90% for the same generation capacity.

Fig 3. Sunpower module's performance warranty shows linear decline in module output



While increased efficiencies theoretically enhance the performance and output of solar panels, they also contribute to the early retirement of panels in the UK and worldwide. As cheaper, newer, more efficient panels become available, older panels with lower efficiencies become less economically viable. This phenomenon is particularly relevant in regions like the UK, where government incentive schemes, such as the Feed-in Tariff (FiT)[d], encouraged widespread adoption of solar panels over a decade ago, often with less efficient panels compared to those available today. Consequently, economic incentives for replacing older panels with cheaper, newer, more efficient models have become financially attractive.

In the UK, data shows there was a rush to commission solar projects from the year 2012 to 2019 to take advantage of the deadline of the FiT scheme offered by the UK government. However, workmanship was poor in many of these plants[47], resulting in sub-optimal performance. This has necessitated asset owners (who are buying and aggregating these plants under their portfolio from original developers) to retire the solar panels early with each of these solar sites having potentially tens of thousands of panels being decommissioned. In some cases this is less than 10 years for utility scale asset owners to claim warranties of batches of underperforming assets prior to their product warranty period expiring. There is also suggestion of large-scale manufacturing defects in batches of solar panels from 8-10 years ago that is causing large scale decommissioning of panels. Panel defects can include delamination, cracked backsheet, PID, discolouring, faulty bypass diodes, microcracks, or burned solder joints[48].

These two factors, poor workmanship and defective panels, are resulting in significantly more solar panel waste being generated than previously expected leading to the early stages of a hidden recycling tsunami[49]. In one example, a developer in England plans to retire approximately 250 tonnes of PV panels within the next 18 months. Of this total, 100 tonnes will come from just two solar sites commissioned in 2013. Another 25 tonnes will be sourced from two more recently commissioned sites, dating from 2020 and 2021.

6. End-of-life management

It is projected that global solar panel waste will increase to approximately 78 million metric tonnes by the end of 2050, with annual waste amounts matching the total mass of new installations[50]. In the UK, current estimates suggest that end-of-life PV panel waste will experience exponential growth in the medium to long term, with cumulative waste expected to range from 30,000 to 200,000 tonnes by 2030, potentially escalating to 1-1.2 million tonnes by 2050. This is in-keeping with the global trend of e-waste from PV panels that is expected to quadruple from 0.6 million tonnes in 2022 to 2.4 million tonnes in 2030[51]. The regulatory framework for PV waste management in the UK is predominantly shaped by the Waste Electrical and Electronic Equipment (WEEE) Regulations 2013 No.3113. These regulations were integrated into national law in January 2014, coinciding with a substantial increase in generation capacity. Almost 85% of cumulative installed capacity until 2024 occurred after this integration. In the UK, the Environment Agency (EA) states that producers must register with a Producer Compliance Scheme (PCS), such as PV CYCLE.

The UK has a "pay as you throw" principle, with most of the costs placed on the final waste holder, as opposed to upfront costs being paid for when the product is placed on the market. Accordingly, 'contribution fees' from producers make up a small proportion of the overall costs of disposing of PV panels, with the majority paid for at the end of the panel's life.

However, a data mismatch between products placed on the market and WEEE data records suggest that many companies, including subsidiaries of foreign manufacturers, have evaded registering with these compliance schemes, undermining their effectiveness[52]. This is following the same pattern of "free-riders"- WEEE non-compliant companies- present in most of the EU member states resulting in a distortion of the solar PV market and unfair competition[53]. Quantifying the extent of free riders is challenging both for the UK & EU. For instance, in Spain, an estimated 300,000 T (tonnes) of solar PV materials are installed, but only 169,000 T are officially reported as per the WEEE Forum[54].

[d] The UK's Feed-in Tariff (FiT) scheme, launched in April 2010 and closed to new applicants in March 2019, was designed to promote renewable energy by offering payments for both electricity generation and excess energy exported to the grid. Existing participants continue to receive payments, and the scheme has since been succeeded by the Smart Export Guarantee (SEG).

Challenges in accurately predicting the economic lifespan of solar panels have hindered recyclers in building sufficient capacity to process this waste stream in the UK. Post Brexit has led the UK to a shift away from accessing centralised European PV recycling facilities, impacting recycling rates and economies of scale[55]. Consequently, solar asset owners with the resources to store PV waste are being offered little to no incentive to dispose of the waste until it becomes cost-effective. This is skewing the overall volumes of PV waste coming through the system. There are also accusations by industry experts that waste is being stored or exported illegally on the black market.

Despite growing market interest in best-in-class recycling solutions due to increased ESG compliance requirements, the lack of end-of-life (EoL) regulation and oversight has left the industry vulnerable to infiltration by bad-faith stakeholders, with the potential to tarnish the reputation of the solar recycling industry. There is currently no enforcement mechanism by the regulatory authorities to place the burden of proof for recyclers to prove their recycling rates advertised to customers, making it an uneven playing field and business environment open to unsubstantiated and misleading claims. Consequently, due to a lack of enforcement or transparency, solar waste is vulnerable to being handled illegally or exported on the black market, often without the original waste holder's knowledge, and at the expense of legitimate partners who play by the rules.

Furthermore, the design of solar panels for extended lifespans presents challenges in recovering precious metals such as silver, tellurium, and molybdenum embedded within them. While components like solar glass, silicon, and plastics are commonly downcycled during the recycling process to be used as filler materials in the manufacturing and construction industry, the cost of recovered materials barely covers recycling expenses. This underscores the importance of research into advanced recycling technologies capable of recovering high-value metals along with a need for policy-driven research focus at the design stage of modules to allow for disassembly for easy recovery of components and for repair and reuse of panels.

Currently, most UK research and development focuses primarily on the technical design, advanced materials, and manufacturing aspects of third-generation solar technologies such as perovskite and organic solar cells[56]. Despite funders aiming to support all solar technologies[57], there is little research or expertise dedicated to crystalline silicon technology, which remains the dominant technology now and for the foreseeable future. Additionally, there is little support for exploring end of life of PV modules as evident from the current grant landscape[58] which will lead to a need for importing technological expertise, and partnerships for handling the increased amount of PV waste in the UK in the future. This is despite the UK having world-leading academic expertise and outstanding facilities to find innovative solutions to PV waste, and export IP (intellectual property) to other regions.

In summary, there is a lack of co-ordination of the full lifecycle of solar plants, especially EoL scenarios for PV modules. A consequence of this is a highly linear sector, with high levels of avoidable waste, uncontrolled and mismanaged end of life disposal and technological and ESG supply chain risks. To overcome these challenges requires a whole system approach with clear understanding of the baseline conditions and analysis of the various points of intervention required to make the shift from linear to circular. How this could be achieved is set out in the second half of this report.

The Structural Solution: A Circular Solar Energy System

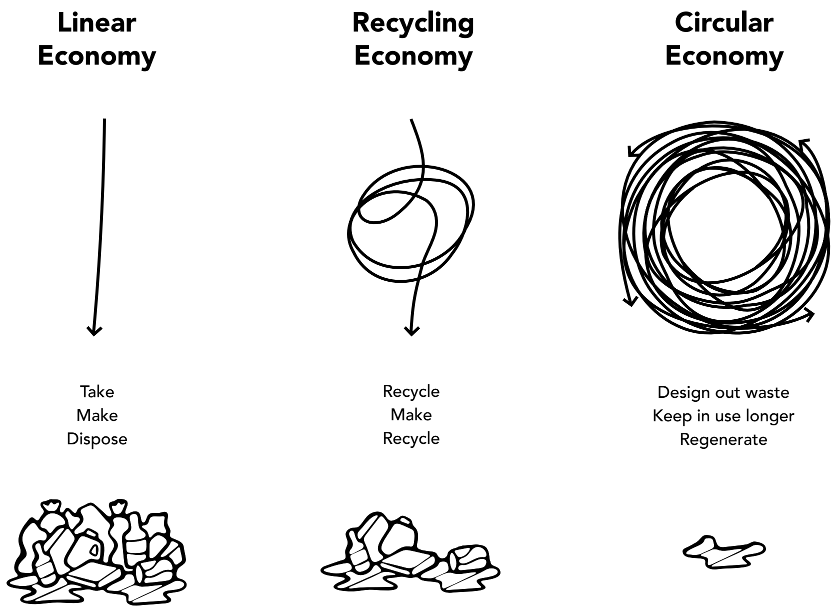
The Foundation of a CE

While there are many definitions of CE, the majority are underpinned by a set of core principles, which originate from the work of the Ellen MacArthur Foundation (EMF). Four of the core guiding principles are:

- **Eliminate** waste and pollution (through design),
- **Circulate** materials and products at their highest value for as long as possible,
- **Regenerate** natural capital,
- **An economy run on renewable energy.**

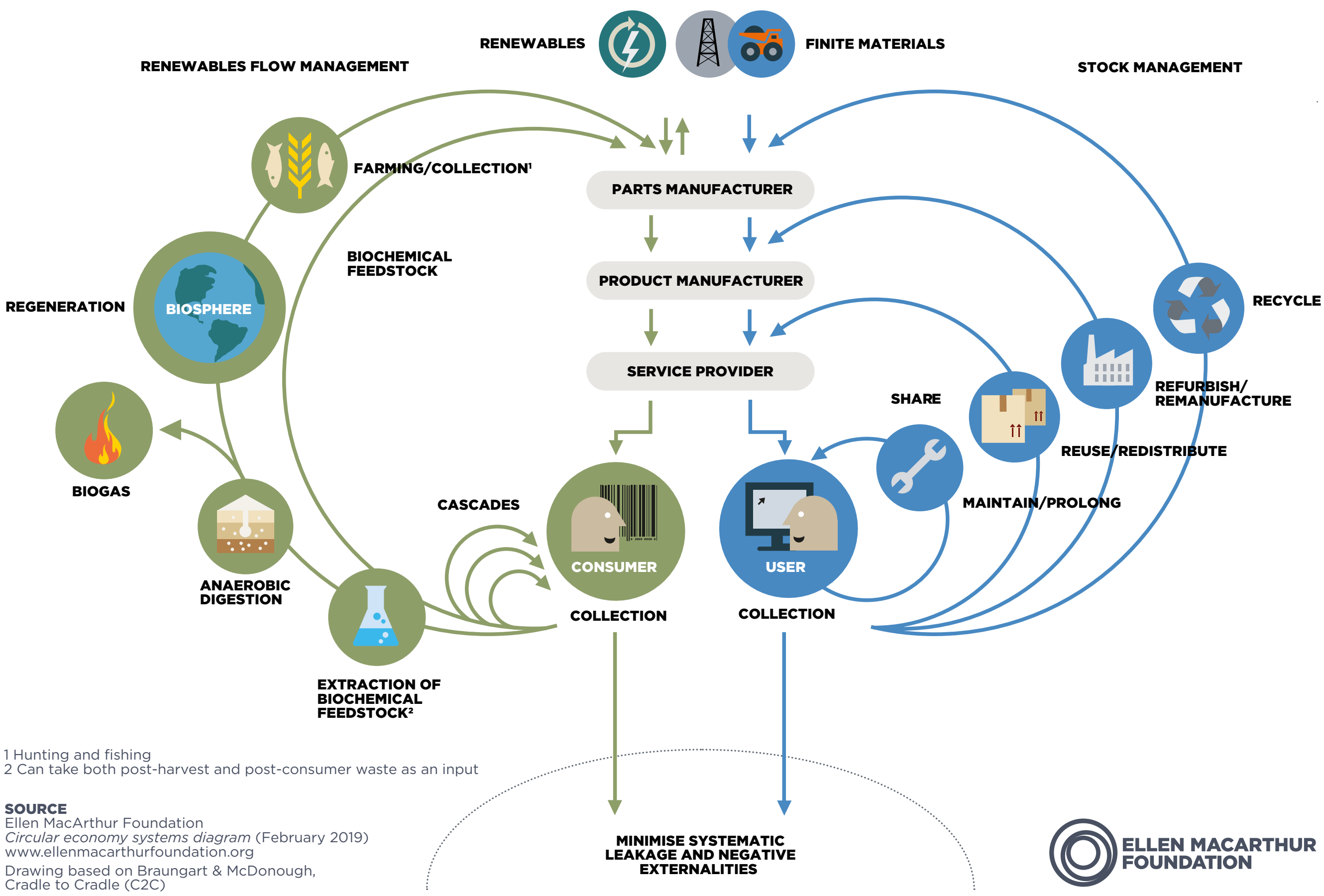
The CE concept has been subject to many diverse debates and definitions by multiple authors and organisations, and sometimes interpreted as being a slightly enhanced form of recycling. As Figure 4 below shows, a CE is more than just improved recycling, which only slows down the rate of resource consumption and should be a last resort. Rather a truly CE rebuilds and maintains capital, promoting higher quality stocks and flows of materials, components and products for repeated life cycles and cascades.

