Photovoltaic and Thermal for Europe

D3.1 Report on PVT4EU ecodesign recommendations

Work Package: WP3 Synergic thermal and electrical design of PVT4EU technologies

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Executive Summary

This report serves as a comprehensive guide for making PVT technologies more eco-friendly and energy-efficient. Its goal is to reduce their environmental impact and help them use energy better. By following the suggestions outlined in this report, PVT technologies can operate more sustainably and efficiently.

In the first part, the report focuses on ecodesign concept and recommendations within the lifetime of PVT4EU technologies, emphasising Material Selection, Reparability, Recyclability, and Circular Economy principles. These recommendations underscore the importance of choosing materials with minimal environmental impact, designing products for ease of repair, ensuring they are readily recyclable, and embracing principles of circularity to minimise waste and maximise resource efficiency. The second part develops Energy Labelling, providing recommendations to optimise energy use during the manufacturing process and enhance the efficiency of the technology itself. Through these measures, the report aims to not only minimise energy consumption but also maximise the overall efficiency and sustainability of PVT4EU technologies in line with ecodesign principles. Lastly, the report introduces two environmental labels that can validate the actions taken during the conception phase, ensuring quality and facilitating easy comparison between products for customers.

This report closely relates to deliverable 6.1, 'Report containing the final KPIs and the methodology to evaluate the PVT systems' impacts.' The KPIs for evaluating the environmental performance of PVT4EU technologies, as developed in WP6.1, are based on the strategies outlined in this report.

Background

Ecodesign is essential in product development as it integrates environmental considerations throughout the lifecycle of a product, from conception to disposal. By adhering to these principles, we ensure that technologies, such as solar energy systems, are not only efficient but also eco-friendly throughout their entire lifespan. Embracing ecodesign principles in solar energy is crucial for maximising sustainability and minimising environmental harm. This approach fosters recyclability, materials safety, and efficient resource use from a 'cradle-to-cradle' perspective, utilising a streamlined Life Cycle Assessment (LCA). Prioritising ecodesign reduces environmental impact, ensures compliance with regulations, enhances reputation, and contributes to a healthier planet.

1. Ecodesign

1.1. Definition

The term "ecological design" arose in the early 1970s. However, in the 1990s, the term "ecodesign" began to be more widely used. This decade saw the development of frameworks and guidelines for incorporating environmental considerations into product design. The European Union, for instance, started to develop ecodesign directives to regulate the environmental performance of products, culminating in the Ecodesign Directive (2005/32/EC). The circular economy concept arose in the 2010s, and ecodesign became a vital component of this sustainability strategy. The circular economy emphasises the importance of designing products for longevity, reparability, and recyclability. Today, more and more products are developed following an ecodesign perspective thanks to innovation and technology. Moreover, ecodesign is increasingly recognised as essential for addressing global environmental challenges such as climate change, resource depletion, and pollution.

Ecodesign integrates environmental considerations at each stage of the product development process and its lifecycle. The product lifecycle (cradle-to-grave) consists of five phases: raw material extraction, production, transport, use-phase, and waste processing, as shown in **Figure 1.1**. According to the European Environment Agency main goal is to anticipate and minimise adverse environmental impacts during a product's lifetime. As for the circular economy concept, ecodesign advocates for "no-raw-material-extractions, no-waste", aiming to keep materials in the economic loop and adopting a cradle-to-cradle perspective.

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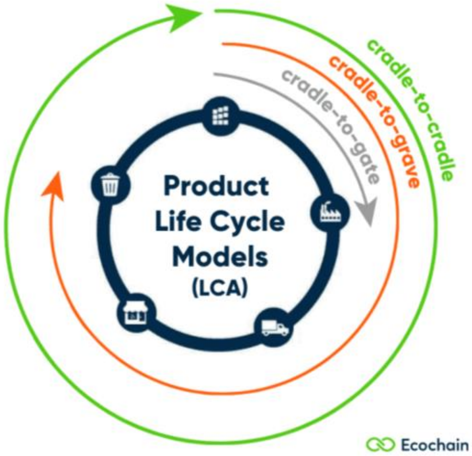

Figure 1.1 *The five product life cycle phases and corresponding life cycle models* [1]

Implementing ecodesign involves integrating environmental considerations into every stage of the product lifecycle, from raw material extraction to end-of-life disposal. Key steps include conducting a lifecycle assessment to identify high-impact areas, selecting sustainable materials, optimising energy efficiency in production and use, designing for durability and easy disassembly, minimising waste, and using efficient packaging and logistics. Additionally, companies should establish take-back programs for recycling, continuously innovate and improve their designs, and communicate their efforts transparently to consumers. Obtaining relevant certifications can further validate their commitment to ecodesign.