Fig 4: A linear, recycling and circular economy in 3 images (adapted from Circular Flanders)[59]



Developing a CE is therefore a system challenge. The CE visual originally developed by the Ellen MacArthur Foundation, known as the 'butterfly diagram' is a useful heuristic that demonstrates the CE as a whole system framework (Figure 5). In this conception, the current linear take-make-dispose economic model is depicted as a vertical value chain, where materials and resources flow through the economy to disposal and externalities, often in a single use cycle. In contrast, in a circular economy, the aim is to preserve, circulate and cascade materials, and products productively back into the economy at various life cycle stages. The way this might be achieved differs depending on whether materials, components and products are designed for one of two spheres – the biosphere or the technosphere. The technical sphere encompasses materials and products (known as products of service) that are that are durable, including solar panels comprising materials such as aluminium, steel, copper, plastics. In the biological sphere, materials biodegrade, are consumed (known as products of consumption) and then metabolise, or compost and dissipate or can become stocks (e.g. soils). Many forms of pollution and harm to life occur when technical durable materials, such as plastics, end up in the biosphere (e.g. ocean plastic, air pollution), or biodegradable materials become mixed with technical materials, which are hard to separate and more costly to preserve the value of either.

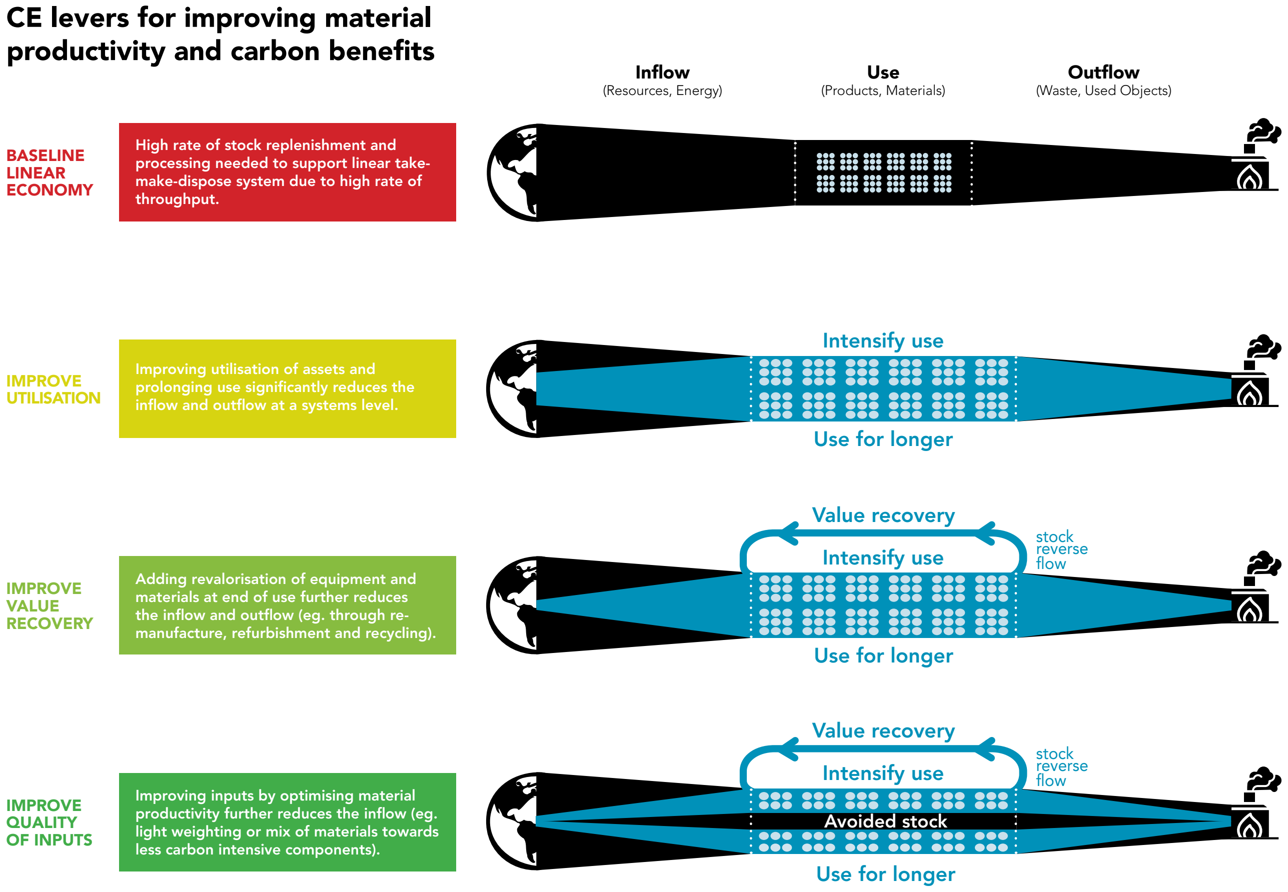
Fig 5: Circular economy systems diagram (courtesy Ellen MacArthur Foundation)



Levers of a CE

In the context of a CE, the value chain is viewed as a continuum where resources, products, and materials flow through various stages, each offering opportunities for circularity. The three key phases within this value chain present distinct levers for advancing circularity, as shown in Figure 6:

Fig 6: CE levers providing non-linear productivity increases and carbon reductions (adapted from Zils, 2021[60])



- **Inflow Phase:** This initial stage involves the acquisition and sourcing of raw materials and components. In the CE, the focus is on optimising resource flows, minimising waste and promoting sustainable sourcing practices. Levers in this phase include:

  Sustainable Material Sourcing: Prioritising the use of recycled, renewable, or responsibly sourced materials to reduce environmental impact and minimise reliance on virgin resources.

  Design for Circularity: Incorporating circular design principles such as modular design, material recovery, and easy disassembly to facilitate repair, reuse, and recycling at end-of-life stages.

  Supply Chain Transparency: Implementing systems to trace the origin and lifecycle of materials, promoting transparency and accountability throughout the supply chain.

- **In-Use Phase:** During this stage, products are utilised by consumers or businesses. Circular strategies in this phase aim to maximise product lifespan, increase resource utilisation, and encourage responsible consumption behaviours. Levers in this phase include:

  Product Longevity: Designing products for durability, reliability, and longevity to extend their useful lifespan and reduce the need for frequent replacements.

  Product-as-a-Service (PaaS): Shifting from ownership models to service-based models where consumers pay for access to products or functionalities, encouraging manufacturers to design for durability and enabling better product stewardship.

  Maintenance and Repair: Promoting repairability and providing access to spare parts and repair services to extend the life of products and reduce premature disposal.

- **Outflow Phase:** This final stage involves the end-of-life management of products and materials, including disposal, recycling, and recovery. Circular strategies in this phase aim to minimise waste, recover valuable materials, and close the loop in the value chain. Levers in this phase include:

  Closed-Loop Recycling: Establishing systems and infrastructure for the collection, sorting, and recycling of materials to reintegrate them into the production process, reducing the demand for virgin resources.

  Extended Producer Responsibility (EPR): Holding producers accountable for the end-of-life management of their products, encouraging take-back programs, and facilitating responsible disposal and recycling.

  Circular Business Models: Exploring business models such as product leasing, remanufacturing, and industrial symbiosis to recover maximum value from products and materials at the end of their first lifecycle.

By strategically applying CE principles and leveraging these levers across the inflow, in-use phase, and outflow stages of the value chain, the solar industry can transition towards a more sustainable and regenerative economic model, where resources are used more efficiently, waste is minimised, and environmental impacts are reduced.

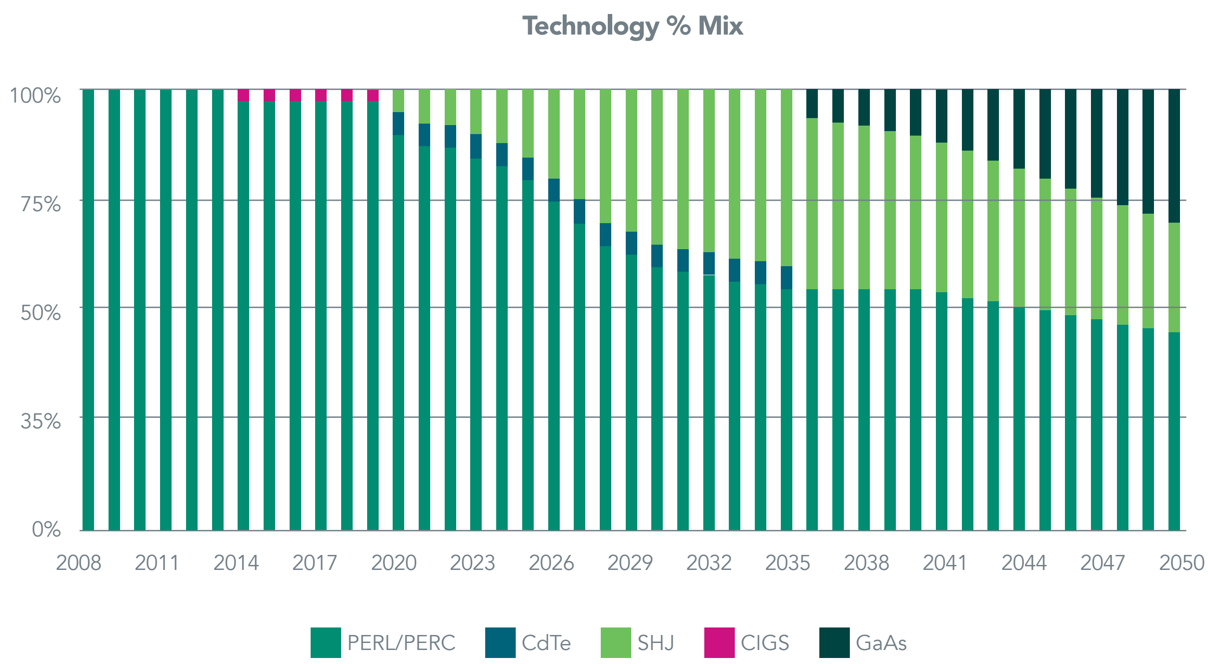
Circular Economy Deep Dive

A case for the circular economy: Solar Panels

Over the past decade, solar PV technology has experienced remarkable evolution, significantly impacting the UK energy mix. The UK increased its cumulative solar capacity from 22MW in 2008 to approximately 15GW in 2023, with the bulk of the equipment including panels being imported. This translates to a large addition of our focal metals (copper, aluminium, silver), and other materials such as glass, within the UK's borders. We assess the implications for this growth in terms of volumes and quantities of material inflows and outflows, seeking to better understand the potential material reduction from increasing product lifetimes and recycling rates.

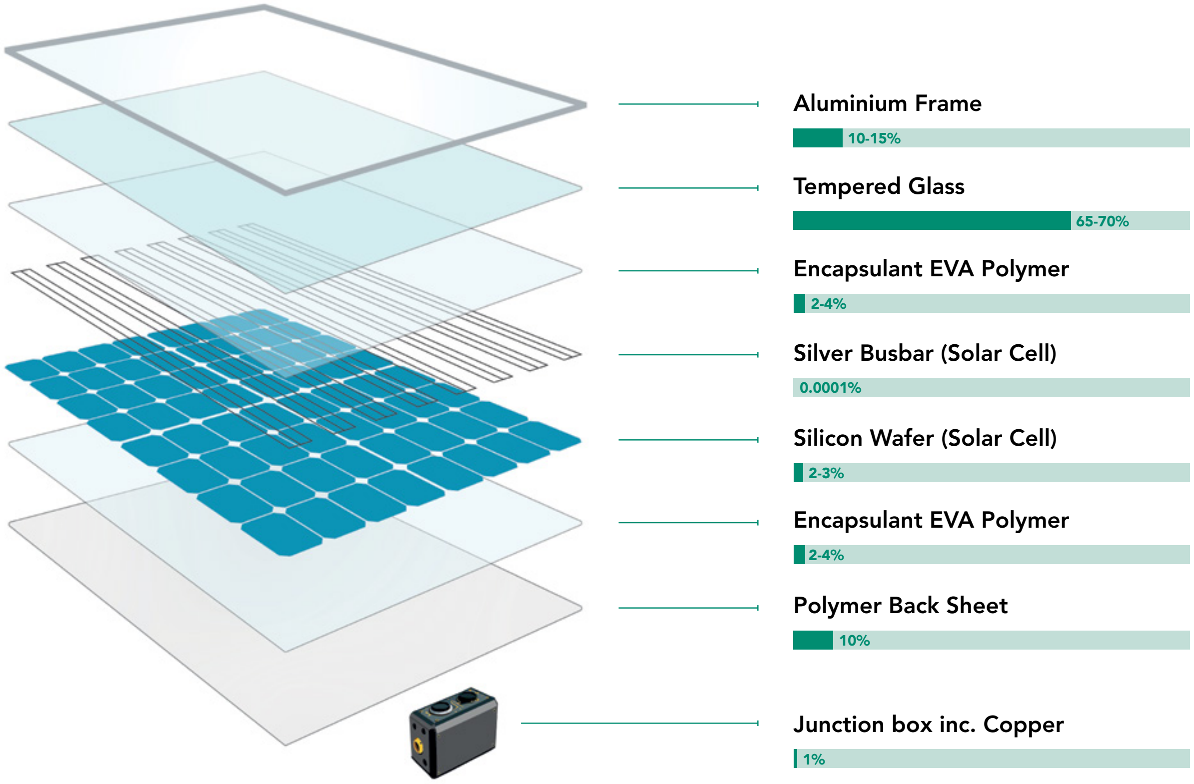
We modelled capacity additions for five energy technologies from 2008 to 2050. These technologies, discussed in Appendix A, were incorporated in varying proportions (see Figure 7). Our projections were based on IRENA forecasts[61] and align with National Grid's FES 2023[62] "Consumer Transformation" (CT) scenario. This realistic scenario projects 79GW of cumulative solar capacity added by 2050 which meets the UK Net Zero target.

Figure 7: Predominant solar panel technologies in the UK from 2008-2050



Crystalline silicon technology is poised to keep its dominant position till 2050, under the different hats of HJT & PERC and innovative new thin film technologies such as perovskite are expected to reach commercial maturity in the coming decades. Figure 8 shows the exploded view of a typical monofacial PERC module showing the incorporation of the focal metals aluminium, copper & silver.

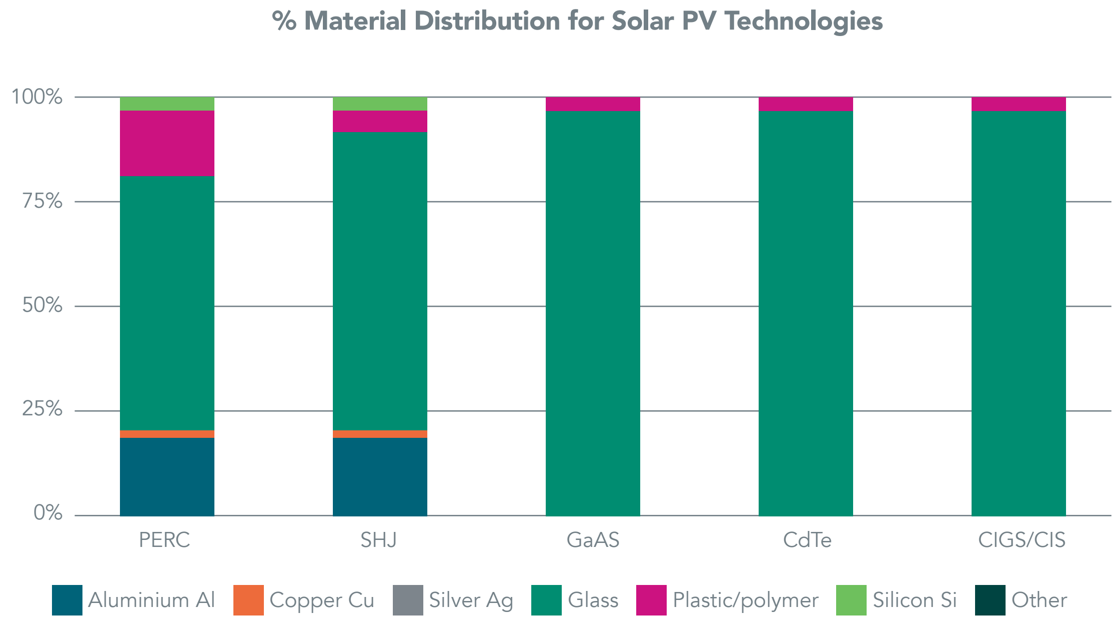
Figure 8: Main components and constituent materials of a monofacial crystalline Si PERC PV panel



Each of the five energy technologies considered (PERC, SHJ, GaAs, CdTe and CIGS/CIS) were estimated to have constituent materials in varying proportions as shown in Figure 9 and this was used to model the material flows.

The material distribution is assumed to be constant from 2008 to 2050 i.e. there is no technological learning curve in terms of composition of metals.

Figure 9: Material distribution for different technologies from 2008-2050



From linear to circular

To manage the anticipated increase in use and decommissioning of PV panels, three main CE strategies can be employed:

1. recycling decommissioned panels and feeding the material into UK secondary market or domestic UK PV supply chain.

2. repair & refurbishment PV modules by extending their service lifetime to the typical design life of 25 years through circular economy practices.

3. re-using previously decommissioned but fit-for-use panels to reduce the virgin material input required for added capacity. This will result in a new business model of selling modules for re-installation after ensuring fitness for purpose[e]. The three strategies will have different environmental and economic trade-offs. For example, preliminary IEA research[63] indicates that maintaining panels until the end of their technical lifetimes is more environmentally beneficial than replacing them with new ones every 10 or 15 years. Repairs that could be easily undertaken, such as junction box replacements, have a negligible impact on overall environmental burden. Prolongation of lifespan through repair is generally more viable for relatively young panels with high remaining power, while recycling is more suitable for panels with costly-to-repair failures. However, the current economic system makes the costs of reuse or repair uneconomic.

Quantifying current baseline stocks and flows of solar panels and materials:

Table 1 shows an estimate for a combined material stock of 830,000 tonnes of aluminium, copper, silver and glass, with a material value (excl. glass) of around $520mn.

Table 1: Estimated material stock and material value at the end of 2023 (author's analysis based on National Grid data and London Metal Exchange Sep'24 prices)

	Aluminium Al	Copper Cu	Silver Ag	Glass
Weight in Tonne	152,523	8,745	87	667,947
Value in Mn USD	359	79	84	NA

Table 2 shows an estimated cumulative material inflow by 2050 of 6.6mn tonnes and a cumulative outflow of 3.5mn tonnes of aluminium, copper, silver and glass at end of life based on assumed 15 year lifespans, with an estimated outflow material value of $2283mn.

Table 2: Estimated cumulative material flows at end of 2050 material value at 2024 prices for base scenario (National Grid CT scenario with no recycling/recovery)

	Aluminium Al	Copper Cu	Silver Ag	Glass
Cumulative inflow 2008-2050 (Tonne)	1,240,000	71,065	710	5,270,000
Cumulative outflow 2008-2050 (Tonne)	660,000	38,134	381	2,740,000
Potential material value due to outflow till 2050 (Mn USD)	1,570	343	369	NA

[e] Research has shown that reselling currently is only attractive and might be financially viable if the panels are less than 10 years old and free from any defects. Testing and recertification costs, heavily influenced by local labour costs could significantly impact the reuse business case as well.

Modelling potential impact

To illustrate the potential benefits of applying CE strategies, we chose National Grid's FES 2023 Consumer Transformation scenario as our base scenario. Our base scenario assumes no provisions for circularity in the solar panel lifecycle, including no/very low recycling within the UK, early replacement of panels every 15 years, absence of large-scale repair or reuse practices, and material flows as detailed in Table 2.

The following three CE scenarios (based on key assumptions as detailed in Appendix B) were tested:

Low Circular - Prolongation of panel life from 15 years to 20 years for panels installed from 2020 onwards. This practice comes into effect in 2025 through adoption of repair activities. We assume a 40% recycling rate which is then completely fed back into domestic PV supply chain.

Recycling rates of aluminium, copper and glass are assumed at 70%, whereas for silver it is set at 40% (refer Table 3).

Medium Circular - Prolongation of panel life from 15 years to 25 years for panels installed from 2020 onwards through repair. This practice comes into effect in 2025. Increased high-efficiency recycling capacity within the UK is assumed to be able to collect and process 60% of the decommissioned volume and completely fed back into domestic PV supply chain. Recovery rates of materials during recycling is assumed higher (80% for aluminium, copper and glass, 50% for silver) (refer Table 3).

Highly Circular - Prolongation of panel life same as per the medium scenario above (25 years). Technological advances in recycling increase recycling rates to 85% of the decommissioned volume (as mandated by WEEE regulation) and 90% recycling rate for aluminium, copper, glass and 60% silver (refer Table 3).

Table 3: Assumed recovery rates during recycling for various scenarios

		Low	Medium	High
Total recovery/ collection rate of decommissioned solar panels		40%	60%	85%
Functional recycling rate of materials i.e. yield rate	Aluminium, Al[64]	70%	80%	90%
	Copper, Cu[65 66]	70%	80%	90%
	Silver, Ag[67]	40%	50%	60%
	Glass[68]	70%	80%	90%

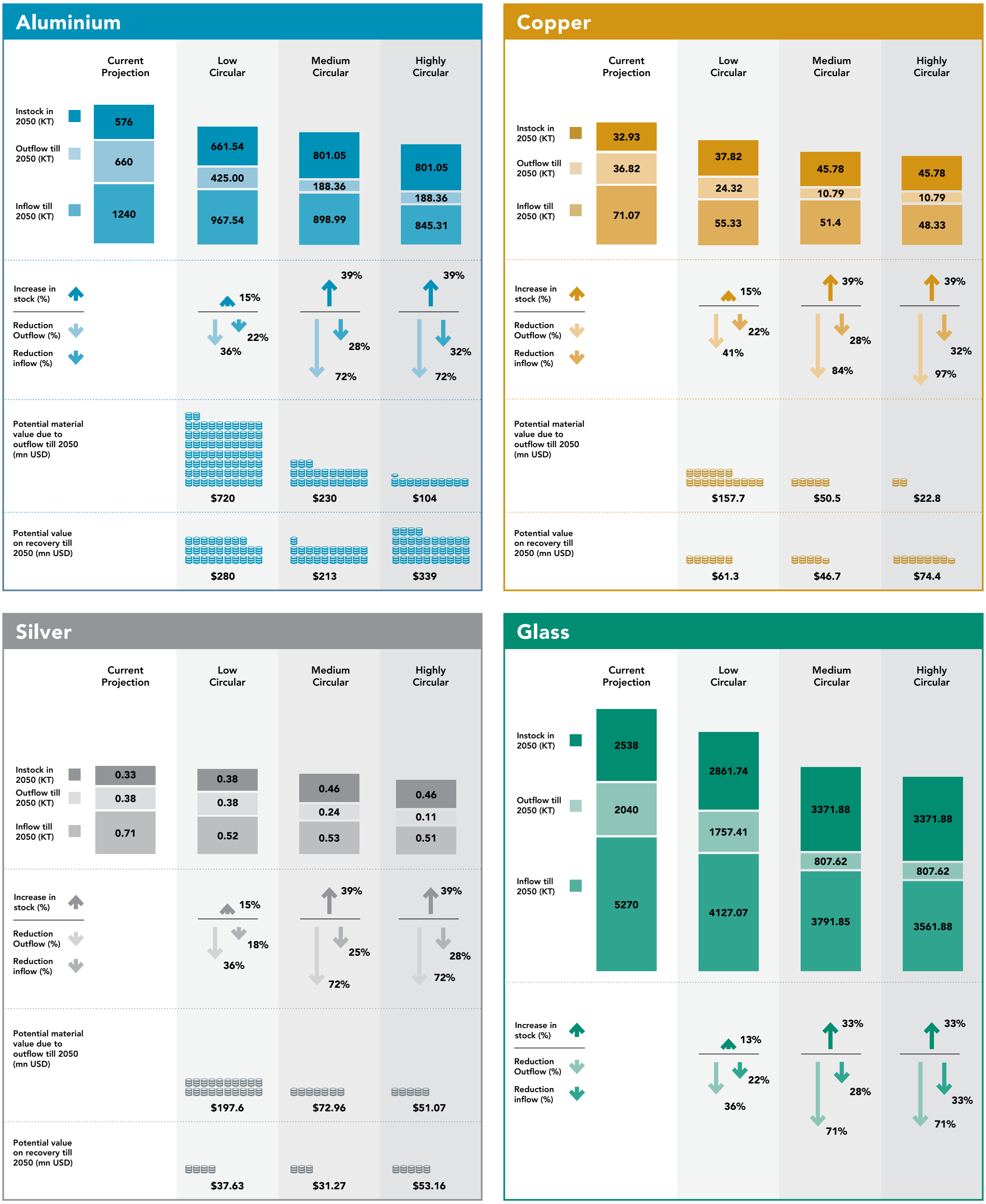
Material reduction opportunity

Figure 10 summarises material savings for each major material in all 3 scenarios compared to the base scenario i.e. current projection.

Material inflow is reduced between 18-33% for the low, medium and high circular scenarios for all the materials as there is less demand for new panels due to longer lifespan of existing panels. This means there is reduced need to import panels i.e. reduced dependency for energy security.