For the PVT technologies aimed to be developed in the PVT4EU project, ecodesign will focus on the four strategies integrated throughout the product's lifecycle:

- Material selection for raw materials,
- Reparability during use,
- Recyclability at disposal,
- Circular Economy principles using recycled materials.

These strategies follow the lifetime of the product to help consider each aspect of the life of the product to reduce its environmental impact and to embrace a cradle-to-cradle vision (**Figure 1.2**).

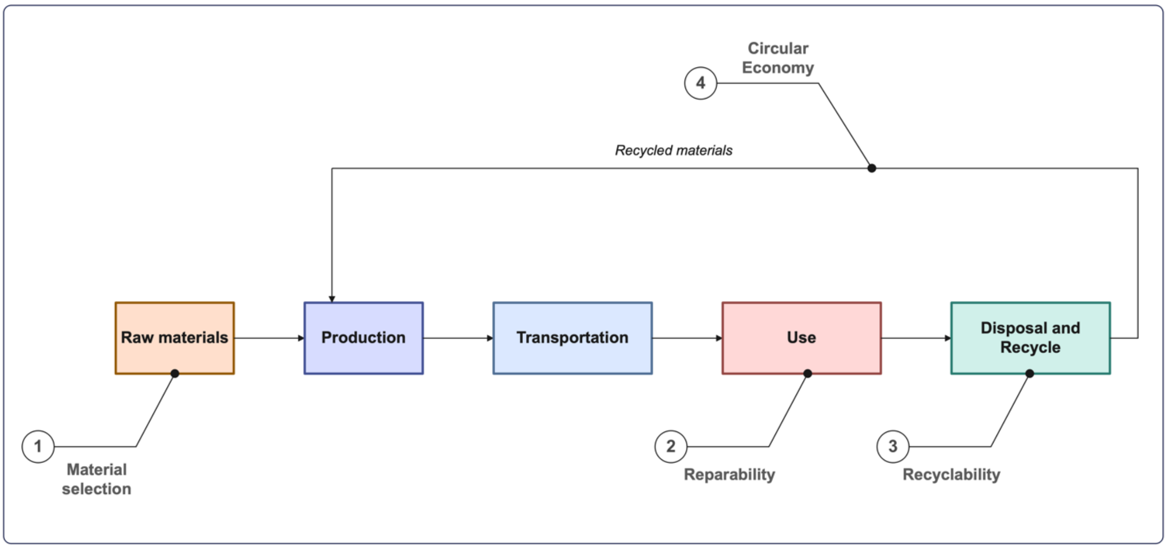

Figure 1.2 *Illustration of ecodesign strategies incorporated in the lifetime of a product.*

1.2. European regulation

The EU Ecodesign Directive (2009/125/EC) establishes a framework under which manufacturers of energy-using products are obliged to reduce energy consumption and other negative environmental impacts occurring throughout the product life cycle. The Energy Labelling Directive complements it. The Energy Labelling Directive (2017/1369) requirements for product energy labelling are often adopted alongside ecodesign implementing measures.

Ecodesign and Energy Labelling are essential guidelines aimed at minimising environmental impact throughout the entire lifecycle of solar technologies. By adhering to these recommendations, we ensure that solar technologies are efficient and eco-friendly, from manufacturing to disposal. Embracing ecodesign principles in solar energy is crucial for maximising sustainability and minimising environmental harm, fostering recyclability, materials safety, and efficient use from a 'cradle-to-cradle' perspective using a streamlined Life Cycle Assessment (LCA).

From 26 September 2015, an energy label with the energy classes from A+++ to G is required for space heaters combined with solar devices (Commission Delegated Regulation (EU) No 811/2013) and for water heaters combined with solar devices (Commission Delegated Regulation (EU) No 812/2013). However, for now, there is no requirement for energy labels for solar devices such as solar collectors; only a data sheet must be released with the product. On 30 March 2022, the European Commission proposed an Ecodesign for Sustainable Products Regulation (ESPR), replacing the current

Ecodesign Directive (2009/125/EC) and introducing more Ecodesign criteria for a broader range of products. It aims to make sustainable products the norm on the EU market. This Regulation will introduce a Digital Product Passport (DPP) and the interdiction to destroy unsold products. The adoption and entry into force of the ESPR is currently expected for June 2024 and will start to be applied 18 months after this date. The new Ecodesign requirements will go beyond energy efficiency and aim to boost circularity, covering, among others:

- product durability, reusability, upgradability, and repairability
- presence of chemical substances that inhibit the reuse and recycling of materials
- energy and resource efficiency
- recycled content
- carbon and environmental footprints
- available product information, with a Digital Product Passport

This new regulation will apply to all products placed on the EU market and, by extension, to solar technologies. To prepare for ESPR, a draft from the European Commission provides some guidelines for future regulation in the document titled "Explanatory memorandum for the Consultation Forum on Ecodesign and energy labelling – Photovoltaic modules, inverters, and systems."