Material outflow, i.e. the loss of materials from the UK borders, is reduced even more significantly than inflow, with material outflow reduced by 36% for the low circular and 72% for the medium and high circular scenarios due to higher collection and recovery rates. This leads to an increase in materials in stock in the circular scenarios, meaning more material is kept in use for longer within the UK. The outflow for aluminium is reduced from $1.57bn to $1bn for the low circular and further reduced to just $0.44bn for the medium and high circular showing an increase in UK domestic stock of this metal. This again translates to reduced dependency on virgin, imported materials. The material outflow is predominant during periods from 2028-2036 and 2045-2050 for all scenarios making short-term and long-term infrastructure planning/ capacity development to process the solar waste in the UK an urgent task.

Figure 10: Material flow analysis under different circular scenarios



Seemingly counter-intuitive, the amount of material recovered via recycling is reduced from the low circular scenario to the medium circular scenario before again increasing for the high circular scenario. The reason for this is that the reduction in feedstock of retired solar panels to be recycled outweighs the increase in recycling efficiency initially. As expected, there is progressive reduction in the net materials lost (i.e. Total Outflow – Recycled value) through the 3 different scenarios with high circular having the least outflow. Overall, while comparing the base scenario to the high circular scenario would retain $2.1bn of aluminium, copper and silver in stock and an estimated increase of between $0.37bn (low circular) to $0.46bn (high circular) available for recycling from end of 1st life PV (aluminium, copper and silver).

Our initial modelling highlights the rapid build-up of material and component stocks in the UK economy, which have potential to be retained and reclaimed through enhanced recycling infrastructure and technology. At the same time extending product and component lifespan offers the opportunity to optimise power output to material input and overall system performance for any given technology and reduce potential future supply chain risks. The following section outlines some of the ways that startups, and technological advances are already seeking to create and capture value from these two strategies.

The circular economy in practice

Evidence of CE adoption and implementation across the inflow, use and reverse flow stages of the value chain are emerging, often led by SMEs. Here we present, explore and illustrate examples from both solar and the wider energy storage industry of circular interventions across the value chain.

Inflow phase: reduce inflow

Grafmarine: Designing solar products for the future

Grafmarine is an example of an R&D company at pre-revenue stage, but close to commercialisation with an order book from major shipping companies wanting to decarbonise their fleet. NanoDeck™, is a modular solar energy solution designed to reduce fuel demand and extend the serviceable life of maritime vessels through regulatory compliance.

Photo of NanoDeck™ being tested *(Photo credit: Grafmarine)*

Grafmarine's approach combines design, material selection and data integration.

1. **Design for assembly/disassembly**: NanoDeck™ features a simplified design with minimal components, allowing easy assembly and disassembly. This allows for straightforward repairs and replacements of only the damaged modular tiles. The design extends the product's life, enabling it to be relocated (to land based applications for example) and reused in different settings without the need for specialised tools.

The Lithium-based battery technology used for energy storage in the NanoDeck™ module is also designed with circularity in mind. Its modular design allows for easy updating of battery packs at sea by retaining the core components and simply replacing the electrolyte, which can then be recycled.

2. **Sustainable material choices:** The company is committed to sourcing sustainable materials and manufacturing responsibly. Their third generation solar PV technology uses materials that are soluble in hot water and free from toxic chemicals. They have 3D printed large sections of prototypes with recycled ocean plastics and are collaborating with a company in England to extrude nylon into printable threads. Additionally, they have global partnerships focused on reusing fishing nets and second life plastics for non-critical parts of the final product. Working with Innovate UK & foundries in India, they are looking to incorporate recycled Aluminium into their frames and are working with several UK universities and research institutes to identify more sustainable alternatives to aluminium. Although still in the early stages, Grafmarine aims for NanoDeck™ to be fully recyclable by 2030.

3. **Data integration for adaptability/longer lifespan:** Grafmarine plans to deploy a blockchain-based parts management system for preventive maintenance in their NanoDeck™ technology. This system will enable precise monitoring of the supply chain and optimize component usage by predicting points of failure and necessary updates before they occur. It will consider the varying environmental conditions that ships encounter, such as extreme temperatures, to ensure the batteries are fine-tuned for long-term performance. By collecting and analysing data, the system will allow for the customisation of batteries to withstand diverse conditions, from the frigid temperatures of Northern China to the intense heat of Australia. This approach aims to ensure the reliability and efficiency of the NanoDeck™ technology worldwide.

Re-Solar: Supporting the reconstruction of Ukraine with reused solar panels

Introduction

As an example of product re-use, Hammersmith & Fulham Council, in collaboration with the Cornish start-up Re-Solar™ and other partners, has successfully rescued and rehomed 50 solar panels generating 9kW electricity and worth approximately £1000. This initiative has resulted in substantial carbon savings but also made small contribution to Ukraine's reconstruction efforts by providing renewable energy to critical infrastructure.

Background

In early 2023, around 700 solar panels were removed from the Edward Woods estate in London due to changes in building regulations following the Grenfell Tower fire. Normally, these panels would be recycled, but recognising their remaining life potential, the council and ReSolar saw an opportunity to reuse them. Collaborating with Energize Ukraine, Ultra Low Carbon Alliance, the Ukrainian embassy to Canada, UK Friends of Ukraine, and Repair Together, they aimed to rehome some of these panels for humanitarian aid.

Implementation

Re-Solar, a Cornish start-up, meticulously managed the retrieval and testing of the panels. After being removed from the estate, the panels were transported, inspected, and tested to ensure they were still functional, and that waste was not being exported. The panels were then shipped to Ukraine, where they were installed to power a clinic and other facilities, supporting reconstruction and providing a stable energy source.

Results

By rehoming 50 solar panels, the initiative led to significant lifetime carbon saving. The panels, which still had more than 10 years of operational life, are providing renewable decentralised power to Ukraine at a time when its traditional energy source are under continual threat. Moreover, this initiative showcased the potential for a secondary market for used solar panels, emphasising the importance of rethinking waste and promoting sustainability.

Conclusion and implications

This case study demonstrates the practical feasibility and benefits of reusing solar panels, and the role of collaboration in achieving product re-use – in this instance across international borders. It highlights that the reuse and repair of solar technology, rather than premature disposal and or recycling, can extend the life of solar panels by many years.

Photos of solar panels being transported to and received in Ukraine for re-use *(Photo credit: Re-Solar)*

Application of recovered carbon black in photovoltaic devices

Background

Each year, about 29 million metric tonnes of vehicle tyres reach the end of their lifespan worldwide, causing significant environmental impact. Nearly 10% end up in landfills, leading to pollution, while most are incinerated, releasing approximately 22kg of CO2 per tyre with poor energy recovery.

This one-year project, funded by UKRI's NICER programme and led by Newcastle University, in collaboration with RAF Leeming (MOD) and Wastefront – a Norwegian waste-to-fuel business, explored the potential of using recycled carbon black from waste tires in high-value applications like printable photovoltaics. The initiative aimed to determine if recycled carbon black could match or surpass the performance of virgin materials, supporting circular economy principles and reducing waste. Additionally, it sought to provide data to MOD decision-makers, demonstrating how using UK-recycled materials for power equipment manufacturing can support the transition to clean energy and enhance defence security to meet the Net Zero by 2050 target.

The Challenge

The project's goal was to evaluate the feasibility of applying recycled carbon black in printable electronics and photovoltaics. Given that the EU prohibits tire disposal in landfills and incineration yields poor energy recovery with high CO2 emissions, finding high-value applications for recycled carbon black is crucial. Current recycling efforts mainly produce shredded materials for sports pitches and playgrounds, which pose pollution concerns.

A new Wastefront recycling plant in the Sunderland, UK plans to process 80,000 tonnes of tires annually, producing sustainable aviation fuel, sustainable chemicals and recovered carbon black. Identifying new markets for recovered carbon black, particularly in photovoltaic technology, is essential due to the anticipated 70 million tonnes of PV waste by 2050 and challenges in the supply chains for renewable energy materials.

The Approach
The project utilised a triple mesoscopic stack technology for printable photovoltaics, which is easy to scale. The team developed inks from recycled carbon black provided by Wastefront and compared them with virgin carbon black. The research involved characterising the recycled carbon black, formulating screen-printable ink, assembling and testing devices both indoors at Newcastle University and outdoors at the ViTAL living lab at RAF Leeming. They also focused on recycling the light-absorbing component, reinfiltrating the cleaned stack, and retesting.

Unexpected Outcomes
Initial results were surprising as the recycled carbon black, despite impurities, performed as well as the virgin material. This indicates that impurities might be beneficial for certain applications. The project highlighted that the processing conditions for recovering carbon black could enhance processability, textural properties, and surface chemistry.

Key Learning
The key insight is that recycled carbon black can match the performance of virgin materials. Future projects could benefit from optimising the processing conditions to tailor the properties of recycled carbon black for specific applications. This project underscores the potential for high-value applications of recycled materials and suggests a path forward for more sustainable practices in electronic and photovoltaic device manufacturing.

The Outcome
The proof-of-concept study showed positive results for using recycled carbon black in recyclable solar cells. The findings have strengthened academic-industry collaborations, led to presentations at conferences, and have been submitted for scientific publication. The results have been shared with decision-makers in the RAF and MOD to illustrate more resilient supply chains for renewable energy materials.

The project has created a new business opportunity for Wastefront and supports further funding applications to scale up the approach and explore additional applications in electronic devices. This project thus contributes to a CE by promoting the use of recycled materials in high-value applications.

In Use phase: asset optimisation

Revive Battery BV

Lead-acid batteries remain a common component in solar energy storage due to their affordability, reliability, and mature technology. By leveraging the stocks of lead-acid batteries in use, solar energy systems can provide cost-effective energy solutions, particularly in off-grid and hybrid applications. While lead-acid batteries have many advantages, they also face following challenges:

Limited Lifespan: Lead-acid batteries typically have a shorter lifespan compared to lithium-ion batteries, often requiring replacement every 3-5 years.

Maintenance Requirements: These batteries need regular maintenance, including electrolyte level checks and ensuring proper charging to avoid sulfation and extend battery life.

Solving both these problems is a start-up called Revive Battery BV based in the Netherlands. Revive regenerates dead & degraded lead acid batteries to up to 90% of its original capacity through high voltage currents managed by algorithms, using electrical high-frequency pulsation. This method dissolves hardened lead sulphate crystals, restoring the battery's active material without opening the battery or using chemical additives. This can be done 2-3 times before the battery performance drops beyond economic viability, thereby extending the life of the battery between 8-12 years and saving approximately 3.5T of carbon emissions per battery.

This innovative on-site battery regeneration minimises logistical problems for clients, by using lightweight, compact and portable machines powered by solar energy. Regenerating batteries reduces the carbon emissions associated with the energy intensive recycling process, and reduces the pollution leaked into the environment. Revive operates a machine learning enabled battery management system which helps keep track of the health of individual batteries and carry out preventive/routine maintenance as per the discharge profile unique to that battery.

Re-Solar: Repair

Re-Solar™, a UK-based start-up, embarked on a project to explore the energy generation and reuse potential of damaged solar panels retrieved from the waste stream. They collected 204 panels from a new 44,000 panel solar farm development in the Southwest of England, UK in 2022 that arrived damaged in transit, resulting in cracked glass. The project involved visual inspection, grading of damage, transporting and flash testing the panels at University of Exeter's flash testing facilities at Penryn Campus, Cornwall.

The feasibility study comprised several key components:

1. Inspection: On-site visual inspection and basic continuity of panels to retrieve panels with the least damage in the first place and careful transportation to avoid further damage.
2. Testing: flash testing of panels to assess their maximum power output potential under Standard Test Conditions (STC) despite physical damage. Panels are then categorised based on their electrical performance.
3. Repair: Various remediation techniques have been applied to analyse potential treatments for cracked glass, including resin repair, acrylic adhesives, and specialised PV coatings. The effectiveness of these methods in restoring panel functionality has been evaluated through systematic testing and monitoring.
4. Re-install: Re-Solar installed a test bed using two varying glass repair methods, silicon and UV glue, to establish the degradation rates over time in the field environment. Results of this study are pending and will be published in late 2024.

Conclusion
Re- Solar has highlighted how effective remediation techniques and accompanying guidelines for refurbishment could support the UK solar industry to reduce waste, prolong operational lifespan and delay the point for recycling or disposal.

Outflow phase: post-use asset recovery/repurpose

Flaxres: Modular recycling unit

Flaxres based in Dresden, Germany is an innovative company looking to advance photovoltaic (PV) module recycling, they have designed a mobile and flexible recycling plant, Flaxthor 2.0, which can fit into a shipping container.

Flaxthor 2.0 is deployed directly to the site where PV modules are decommissioned, reducing expensive and carbon intensive transportation.

Flaxres can recycle up to 10 tonnes of solar modules per day, with a capability to recover over 95% of materials, including high-quality glass, silicon, and silver. The pilot plant has a recycling capacity exceeding 1,000 tonnes annually (approximately 50,000 panels).

Flaxres's mobile recycling units are set to be available by 2025, leased to customers with the company's personnel managing operations and the company retaining ownership of the assets. These units are designed to be versatile, capable of processing both crystalline and thin-film modules, and handle damaged panels with low energy input. The recovered materials are of high purity, facilitating their reintegration into the manufacturing cycle,

The extent to which Falxres technology and business model will be successful remains to be seen, but the ability to take the recycling to the solar panels removes one big barrier in the economics of solar panel recycling.

ROSI: Effective recovery of silver

ROSI, a company based in Grenoble France, is the first company to extract the silver value from end-of-life PV modules with high-efficiency and low impact processes. They are advancing technologies for treating waste PV modules through a thermal delamination process that ensures high purity of recovered materials. This process, combined with a soft chemistry method to separate silver from silicon wafers, allows ROSI to recover high-purity silver and silicon, making the treatment process cost-competitive. Additionally, ROSI has developed methods to recover fine silicon particles and sawing liquid from the wafer manufacturing slurry (kerf), which can be reused in ingot slicing and purified for photovoltaic silicon production, enhancing efficiency by 15% in existing plants.

Solarcycle: Innovations in PV panel recycling (USA)

Solarcycle, a California-based startup, has developed proprietary technology to recycle old solar panels into valuable materials for new ones. The company can recover over 95% of essential materials such as aluminium, glass, copper, silver, and silicon and supports a more circular and scalable solar industry in the United States by reducing reliance on overseas suppliers.

In 2022, Solarcycle raised $30 million in Series A funding, bringing its total funding to $37 million to help expand the capacity of their Texas recycling plant from 500,000 to 1 million panels annually and support further research and development.

Solarcycle is recognised as one of only 5 companies in USA. capable of providing advanced and cost-effective solar panel recycling services by Solar Energy Industries Association[69]. Unlike other recyclers, Solarcycle integrates its recycling processes with solar energy production. Their Texas facility will utilise "second life" solar panels to power the plant, enhancing sustainability.

In addition to its recycling initiatives, Solarcycle plans to construct a $344 million solar glass manufacturing facility in Georgia. Scheduled to begin in 2024 and operational by 2026, this plant will use recycled materials from retired panels to produce solar glass, addressing a critical supply chain gap. This facility will have the capacity to produce 5 to 6 GW of solar glass annually, significantly contributing to the US domestic solar manufacturing industry.

Solarcycle's innovative approach not only advances PV panel recycling but also aligns with broader sustainability goals of the US govt., making significant strides toward a circular economy in the solar industry.

The Indian Institute of Science: Homes out of decommissioned solar panels, sustainable innovation in India

The Indian Institute of Science (IISc) in Bengaluru, India has embarked on a pioneering project to address the growing challenge of managing decommissioned solar panels by developing an innovative approach to upcycle these panels into building materials[70]. This initiative not only tackles the waste problem but also promotes sustainable construction practices.

By reusing silicon from old solar panels, the researchers have created efficient photovoltaic systems embedded in building materials. These materials can be used for constructing roofs and facades that generate electricity, making buildings more energy-efficient and reducing their carbon footprint. The project aims to extend the lifecycle of solar panels by another 30-40 years[71], thereby supporting the CE by reducing the need for new raw materials and minimising waste. The success of this project could pave the way for broader adoption of similar techniques in the construction industry, particularly in countries that are aggressively pushing for renewable energy solutions.

The research team at IISc is working on refining the upcycling process to enhance the efficiency and scalability of the technology. Future projects may involve collaborations with construction companies and government agencies to implement these sustainable building materials on a larger scale.

Photo of solar panels used as walls
(Pic credit: Better India)

Full System

CIRCUSOL project

The CIRCUSOL project, supported by the Horizon 2020 program, aims to create circular business models in the solar power industry in Europe, focusing on Product-Service Systems (PSS). This approach shifts from selling solar panels and batteries to providing them as a service, maintaining supplier ownership to optimize their lifecycle. This model enhances resource efficiency, extends product life, and reduces waste. The project includes five demonstrators in Belgium, France, and Switzerland, validating these models across various market segments. CIRCUSOL collaborates with 15 partners from seven EU countries to achieve its goals. The project also emphasises second-life applications for PV modules and batteries, developing labelling, certification protocols, and policy recommendations and creating a more resilient and sustainable supply chain.

CIRCUSOL aims to drive systemic changes within the solar power industry, focusing on three main areas:

1. **Redesigning Internal Relationships:** The project encourages a reconfiguration of value networks to support circular economy principles. Short-term actions include enhancing communication and cooperation among stakeholders, while long-term actions focus on establishing standardized procedures for recycling and reuse.
2. **Mindshift Among Stakeholders:** Achieving a circular economy requires a cultural shift among industry players, policymakers, and consumers. Short-term actions involve raising awareness and providing education on circular practices, whereas long-term actions target embedding circular economy principles into industry standards and regulations.
3. **Redesign of Solar Power Products:** The project advocates for designing PV panels and related products with their end-of-life stage in mind. This involves using materials that are easier to recycle and designing products for easier disassembly.

Lessons Learnt from CIRCUSOL

Ecosystem and supply chains: Material banks are emerging as valuable resources, enabling the reuse of materials and promoting circular thinking. The sharing economy model shows promise for broader application due to its efficiency gains. However, the supply of high-quality second-life photovoltaic (PV) panels is limited, with these panels often command premium prices. On the demand side, the product-service system (PSS) model has yet to gain traction in the residential market but may hold potential in the business-to-business (B2B) sector for utility-scale systems. The CIRCUSOL project team found out that the PV market is interested in procedures and standards for 2nd life and one of the main challenges is to find methodologies to test large batches of PV in an economically responsible way. CIRCUSOL has also led to better knowledge about what types of modules are fit for reuse and that age does matter.

The project's efforts to enhance the circularity of PV design have revealed that implementing proposed design changes is challenging due to rapidly evolving technologies. A systemic approach is necessary: that analysis of not only the circular design changes is required, but also the production processes of PV panels, including their components and materials.

Demonstrators and Business Models: The project proved that a product-service system (PSS) using second-life PV installations is technically feasible. However, its adaptability is limited, with challenges in engaging stakeholders, particularly in the residential market, where the complexity of the solar industry was underestimated. Tailored solutions are needed to address regional differences and market dynamics, while regulatory barriers favouring centralised energy systems hinder innovative business models. Despite this, research shows that PSS models can lower adoption costs and make PV systems more accessible to low-income households, with broad appeal across diverse demographics.

System enablers

SecondSol: Solar PV second hand trading platform

SecondSol is Europe's largest online marketplace for photovoltaic (PV) products, promoting sustainable trade by allowing users to buy and sell both new and used items and access services to extend product lifespan. The platform offers over 1 million products, including PV modules, inverters, storage systems, cables, and plugs, supporting both private individuals and businesses in showcasing their offerings. Their commitment to sustainability is highlighted by their motto, "No Electronic Waste to Africa," ensuring that only products meeting stringent quality criteria are resold. Substandard items are professionally recycled or disposed of properly, preventing electronic waste and contributing to environmental responsibility.

In addition to trading, SecondSol provides extensive repair, rebuild, and testing services to enhance the longevity and efficiency of PV components. Their repair service focuses on fixing damaged PV modules, ensuring they are restored to optimal functionality. The rebuild service involves reconstructing modules that may not be repairable, creating custom-built replacement modules that meet specific performance requirements. These services help extend the life of existing PV systems, promoting sustainability and reducing waste.

SecondSol's testing service ensures that both new and used solar modules meet stringent quality standards. This service includes comprehensive assessments of module performance and reliability, providing users with confidence in the products they purchase. By maintaining high standards, SecondSol ensures that only quality items are resold, while substandard products are professionally recycled or disposed of, in line with their commitment to environmental responsibility.

SecondSol also stands out as Europe's largest dealer of PV spare parts, maintaining over 250,000 items in an 8,000 square meter facility. This extensive inventory ensures that operators can find the necessary parts to keep their PV systems running efficiently for 25 years or more. The company's global reach allows for the delivery of these products worldwide, supporting the sustained operation of PV systems across various regions.

Overall, SecondSol's innovative approach to PV product trading, combined with their repair, rebuild, and testing services, supports long-term sustainability and effective operation of PV systems. Their commitment to high standards and environmental stewardship makes them a key player in the European PV market enabling circularity in the whole PV sector.

Regulation: The USA Inflation Reduction Act

The Inflation Reduction Act (IRA), enacted in 2022, significantly supports the U.S. renewable energy sector, particularly solar photovoltaic (PV) manufacturing. Key components of the IRA include financial incentives such as the extension of the Investment Tax Credit (ITC), offering a 30% tax credit for solar installations through 2032. This stability encourages investment in solar manufacturing and technology. Additionally, the Advanced Manufacturing Production Credit (AMPC) promotes domestic production by making U.S. made solar components more competitive globally.

The IRA also focuses on strengthening domestic supply chains through substantial funding for the development of critical materials and components, alongside grants and loans for building or expanding manufacturing facilities, thus creating jobs and ensuring a steady supply of solar products.

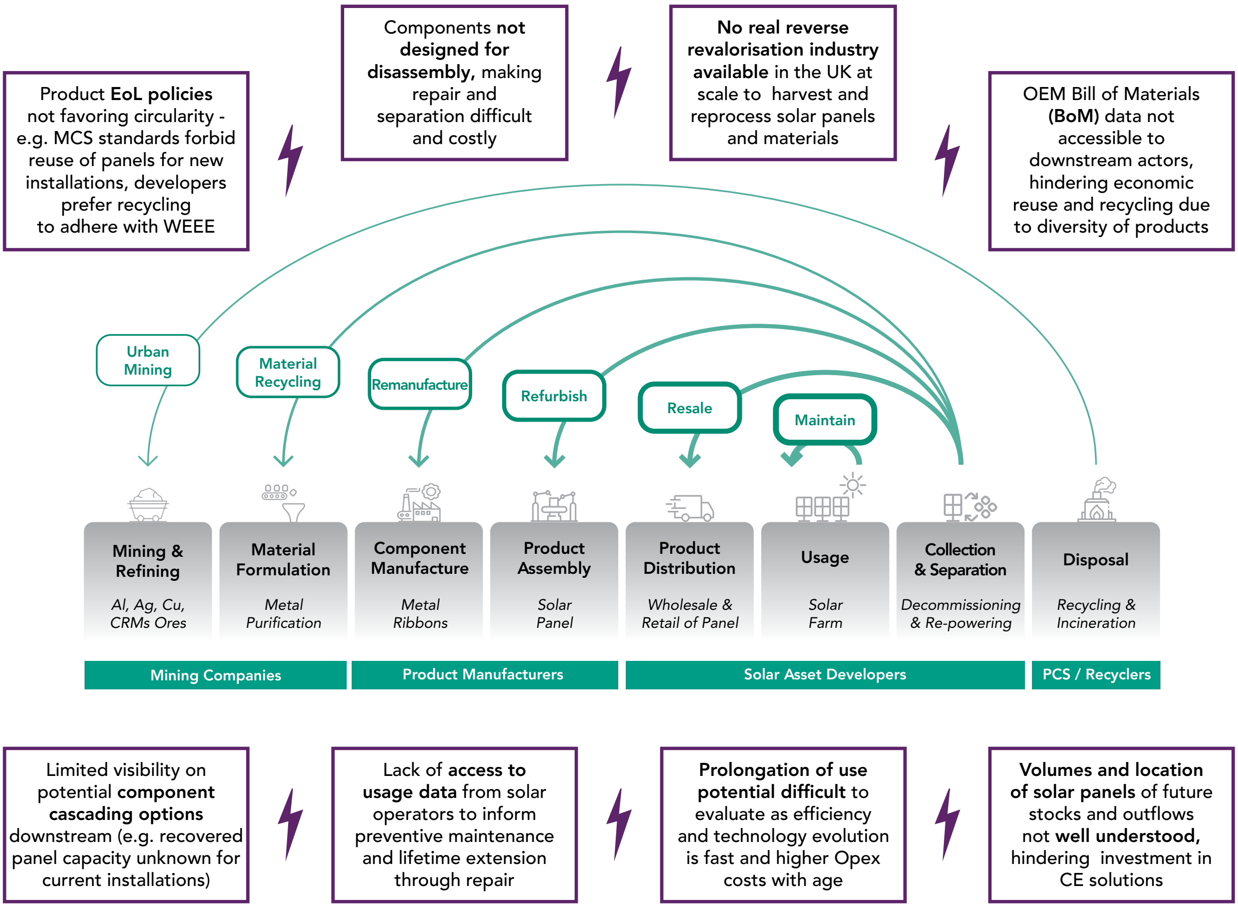
A notable aspect of the IRA is the support for establishment of a robust solar PV recycling infrastructure which companies like Solarcycle are currently capitalising on. This includes funding for facilities that can recycle decommissioned solar panels, recovering valuable materials like silicon and glass, supporting a circular economy, and reducing environmental impact. By incentivising domestic production, the IRA aims to reduce reliance on imported solar panels, enhancing U.S energy security and retaining economic benefits within the country.