1.3. Ecodesign considerations

1.3.1. Material Selection

Choosing materials carefully is a crucial aspect of ecodesign, as it directly impacts the environmental footprint of a product throughout its lifecycle. By selecting materials that meet product specifications while minimising negative environmental impacts, ecodesign aims to optimise material usage and manufacturing processes. This approach not only enhances product efficiency but also contributes to overall sustainability by reducing resource consumption and waste generation through the selection of environmentally friendly, recyclable, and non-hazardous materials.

In this subsection, ecodesign recommendations focus on several key aspects of material selection. These include prioritising the durability of the PVT technology, minimising the use of carbon-intensive materials such as silver and aluminium, and exploring the feasibility of utilising bio-composites.

Durability

Durability is crucial to consider, as it directly impacts resource conservation. Durable products not only lessen the need for additional production, thus reducing the demand for raw materials, but they also decrease the volume of End-of-Life (EoL) products. Given that the industry standard lifespan for most solar panels ranges from 25 to 30 years, each material within PVT technologies must maintain a minimum lifespan of 25 years to ensure longevity and sustainability (standards IEC 61215-1/-1-1/2:2016, ISO 61730-1/2:2016, ISO 9001, ISO 14001, ISO 50001). This requirement should also be complied with the thermal absorber and subsystems needed for the PVT collector to operate.

Limitation of metals

Solar technologies comprise several vital components such as silicon, metals, and glass, with silver and aluminium being the primary metals used. The mining and processing these materials pose significant environmental consequences, including habitat destruction, soil erosion, water pollution, and ecosystem disruption, all of which contribute to the overall environmental footprint of solar technologies. Therefore, reducing the use of metals like silver and aluminium in solar technologies is crucial to mitigate these environmental impacts.

The demand for silver in photovoltaics has risen in recent years due to the increasing demand from the solar industry. In 2023, photovoltaics consumed 142 million ounces of silver, comprising 13.8% of total global silver usage, a notable rise from nearly 5% in 2014, as reported by the Silver Institute. Silver is used in PV cells for its excellent electrical conductivity. It forms the front and rear electrical contacts, facilitating efficient collection and transmission of electrical current generated by sunlight. Additionally, silver is used in the metallisation process to create interconnections between individual solar cells, optimising performance. The average solar panel contains 20 grams of silver, around 3.2 to 8 grams per m2. However, silver does not account for a significant part in terms of the mass of the PV panel but represents almost half of its value, as shown in **Figure 1.3**.

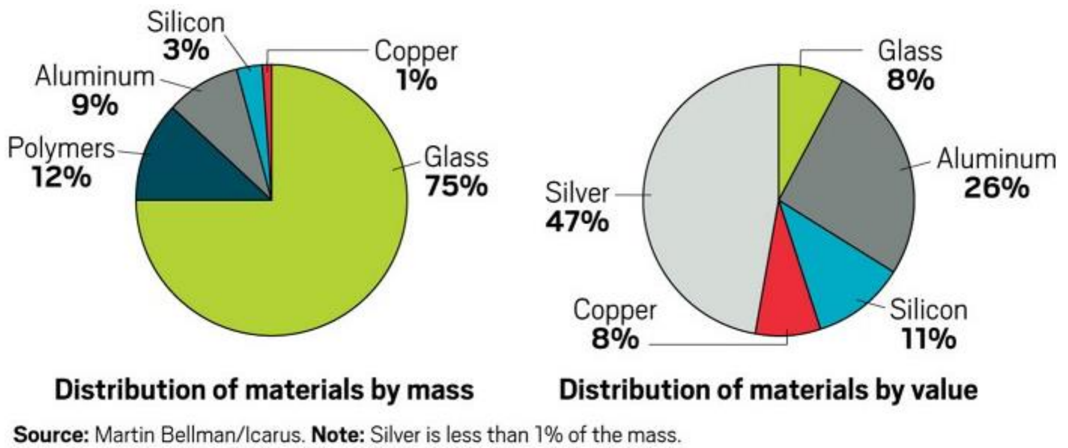

Figure 1.3 *Materials in a typical silicon photovoltaic panel* [2]

However, silver belongs to the group of precious metals and the refining and processing of silver ores can result in the release of toxic chemicals and heavy metals into the environment, leading to water and soil contamination [3]. Furthermore, producing silver paste used in solar cells often involves chemical processes that generate hazardous waste using acidic solution [4].