These case studies on CE practices reveal significant innovation potential, offering technologies that reduce inflows, increase utilisation and promote recirculation, but also highlight challenges in scaling and market reach. While these initiatives offer promising sustainable solutions, they are dwarfed by the overall industry's scale and face systemic barriers worldwide that limit their broader impact. To realise their full potential, these innovations require overcoming these challenges through stronger collaboration between stakeholders, broader market integration, and supportive policies to unlock their full potential.

Identifying challenges to CE adoption of Solar in the UK

This section explores the systemic barriers in the solar energy sector in the UK that poses a hurdle to the widespread, large-scale adoption of CE practices explored in the previous section. Key challenges to the implementation of a CE model include: requirements regulatory compliance, physical recycling infrastructure, logistics, lack of data availability and reporting to inform reuse and repair as mapped in the below figure.

Figure 11: Barriers to CE adoption at scale in the UK solar sector



1. Policy and Regulation

MCS: The Microgeneration Certification Scheme (MCS) is a quality assurance scheme in the UK that certifies renewable energy products, installers and their installations. Its primary role is to ensure that installers are technically competent, solar panels and other components of (mainly residential) solar installations meet high standards of performance and safety. All MCS compliant installations are required to be registered by installers in a database to generate an MCS certificate. MCS certification is crucial as it provides customers with confidence in the reliability and efficiency of their systems, ensures compliance with industry standards, and is often a prerequisite for receiving government incentives (erstwhile Feed-in-Tariff), insurance coverage and other financial support like export tariff currently provided by some energy companies. This certification thus plays a vital role in promoting the adoption of solar (& other renewable) technology across the UK.

However, as part of the rigorous standard for its contractors, MCS has set down mandatory conditions that "Products and materials installed shall be new and not previously used"[72]. Although the reasoning behind this clause is twofold – to ensure high quality products & materials are used to protect the consumer, and also to deter unfair practices to access financial incentives (i.e. a form of accounting check), this has ultimately ensured that solar panels and other equipment, which may be technically fit-for-purpose after early retirement cannot be legally reused within the UK and are then sent as PV waste, or in some cases sent abroad for reuse.

Ironically, the new equipment requirement may counteract some environmental benefits. Reusing existing, functional equipment would reduce the demand for new products and mitigate environmental impact across the life cycle. Innovative projects focusing on the reuse and refurbishment of solar panels and other equipment face significant hurdles under the current MCS framework. As highlighted in the previous section, companies like ReSolar, which aim to promote the reuse and repair of solar panels, struggle to gain certification for their projects, thus limiting the scope of the resale market.

The MCS condition hampers efforts to promote a circular economy and emphasizes the need to develop a PV reuse standard that will satisfy MCS requirements for customer protection.

WEEE: Currently, PV waste has been 'orange listed' by UK policymakers (Environment Agency & DEFRA) and continues to fall within the UK WEEE regulations adopted a decade ago despite calls from the industry to remove it from the classification. Prominent industry practitioners (PVCYCLE) with extensive experience in providing WEEE compliance services across Europe, argue that PV panels do not align well with European & UK WEEE regulations. They highlight that PV panels and traditional electrical and electronic equipment (EEE) have fundamental differences that make the current WEEE regulations unsuitable for PV panels that necessitate a different regulatory approach. These differences include:

a) PV panels generate electricity, while other EEE consumes it

b) PV panels have a long lifetime and are considered investment products, unlike the shorter lifecycle and consumable nature of most EEE, notwithstanding the fact that many PV panels are replaced over much shorter lives than their technical lifespan

c) The financing and replacement cycles for PV panels are vastly different from those of typical EEE, requiring equal financing for future costs rather than the rolling (pay-as-you-go) financing suitable for short-lifecycle products

d) The market for PV panels is more volatile and impacted by energy policies and geopolitical decisions, unlike the relatively stable market for other EEE.

Current collection targets for PV waste under the UK's WEEE Regulations present several challenges, making compliance difficult and often impractical for producers and compliance schemes. Annual collection targets of PV waste in terms of tonnage, which are based on the previous year's sales data, do not accurately reflect the actual amount of PV waste generated in a given year. Consequently, producers and compliance schemes struggle to predict and meet these targets, leading to significant financial penalties in the form of compliance fees when targets are not met.

Furthermore, the collection targets do not account for the preventive role that PV panels play in waste generation, for example replacing fossil fuel technologies. Despite this, the targets focus solely on recycling rather than rewarding reuse or extended use, ignoring the environmental benefits of prolonging the life of these panels.

Additionally, the publication of annual collection targets late in the operational year (March 31) hinders effective planning and budgeting for producers and compliance schemes, which need more lead time to adapt to new targets. This misalignment creates an operational burden and financial uncertainty, particularly for new solar farm developments that cannot accurately forecast future compliance costs. The inherent unpredictability of PV panel sales, influenced by factors such as subsidies, energy prices, and policy changes, further exacerbates these challenges.is this your opinion and analysis or from someone else.

Industry has therefore argued that this necessitates a reconsideration of how PV waste collection targets are set and managed to better align with the unique lifecycle and environmental contributions of photovoltaic technology[73].

2. Lack of visible and legitimate secondary market

As stated earlier, the MCS certification requirement disincentivises reuse of solar panels that have been retired within the UK. A few installers who are MCS certified are trying to do their part in reducing environmental impact by providing options to their customers of either recycling or reusing panels for different customers, thus diversifying the market segments they cater to and generate income as well. Customers who go for secondhand panels often fall under a different socio-economic tier and lose out on the benefits associated with MCS certification notably security of insurance and warranties. These companies don't advertise the resale option publicly as it might affect their MCS certification. Households in the UK who might stand to benefit from a cheaper solar installation by reusing early retired, functional equipment are unable to access the information & services provided by these companies easily.

Furthermore, the preparation for reuse (repair, testing) and reuse market for second life PV panels in the UK (& worldwide) is largely unregulated. Technical guidelines and standards are essential to ensure safe and high-quality second-hand PV panels, requiring that panels maintain at least 70% of their initial power and are free from safety-related defects. The absence of such standards by overarching bodies like International Electrotechnical Commission (IEC), and lack of testing facilities today poses a challenge. Reusing PV panels generally supports the circular economy without negative environmental impacts, but the current practice by some UK industry players of exporting second-hand panels without proper testing to verify their performance to countries in Africa & south-east Asia with weak waste regulations creates significant environmental risks.

3. Lack of Circular Economy understanding & shortage of recycling facilities

The Solar Stewardship Initiative (SSI), a solar-specific ESG & supply chain assurance scheme launched by trade associations SolarPower Europe (SPE) and Solar Energy UK (SEUK), and the Responsible Sourcing Steering Group of SEUK focuses on recycling as the default end-of-life treatment method in the UK solar industry. In contrast, SPE is involved in various circular economy (CE) projects in Europe, such as CIRCUSOL, and supports the EU's introduction of Ecodesign and Energy Labels for PV modules, inverters, and systems, including carbon footprint information. This indicates that the UK needs to improve in Circular Economy (CE) and sustainability efforts, likely because of limited understanding of how CE can help achieve net-zero targets and because current WEEE regulations and collection targets restrict industry progress.

Stakeholder feedback[74], highlighted three issues combine to present a growing problem -

a) a current lack of capacity in the UK to handle substantial volumes of solar panel waste

b) a lack of understanding within the sector regarding the necessary steps for accessing treatment and collection

c) a potential lack of funding for investment

Various industry reports and stakeholders highlight solar's key circularity challenge involves both scaling up the recycling capacity in the UK to recover the largest bulk of materials through existing mechanical treatment and recycling, and secondly the challenge of recovering the small fractions of valuable materials. There are only a handful of recyclers in the UK who currently offer PV panel recycling services and there is a wide variation in recovery rates amongst them as well. Most of the components of the panels (e.g. glass, silica) are converted to low value building materials like breeze blocks or recovered via incineration, with many critical materials lost. The collection rate for PV panels in 2023 was 460T (tones) in the UK (with 35% annual increased target of 630T in 2024) and it is expected to grow by at least 10 times to 4800T by 2030 as per some industry experts.

Consequently, some solar asset owners in the UK are storing retired and defective panels until UK recyclers declare full traceability of their processes and have the technological capability to deal with higher volume. These asset owners are willing to pay a premium to get higher recycling rates, and incurring storage costs of PV waste, to avoid the risk of reputational damage associated with a recycler scheme improperly processing their PV panel waste, for example PV waste to ending up in the global south, having adverse consequences for the recipient community and the reputation of the PV waste value chain.

4. Logistics challenges

Using publicly available data from Renewable Energy Planning Database ('REPD')[75], the lead author mapped out the location of utility scale solar plants in the UK according to the year of commissioning as seen in figure 12. Preliminary analysis shows that, the location of these utility scale solar plants (as well as those of residential installations which are not mapped in the figure) are widely dispersed across the UK, with most installations located in southern England where it is sunniest. However, from our market research, the known PV recyclers at the time of writing this report are based near London, Birmingham & Leeds, resulting in a mismatch between where the waste is generated and where the waste will end up, causing difficulties in logistics co-ordination, increased carbon emissions, and increased transportation costs.

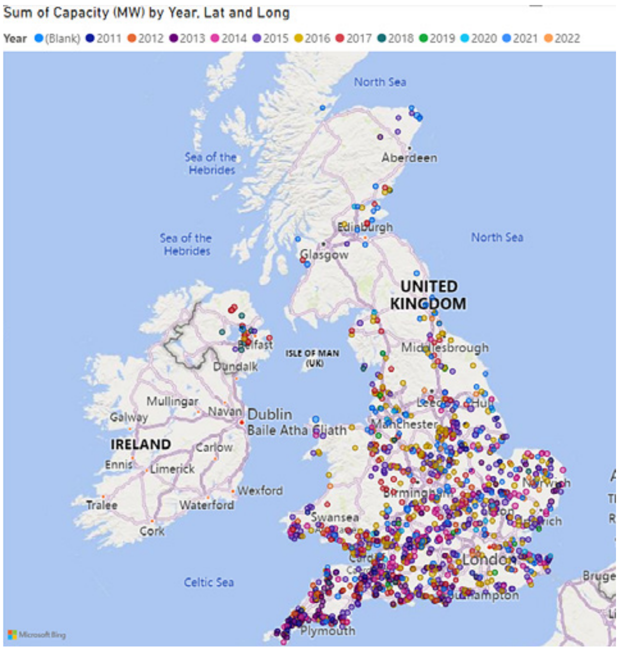


Fig:12 Location of utility scale solar plants across the UK according to the year of commissioning

When loaded onto vehicles with fabric (curtain) sides, the panels tend to shift and break due to the fragile and slippery glass, making them dangerous to handle. Furthermore, palletized PV waste can't be easily stacked on top of each other under the existing haulage infrastructure, thereby increasing the number of load consignments and subsequently the costs.

5. Externalised cost of panels

Between December 2009 and December 2022, crystalline silicon module prices in Europe dropped by 88% to 94%, with a weighted average cost reduction of about 91%[76]. Globally, prices for all solar technologies have declined, reaching historic lows for crystalline silicon modules.

However, these cost reductions often overlook the significant environmental impacts associated with module production. Solar PV power incurs substantial environmental external costs during production, such as metal resource consumption and emissions of harmful byproducts like silicon tetrachloride and hydrogen sulfide[77]. Ignoring these costs in economic evaluations leads to an underestimation of the true cost of renewable energy.

Current policies in France and South Korea require the inclusion of carbon footprint criteria in public tenders for PV modules, reflecting an effort to internalise these environmental costs. France has enforced such criteria since January 2019, and the EU is moving toward similar measures through the EU Ecodesign Directive[78] which will most likely become mandatory for all modules placed on the European market. In addition to this, several CE progressive countries such as the Netherlands and Norway have introduced environmental product declaration requirements (EPD) for PV modules, which include carbon footprint reporting[79]. In contrast, the UK lacks policies to internalise these costs, which may hinder the adoption of circular practices in the solar PV industry.