Reducing silver consumption in solar cells has thus become one of the industry's primary objectives for economic and environmental reasons, due to its scarcity. Manufacturers are actively exploring alternative materials and innovative techniques to minimise silver usage without compromising the performance and efficiency of solar cells. For instance, start-ups like SunDrive in Australia are exploring innovative solutions such as using copper instead of silver. Additionally, HighLine Technology in Germany has developed a technology for applying conventional silver paste onto solar cells more uniformly, saving approximately 20% of silver.

Ecodesign directives for PV panels have been introduced by SOREN, a French eco-organisation responsible for recycling PV panels. As part of these directives, it is recommended to limit the use of silver to under 20 mg/W for standard panels and to 10 mg/W for higher-efficiency panels [5].

Aluminium is another metal widely used in solar technologies due to its lightweight, corrosion-resistant, and highly durable properties. This makes it an ideal material for frames, mounting systems, and concentrators in solar panels. However, the production of primary aluminium is energy-intensive, with a carbon footprint ranging from less than 4 tons to more than 20 tons of CO_2-equivalents per ton of aluminium (Climate Action). To mitigate the environmental impact, the use of recycled aluminium is essential. Aluminium is infinitely recyclable, and the recycling process requires significantly less energy, emitting approximately 0.5 tons of CO_2-equivalents per ton of aluminium. By prioritising recycled aluminium, the solar industry can substantially reduce its carbon footprint. Incorporating recycled aluminium is a crucial strategy for reducing environmental impact, which will be further developed in the Circular Economy section.

Moreover, there is a trend in PV panel design to eliminate the aluminium frame (Frameless PV panels), which is traditionally used to protect the edges of the panel and provide mounting points. Without the frame, the amount of aluminium required is significantly decreased, which can also lower the overall cost of PV panels. Frameless panels often have a sleek, modern appearance, which can be more visually appealing, especially in residential applications, and in some cases could ease its installation. Reducing aluminium use in PV panels, mainly through the adoption of frameless designs, represents a promising pathway towards more sustainable solar energy systems. While there are challenges to overcome, the benefits in terms of material savings, cost reductions, and aesthetic improvements make this an attractive option for the future of solar technologies. Furthermore, this could also be replicated in solar thermal and PVT collectors. Continued innovation and development in this area will be crucial to maximise the environmental and economic benefits of solar power.

Utilising alternative composites

Alternative materials, especially those that are renewable or biodegradable, often have a lower environmental impact compared to conventional materials. This helps reduce pollution, conserve natural resources, and minimise the carbon footprint. Natural-based materials such as wood or natural fibre could be used in manufacturing PV and PVT panels. A study investigates substituting conventional aluminium module frames with wood to reduce the carbon footprint [6]. The authors suggest that wooden frames offer better environmental performance despite potentially reduced lifetimes. While they are currently more costly, financial incentives could enhance their competitiveness in the future.

Moreover, using natural fibre composites (NFCs) presents a promising alternative to synthetic materials, aligning with the growing demand for environmentally friendly options worldwide. NFCs offer advantages such as high specific strength, low production energy requirements, cost-effectiveness, and improved mechanical properties. However, challenges such as high moisture absorption, low fire resistance, and inadequate interfacial bonding between natural fibres and matrices exist. Despite these challenges, integrating NFCs into PVT technologies can significantly reduce their environmental footprint. NFCs for solar technologies are still in research but have shown promising advances. For instance, flax fibres have been used as natural porous materials in a hybrid PVT solar collector [7]. Another study replaced the steel in the structure of a solar desiccant cooling system with natural fibre-based Biocomposites (NFB), achieving a 50% reduction in weight [8]. However, the research failed to specify which particular natural fibre was employed.

Natural materials are a promising solution for reducing the environmental impact of PVT technologies. However, further studies are needed to verify their ability to meet the performance of conventional materials as well as their cost-effectiveness.

1.3.2. Reparability

As part of ecodesign principles, there is a necessity for modularity and reparability to

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create products that can be easily dismantled to facilitate component replacement. By enabling products to be easily repaired, maintained, and upgraded, ecodesign promotes resource efficiency, reduces electronic waste, and empowers consumers. Additionally, enabling reparability simplifies recyclability, as a product designed for easy disassembly for repair can also be efficiently disassembled for recycling.

Reparability in solar technologies allows to extend the lifespan of solar panels, conserve resources, reduces waste and emissions, supports the circular economy, and enhances consumer confidence. By prioritising reparability, the solar industry can significantly contribute to environmental sustainability and economic resilience, making solar energy a more sustainable and viable option for the future.

PV panels have a known reputation for having low reparability opportunities. They are difficult to repair due to their complex, delicate construction, sealed and encapsulated design, proprietary components, and the advanced materials and technologies they incorporate, as shown in **Figure 1.4**. Economic factors, such as the high cost of repairs, labour shortages, and safety concerns related to electrical hazards and hazardous materials, further complicate the repair process. Ensuring repaired panels maintain performance and reliability also presents significant challenges.

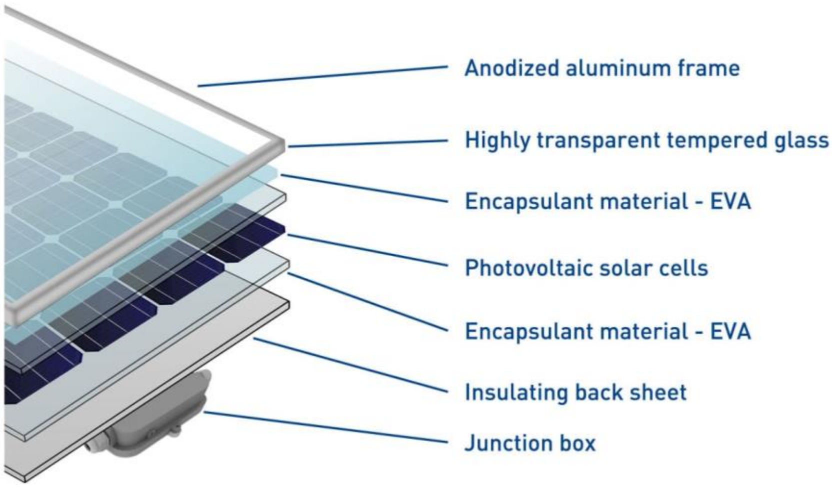

Figure 1.4 *Structure of a photovoltaic module* [9]

To ensure the reparability of PVT technologies, product design must follow the principles of Design-for-Repair and Design-for-Disassembly, ensuring that spare parts are available for an extended period.

Design-for-Repair

Improving the repairability of a product necessitates an appropriate design that makes repair accessible to most users without requiring specific tools or skills. This implies that repair should be achievable by non-experts, facilitated by clear disassembly instructions.

Design for Repair (DfR) is a principle of sustainable product design focused on ensuring that products are designed to facilitate easy repair and maintenance throughout their lifecycle without requiring specific tools or skills [10] DfR aims to extend the lifespan of products, reduce waste, and minimise the environmental impact associated with disposal. The key aspects of Design for Repair include:

- **Accessible Components**: Designing products with easily accessible components that can be repaired or replaced without extensive disassembly or specialised tools. This includes features such as removable panels, access points, and user-friendly interfaces.
- **Standardised Parts**: Using standardised components and parts where possible to facilitate easy replacement. This allows consumers to easily find and install replacement parts, reducing the need for custom or proprietary components.
- **Repair Documentation**: Provide clear and detailed repair documentation, including repair manuals, instructional videos, and troubleshooting guides. This empowers consumers to perform repairs themselves or seek assistance from repair professionals.
- **Spare Parts Availability**: Ensuring that spare parts are readily available for an extended period, even after the product has been discontinued. This allows consumers to repair products long after they have been purchased, extending their lifespan and reducing waste. The European Commission has suggested that spare parts, including all electronic components, should be available for at least 15 years and repair instructions should be provided for at least seven years.

Moreover, since PVT technologies are based on PV modules, thermal and solar technologies must be reparable. The parts of the PV panel, including the PV cells, cover glass, and encapsulant, must be reparable, as well as the electric, thermal, and hydraulic components of the PVT technology, as shown in the **Figure 1.5**. Manufacturers should thus ensure the availability of each component and simplify the design to facilitate an easy replacement of damaged parts without diminishing performance and reliability.