6. Uncertainty of Economic Lifespan

As technology advances and solar panels age, the concept of repowering-replacing older panels with newer, more efficient ones- has gained traction in the UK for utility scale (5MW+/ 10,000 PV panels) solar operations. However, this trend has introduced uncertainty regarding the economic lifespan of solar panels. Industry insiders note significant repowering efforts in recent years, with some projects decommissioning over 20,000 solar panels in under 15 years of operation in the past 12 months, yet data on these activities is scarce. Despite author's attempts to gather data on repowering through the Right to

Information Act, there is no national-level monitoring of solar PV site repowering, rewiring applications, or trends by Ofgem or other governmental bodies. Current tracking of solar plant performance which are reported as monthly output data to the Ofgem register[80] only covers utility scale plants commissioned between 2011 and 2021 under the Renewables Obligation (RO) [f] and Renewable Energy Guarantees of Origin (REGO)[g] schemes, excluding those under the Feed-In Tariff (FIT). This lack of comprehensive data makes it challenging for recyclers and other stakeholders to predict the volume of decommissioned solar panels and plan recycling capacity or other treatment pathways effectively.

Operational expenditure (Opex) costs are critical in determining the economic life of solar plants. Although investors assume a 35-year lifespan for solar assets in the UK, their economic life is likely to be shorter, around 20 years. This is because, after the 20-year[81] subsidy period under the Renewables Obligation (RO), revenues drop significantly, and many plants may no longer cover their Opex costs, leading to potential repowering or decommissioning. Recent changes in depreciation assumptions from 25 to 35 years boost current accounting profits by lowering depreciation charges but may lead to future write-offs, posing risks for long-term investors. Thus, the economic life of solar assets is more crucial than their physical life, and current assumptions may lead to unrealistic expectations, financial planning and plans for EoL management.

7. Diversity of products and lack of data

The proliferation of diverse solar panel models with varied lifespan, performance characteristics and the absence of detailed Bills of Materials (BoM) from manufacturers pose significant challenges to the effective recycling, repair, and reuse of solar panels. The wide variety of models means that recyclers, repair technicians, and testing and reuse facilities must develop and maintain a multitude of processes to handle different materials and constructions, which is both technically complex and cost prohibitive.

Without standardised BoMs, recyclers lack critical information about the composition of panels, such as the specific types and quantities of metals, polymers, and hazardous substances involved. This not only hampers the efficiency and safety of recycling operations but also increases the likelihood of valuable materials being lost and hazardous materials being improperly handled, thereby undermining the economic viability and environmental benefits of recycling efforts.

Similarly, the difficulty of repairing these panels is compounded by the lack of standardised components and clear documentation, making it challenging to source appropriate parts and ensure reliable repairs. Regretfully, the 2021 Right to Repair legislation, which mandates manufacturers are legally obliged to make available spare parts available for professional repairers, is not applicable for photovoltaics[82]. Reusing panels is also hindered by issues of BoM, as mismatched components, and lack of comprehensive information about the original construction and usage can lead to reduced performance and reliability in repurposed installations. Consequently, this situation dissuades recycling, repair, and reuse, leading to increased waste and reduced sustainability in the UK solar industry.

Recommendations (CE Enablers)

In practice, countries and organisations who are already benefitting from the CE transition typically succeed by harnessing four core building blocks of CE:

Design

Design for disassembly, repair, recovery, and recyclability in mind from the outset. The transition to a circular economy for solar PV modules hinges on our ability to design for circularity underscoring the critical gap in the current design and lifecycle management of these product. Panels with backsheets make up a significant proportion of first generation modules providing essential protection and comprising up to 10% of the module's weight, with newer bi-facial modules

[f] The Renewables Obligation (RO) is a key policy in the UK designed to encourage electricity generation from renewable sources. Introduced in 2002, it required electricity suppliers to source an increasing proportion of their electricity from renewable sources, supported by the issuance of Renewable Obligation Certificates (ROCs) by Ofgem. This policy helped stimulate the growth of renewable energy in the UK until it closed to new applications on March 31, 2017. Existing stations continue to receive support for up to 20 years, with the final closure of the scheme set for March 31, 2037

[g] The Renewable Energy Guarantees of Origin (REGO) scheme, managed by Ofgem, certifies that electricity generated from renewable sources is indeed renewable, ensuring transparency for consumers and aiding the verification of environmental claims by suppliers.

being comprised of a higher a glass volume. Traditionally, fluorinated materials have been used in most backsheets, which pose environmental and recycling challenges for legacy assets due to their potentially hazardous nature[83]. The UK solar market could follow the lead of European solar sector by adopting halogen-free backsheets made from PET or polyolefin and implementing lead-free module designs[84]. These changes enhance circularity, reduce environmental impact, and align with the EU's vision of "safe-by-design chemicals."

Manufacturers should be mandated to publish Bill of Materials listing any hazardous materials to ensure proper treatment pathways including repair and reuse in addition to recycling. The solar industry can expect this to be implemented in the future via the pending Digital Product Passport. Implementing these practices has the potential to lower the carbon footprint and environmental impact of the solar industry, which can be tracked through lifecycle assessments.

The UK solar market can demand strict requirements for information on repairability, ease of dismantling along with Environmental Product Declarations (EPDs) and lifecycle assessments (LCAs) in procurement, particularly in public tenders, like the French approach. By adopting these ecodesign measures, the UK can promote circular design practices and improve sustainability in the solar industry.

Reverse Logistics

Enhanced compliance: PCS measures must be strengthened to ensure all producers of panels entering the UK are covered. This includes better monitoring and enforcement (at Customs) to reduce the number of free riders who do not comply with the regulations. By improving transparency and reporting requirements for producers, we can ensure accurate data on the volumes of PV modules being placed on the market and will subsequently enter the waste stream in the coming years.

Infrastructure development: The collection network for end-of-life PV modules must be strengthened, ensuring easy and efficient access for both consumers and businesses to dispose of their PV waste. This can be done by.

Support the separate collection of PV panels exclusively through a Business-to-Business (B2B) network, where professional installers handle the dismantling and removal, grouping panels at their premises or returning them to suppliers, wholesalers, or distributors and not through local authority-operated DCFs.

Investment in the development and expansion of facilities specifically designed for treatment of PV modules must be encouraged through suitable economic policy incentives. This includes establishing new recycling plants and upgrading existing ones to handle the expected increase in PV waste.

Facilities for testing and grading modules for their second life need to be setup at collection/recycling points to ensure that those that can be reused are separated from those destined for material recovery, and that a standard for PV reuse is implemented to embed professionalism and product safety into the PV reuse sector

Business Models

Business models for prolonged use and retaining value: There needs to be a shift in mindset in the UK solar industry towards recognising that recycling may not always be the optimal solution for retaining value. Instead, developing alternative business models that prioritise keeping functional panels in prolonged use is imperative. Policy changes with respect to MCS would aid in business model innovation by players in the residential market.

Case examples described earlier has shown that repair, optimised maintenance, and reuse are feasible and can be enhanced by product-service systems (PSS) models.

Comparative research and business modelling of solar PSS models in the UK is recommended.

System Enablers

Policies

1. **Green Procurement** – Green Public Procurement processes, already prevalent in the EU, are being expanded to include a specific label for PV products. This label would highlight products meeting high socio-environmental standards, encouraging local municipalities and other public entities to adopt sustainable PV solutions. Such a label could also serve as a benchmark for global industry standards, fostering competitiveness among manufacturers to produce environmentally responsible products. Integrating these standards into procurement processes helps internalize environmental costs and supports a CE. The UK should consider adopting such a labelling system for panels deployed in the country.
2. **Revisiting MCS & WEEE regulations** - Allowing products registered within the MCS database to have a second life especially in lower risk ground-mounted community energy programs with initial technical checks done by authorised MCS personnel will be a step forward in circularity and resource utilisation. It is also worth considering the possibility of excluding solar panels from WEEE regulations and instead start up an impact assessment of an Extended Producer Responsibility (EPR) legislation for all Renewable Energy products and equipment. EPR also takes care of current loopholes in the form of incoherent producer definition within WEEE guidelines which encourages free-riders and non-compliance.
3. **Ecomodulation fees** - Implement ecomodulation fees to incentivise the use of environmentally friendly materials in PV modules to penalise materials that are hazardous / harder to recycle and rewards those that are easier to repair, reuse or recycle. By adjusting tax rates based on the environmental impact of materials used, ecomodulation encourages UK solar market to adopt sustainable practices in manufacturing and procuring PV modules.
4. **Repowering fees** - Introduce repowering fees to discourage premature replacement of PV systems before reaching their economic lifespan. These fees should be structured to offset the cost of reuse initiatives and mitigate the environmental impact of early system replacements.
5. **Financial Support** - Provide financial incentives and support to companies involved in the recycling of PV modules including grants, tax breaks, or subsidies to offset the costs of recycling infrastructure and technology development. This could stem from a levy on repowering as mentioned above.

Knowledge creation & capacity development

1. **Standards & certification on reuse/repair** – UK solar industry players and standards organisations like MCS should advocate for the IEC to establish standards for the repair and reuse of PV modules. This would facilitate widespread adoption of circular practices by providing clear guidelines for manufacturers and service providers.
2. **Technological Advancements & business model innovation** - Promote research and development of new materials and design methodologies supporting repair and reuse techniques that help retain product value and on new recycling technologies and processes that can efficiently recover valuable materials from PV modules. This necessitates a robust framework of research, education, and training where right skillsets and capabilities in sustainable design and CE principles are developed. This includes supporting innovative projects and partnerships between industry and academia and training programs for industry professionals to keep pace with evolving technologies and regulatory landscapes. Business model innovation also can be supported through pilot programs with partnerships across industry players.
3. **Reporting & data** - Facilitate data gathering and sharing among developers, producer compliance schemes, and regulatory bodies like Ofgem. This includes monitoring the performance of PV systems and tracking the reasons for failures, which informs future design improvements and regulatory decisions. Also a central government database to monitor repowering activities that would include details such as the quantity, model, and disposal method of replaced modules, as well as the justification for repowering must be created. This would also enable authorities to audit projects to ensure proper waste management and regulatory compliance.
4. **Financial Support** - Provide short-term financial incentives such as grants, tax breaks, or subsidies (like IRA) to companies involved in the high-value recycling of PV modules. These incentives offset the costs associated with developing recycling infrastructure and adopting new technologies, making circular practices more economically viable for businesses till waste volumes at scale are reached in the medium-long term.

Conclusion

As at Phase 1, this spotlight report provides a diagnostic of current CE systems level maturity to identify key pain points, potential opportunities for value creation and future pragmatic piloting and experimentation across a wider range of solar sector activities in the UK (Figs 1 & 11).

Illustrative examples presented highlight some of the key building blocks to move towards a CE target state and benefits with the potential to reduce waste, increase overall resource productivity and generate more value than the current linear set-up. However, despite promising pilots and case studies, European comparators are further ahead in the adoption and implementation of circular interventions.

Fig 13: Transformational steps to a CE target state (adapted from Zils et al, 2023)[85]

Description of current state including limitations

- Describe current state including stakeholders and activities.
- Identify problems in areas such as materials, economy, society and external factors.
- Find opportunities to improve overall value process, at system and individual level.
- Define factors influencing value to enable prioritisation.

Application of CE interventions

- Describe CE interventions based on core principles, CE reverse loops and necessary foundations.
- Combine individual CE actions into a larger plan, starting from small-scale testing to implementation at scale.
- Explain how different stakeholder (especially policy and regulators) engage with and contribute to embedding CE interventions.

Description of CE target state and benefits

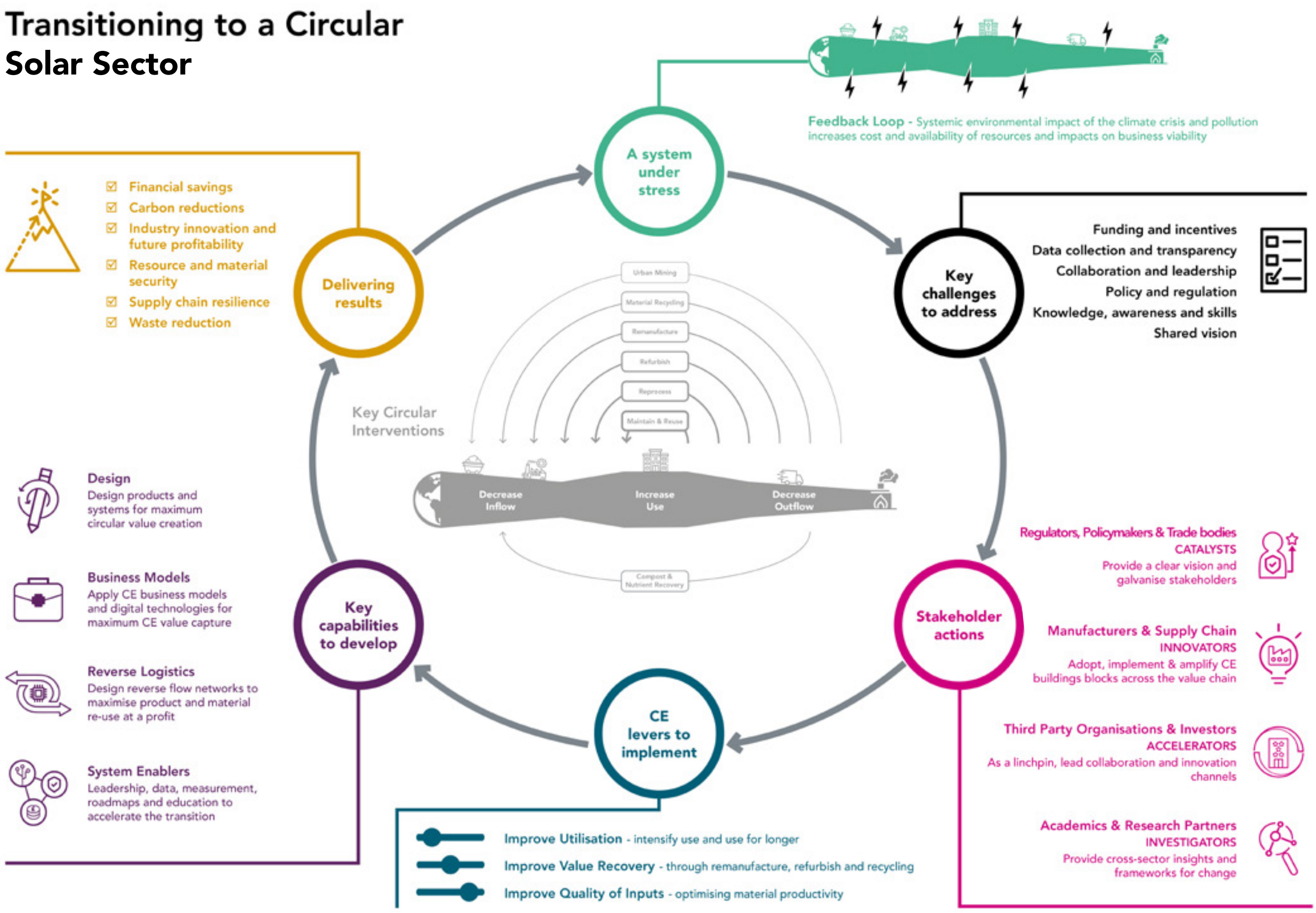
- Describe CE target state including activities and stakeholders.
- Document impact and benefits in various areas such as materials, economy, society and external factors.
- Summarise key learnings and insights that can be applied to comparable starting situations in scaling.

Phase 2 requires the initiation of a dedicated and co-ordinated programme to scale up system- wide trials and interventions to demonstrate further proof of value.

To implement solar CE at national scale requires systematic integration across the value chain with a common data collection and analysis framework. Findings and successes from this stage will identify and develop the capabilities and investments required for a CE system integration into governmental, industry, and solar sector decision making and collaboration.

The time to do this is now. The UK solar sector is at a critical juncture, with substantial growth whilst operating on a linear model. Figure 14 sets out the key building blocks, stakeholders and capabilities to make such a transition. By implementing the recommendations outlined in this report by the key stakeholder groups i.e. policymakers/regulators, manufacturers and supply chain partners, third-party/certification bodies and academic institutions, the UK can lead the way in creating a resilient and sustainable solar energy industry. This will not only contribute to the nation's Net Zero goals but also support economic growth and environmental stewardship. Otherwise, the UK is at risk of adopting the blinkered carbon tunnel syndrome – in trying to solve one problem (Net Zero) we create a series of other problems and issues, which will have to be addressed by other groups and generations down the line.

Fig 14: Transitioning to a Circular Solar Sector

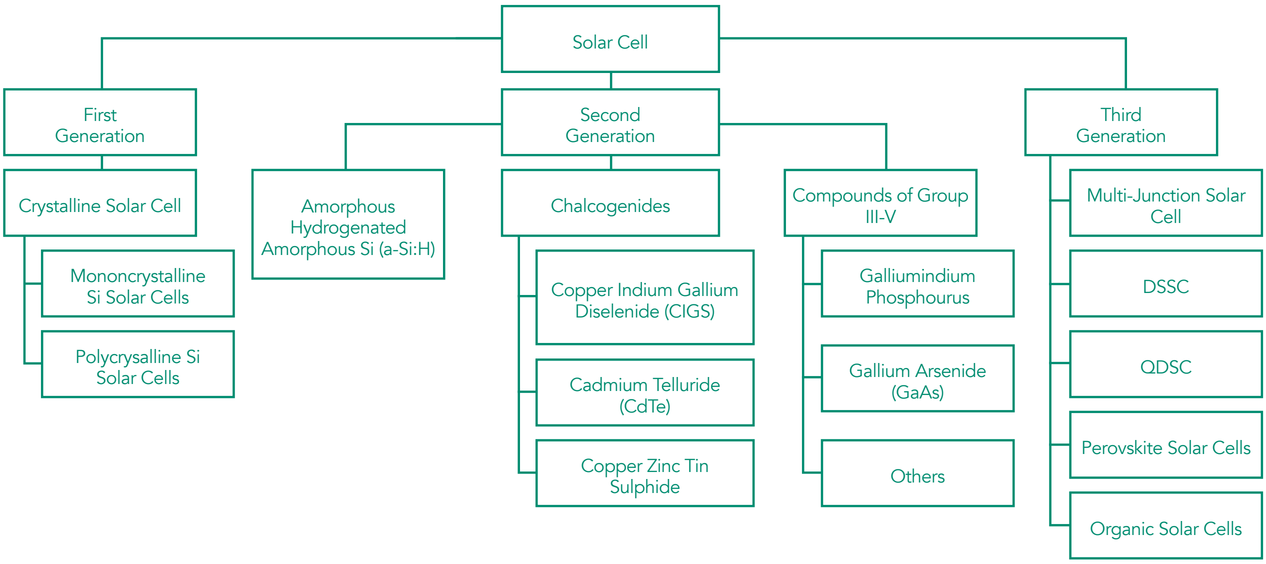


Appendix A

Understanding Solar Panel Technologies[86]

Solar photovoltaic (PV) panel technology has evolved significantly over the years, offering various options to cater to different needs and applications. The typical solar panel is composed of individual solar cells, each of which is made from layers of semiconductors classified as a silicon-based, thin film, organic or advanced nano PV. A typical crystalline silicon solar panel contains 60, 72, or 90 individual solar cells and comes in standardised sizes whereas thin-film panels can come in different sizes to suit specific needs.

Figure 14: Various types of solar cells and current advancements[87] (Dambhare et al., 2021)



Crystalline silicon (c-Si) solar cells are currently the most common solar cells in use mainly because c-Si is stable, delivers high efficiencies (i.e. amount of light converted to electricity) in the range of 15% to 25%, relies on established process technologies for manufacturing with an enormous database, and, in general, has proven to be reliable. Monocrystalline solar panels are known for their high efficiency and longevity, making them a popular choice for residential and commercial installations offering a sleek appearance and excellent performance even in low-light conditions. Polycrystalline solar panels are slightly less efficient (& hence less costly) than monocrystalline panels but still offer reliable energy generation and are suitable for various applications.

Thin-film solar panels are lightweight and flexible, making them ideal for unconventional installations such as building-integrated photovoltaics (BIPV) and portable solar devices. Thin-film technology utilises layers of semiconductor materials like amorphous silicon (a-Si), cadmium telluride (CdTe), or copper indium gallium selenide (CIGS). While thin-film panels may have lower efficiency compared to crystalline silicon panels, they can be more cost-effective and versatile.

Organic solar cells utilise carbon-based molecules or polymers as the active layer, enabling low-cost, solution-based manufacturing processes like inkjet printing or roll-to-roll coating. However, they currently face challenges related to relatively low efficiency and stability. Perovskite solar cells, on the other hand, incorporate mostly hybrid organic–inorganic lead or tin halide-based material known for their exceptional optical and electronic properties. Despite remarkable efficiency gains and low-temperature solution processing, perovskite solar cells encounter stability issues, particularly in the presence of moisture and light. Both technologies hold promise for advancing photovoltaics and expanding solar energy applications, with ongoing research focused on improving efficiency, stability, and scalability for widespread commercialisation.

Monofacial and bifacial solar panels represent advancements in solar technology designed to maximise energy production. Monofacial panels absorb sunlight from one side, while bifacial panels capture light from both the front and rear surfaces, allowing them to generate additional electricity by reflecting light from the ground or surrounding surfaces. Bifacial panels offer increased energy yield and are suitable for installations with reflective surfaces or elevated mounting configurations.

Appendix B

Key Assumptions Used for Data Modelling of Circular Scenarios

In the calculations for all scenarios, we have made the following ultra conservative assumptions focussing on material volumes and material value-

I) that panels are generating at 100% rated capacity throughout their lifetime (i.e. No degradation)

II) Panels are retired only due to end of technical lifespan – early retirement due to breakages/storm damages not accounted for

III) retired panels are replaced with prevalent technology at that time to maintain the cumulative generation capacity within the UK constant as per the National Grid scenario.

IV) no technological learning curve leading to dematerialisation of panels from 2025

V) weight of panels remains constant for each technology from 2025 onwards with some variation from 2008-2025 (refer table 4).

VI) Material values are based on 2024 prices, overlooking potential future relative price increases due to scarcity/inflation or changes in metal grades

VII) Due to the highly volatile price of recycled glass, it is not accounted for in the material flow values

VIII) Solar PV repair and recycler gate fees are not included which might affect the business case.

IX) Inflow is defined as new imported materials constituting new solar panels. In scenarios with recycling, some of the panels will be made from the recycled materials from retired panels. The recycled content is not included in the stock inflow.

X) There is a thriving UK domestic solar panel manufacturing sector capable of using the secondary material output from recycling as feedstock to manufacture new solar panels, thereby keeping the metals in a closed loop.

In the data modelling, we assumed constant percentage of constituent material distribution in the bill of materials for each of the five energy technologies (Figure 9 in main report). The below table shows the weight and generation capacity of panels modelled and combined with the percentage distribution, exact quantities of material was arrived at for estimating the inflow and outflow for the period 2008-2050.

Table 4: Weight and generation capacity of panels for different technologies for 2008-2050 period

Technology	Timeline	Generation Capacity in W	Weight in Kg
PERC/PERL	2008-2012	250	20
PERC/PERL	2013-2016	305	18.5
PERC/PERL	2017-2021	380	22.5
PERC/PERL	2022-2024	450	20.5
PERC/PERL	2025-2050	650	32.5
CdTe	2008-2035	400	32.5
CIGS	2014-2019	240	6
GaAs	2036-2050	240	6
SHJ	2020-2024	450	23
SHJ	2025-2050	650	33.5

The results from the scenario amalysis is given below for ease of reference. Same data has been represented in Figure 10 in the main report.

Table 5: Material flow results for Aluminium for different circular scenario

For Aluminium (Al)	Low Circular	Medium Circular	Highly Circular
Inflow till 2050 (KT)	967.54	898.99	845.31
Outflow till 2050 (KT)	425.00	188.36	188.36
In stock in 2050 (KT)	661.54	801.05	801.05
% Reduction in inflow	22	28	32
% Reduction in outflow	36	72	72
% Increase in stock	15	39	39
Potential lost material value due to outflow till 2050 (mn USD)	720	230	104
Potential value on recovery till 2050 (mn USD)	280	213	339

Table 6: Material flow results for copper for different circular scenario

For Copper (Cu)	Low Circular	Medium Circular	Highly Circular
Inflow till 2050 (KT)	55.33	51.4	48.33
Outflow till 2050 (KT)	24.32	10.79	10.79
In Stock in 2050 (KT)	37.82	45.78	45.78
% Reduction in inflow	22	28	32
% Reduction in outflow	41	84	97
% Increase in stock	15	39	39
Potential lost material value due to outflow till 2050 (mn USD)	157.7	50.5	22.8
Potential value on recovery till 2050 (mn USD)	61.3	46.7	74.4

Table 7: Material flow results for Silver for different circular scenario

For Silver (Ag)	Low Circular	Medium Circular	Highly Circular
Inflow till 2050 (KT)	0.58	0.53	0.51
Outflow till 2050 (KT)	0.38	0.24	0.11
in stock in 2050 (KT)	0.38	0.46	0.46
% Reduction in inflow	18	25	28
% Reduction in outflow	36	72	72
% Increase in stock	15	39	39
Potential lost material value due to outflow till 2050 (mn USD)	197.6	72.96	51.07
Potential value on recovery till 2050 (mn USD)	37.63	31.27	53.16

Table 8: Material flow results for glass for different circular scenario

For Glass	Low Circular	Medium Circular	Highly Circular
Inflow till 2050 (KT)	4,127.07	3,791.85	3,561.68
Outflow till 2050 (KT)	1,757.41	807.62	807.62
In Stock in 2050 (KT)	2,861.74	3,371.88	3,371.88
% Reduction in inflow	22	28	33
% Reduction in outflow	36	71	71
% Increase in stock	13	33	33

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