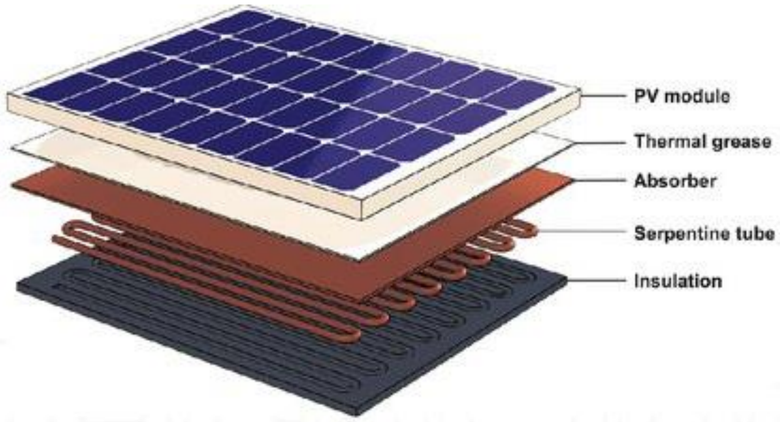

Figure 1.5 *General composition of a PVT panel* [11]

Design-for-Disassembly

Design for Disassembly (DfD) is a sustainable design principle focused on making products easy to take apart at the end of their life cycle. It involves designing products with modular components, standardised fasteners, and clear component identification to facilitate efficient disassembly. DfD aims to maximise material recovery for reuse or recycling, reduce waste, and minimise environmental impact. DfD contributes to a circular economy and promotes resource efficiency by considering disassembly from the initial design stages. DfD is closely related to reparability. Both principles focus on ensuring that products are designed to facilitate maintenance, repair, and component replacement throughout their lifecycle [10]. By incorporating both reparability principles into product design, manufacturers can create products that are not only durable and long-lasting but also easier to maintain, repair, and ultimately disassemble for recycling or reuse.

As part of DfD, it is essential to minimise the use of glue and avoid tape, as these materials can complicate disassembly without causing damage to the components.

1.3.3. Recyclability

Producers are responsible for the end-of-life management of PV panels under the extended producer responsibility (EPR) principle. This framework makes producers both physically and financially accountable for the environmental impact of their products throughout their lifecycle, incentivising the development of greener products with lower environmental impacts. To mitigate the environmental impact at the end of their life and facilitate the recovery of raw materials, PVT panels must be designed with recyclability in mind. This requires careful consideration of design elements to minimise waste

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generation and ensure responsible disposal.

The International Energy Agency Photovoltaic Power System (IEA PVPS) has developed Recycling Guidelines for PV Modules [10]. This initiative aims to design PV modules that can be recycled safely and economically using current technology. This involves eliminating, or at least minimising, materials that are challenging to recycle and avoiding using non-reversible adhesives. Below are some recommendations from this report that can be applied to PVT technologies.

Minimising hard to recycle material

As said earlier, silver metal (Ag) is a rare material, but it also presents a low recycling rate because of its expensive cost. Alternative to silver metallisation should be used, such as copper (Cu) or nickel (Ni), which present higher recycling trade-offs. However, partial substitution with Cu/Ni is less favourable than total substitution because the presence of Ag in the mixture complicates the recycling process.

Minimising encapsulant

Manufacturers use encapsulants to protect PV cells from moisture, dirt, and other pollutants that could damage the solar cells. Typically, a thin layer of ethylene vinyl acetate (EVA) is applied above and below the solar cell, as shown in **Figure 1.6**. However, this polymer poses challenges during the recycling process during the separation phase because it needs high temperatures and chemical processes.

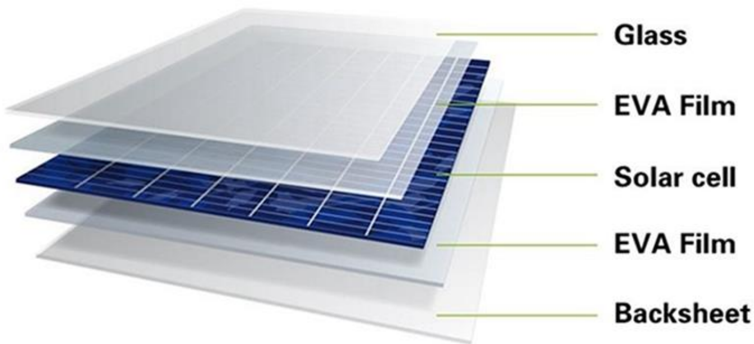

Figure 1.6 *Main component of solar panels, with EVA encapsulant* [12]

An alternative option is the utilisation of silicone encapsulant, which has been done for the Solarus Power Collector (PC) with the use of Wacker Elastosil. Silicon has showcased recyclability advantages compared to EVA. Isopropanol has been employed to dissolve silicone-based encapsulant from c-Si modules, facilitating the separation of the wafer and glass. However, the use of isopropanol is hazardous to the environment. Alternative encapsulants, such as thermoplastics, offer a more sustainable solution as they do not require hazardous substances for dissolution [13]. Thermoplastic encapsulants, like Thermoplastic Polyolefin (TPO), present several advantages over traditional materials such as Ethylene Vinyl Acetate (EVA). TPO encapsulants are easier to remove due to their melting ability, which simplifies the separation process during recycling or repair. This melting property also enhances the recyclability of the PV cell. Furthermore, TPO is generally cheaper than EVA, potentially reducing the overall cost of manufacturing PV panels, and, thus, PVT panels.

Using innovative sealants in the aluminium frame

The initial stage of the recycling process involves removing the aluminium frames, which poses a risk of damaging the components due to the presence of high-performance silicone or glue that is challenging to remove. O-ring or U-profile technologies are alternatives to sealants because they are easily removable, enabling component separation without causing any damage (**Figure 1.7**).

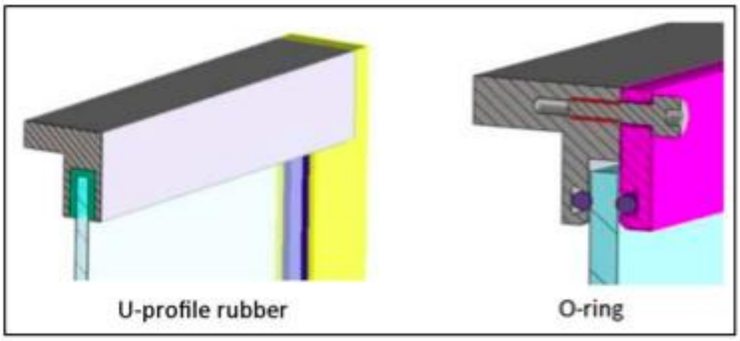

Figure 1.7 *Sample design to test alternative edge sealants* [14]

Recycling guidance

To enhance the recyclability of PVT collectors, it is essential to develop comprehensive guidance that meticulously outlines each step of the recycling process, from initial disassembly to final waste sorting. This guidance should include detailed instructions on disassembling PVT collectors safely and effectively, separating the various materials such as metals, plastics, glass, and silicon. Furthermore, the guidance should provide specific recommendations for appropriate organisms, facilities, or techniques that can be used to recycle or repurpose each component. For example, thermal collectors may be sent to specialised metal recycling facilities, while PV cells could be processed at electronic waste recycling centres. This guidance should be detailed enough to address the challenges of handling hazardous materials, ensuring that these components are managed environmentally safely.

Additionally, to facilitate the recycling process, developing and implementing a labelling system for each component of the PVT collectors would be beneficial. These labels should clearly identify which parts are recyclable and which are not, along with instructions on where each component should be sorted. For instance, labels could include symbols or QR codes that, when scanned, provide detailed information about the material composition and recycling instructions. This system would not only aid recyclers in efficiently processing PVT collectors but also help manufacturers design products that are easier to recycle by highlighting which materials are more problematic.

By establishing such comprehensive recycling guidance and labelling systems, we can significantly improve the efficiency and effectiveness of recycling PVT collectors [15]. This approach will contribute to reducing the environmental impact of these technologies and promote a more sustainable lifecycle for PVT systems. However, the responsibility for the end-of-life management of PVT panels is shared between producers and consumers [16]. While producers are accountable for the environmental impact of their products under the extended producer responsibility (EPR) principle, consumers also play a crucial role in the disposal and treatment of panel waste. Developing clear recycling guidance and labelling systems can empower consumers, ensuring they actively participate in responsible waste management.

1.3.4. Circular Economy

The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible (*European Parliament*). In this way, the life cycle of products is extended. It implies reducing waste to a minimum and using raw materials more efficiently. Adopting a circular economy perspective helps to mitigate the environmental consequences of extracting resources, production processes, and waste disposal. A circular economy contributes to the preservation of natural ecosystems and biodiversity by maintaining the cycle and prolonging the utilisation of products and materials. It involves adopting a cradle-to-cradle approach and following the waste reduction principles of the 3Rs: reduce, reuse, and recycle (**Figure 1.8Figure 1.8**). This subsection highlights how to implement the three Rs strategies in ecodesign: reuse and recycle.

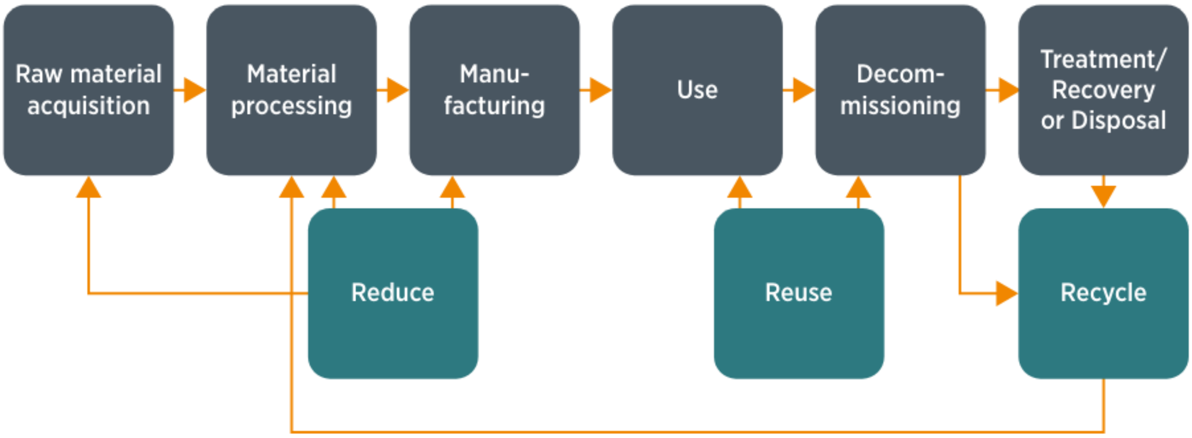

Figure 1.8 *Process diagram of the life cycle stages for PV panels and waste management* [16]

Reduce

The first 'R' of the circular economy model focuses on reducing the consumption of natural resources by increasing the efficiency of product manufacturing. This principle is reflected in the ongoing efforts to produce lighter PV panels in the solar industry. **Figure 1.9** illustrates how the weight-to-power ratio has continuously decreased over time, driven by advancements in PV technologies, material savings, and improved solar cell efficiencies. This weight reduction is achieved through the optimisation of cell and panel designs, as well as the use of thinner frames, glass layers, and wafers [16].

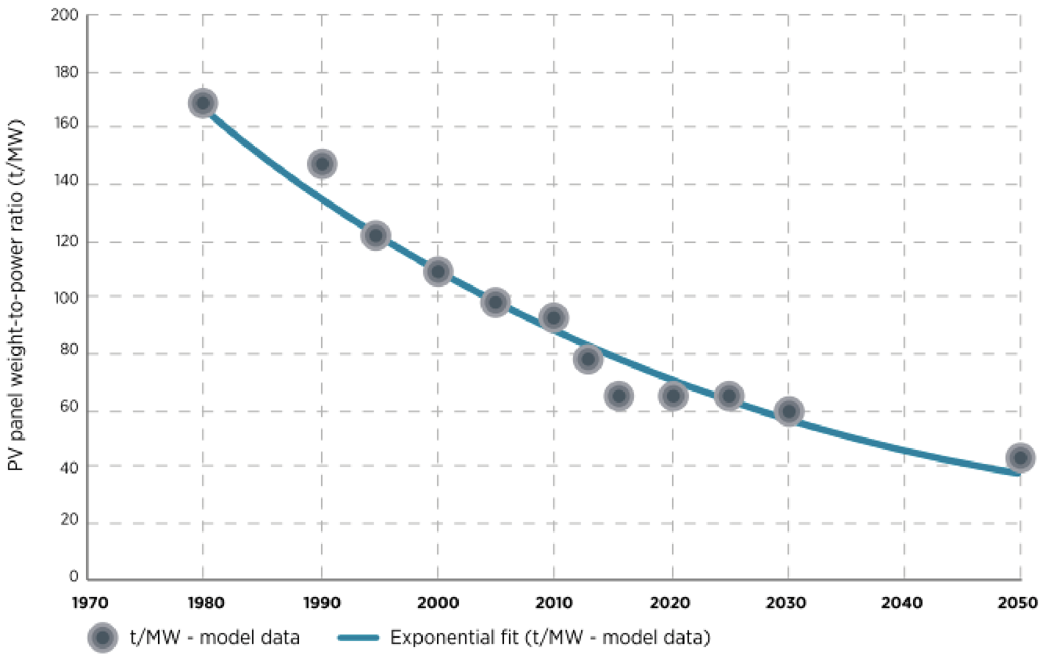

Figure 1.9 *Exponential curve fit of projection of PV panel weight-to-power ratio (t/MW)* [16]

Moreover, lighter panels, known as frameless panels, have been developed without the conventional aluminium frame. The Netherlands-based company Solarge has created a PV panel that is 50% lighter than traditional panels by eliminating the aluminium frame and the protective solar glass, resulting in a weight of 5.5 kg per m² compared to the conventional 11 kg per m². Despite removing the frame and glass, the SOLO Ultra Low Carbon panels are mounted in an innovative structure resembling a honeycomb as shown in **Figure 1.10**. Each layer has been meticulously designed to facilitate recycling, ensuring reduced weight and enhanced sustainability.

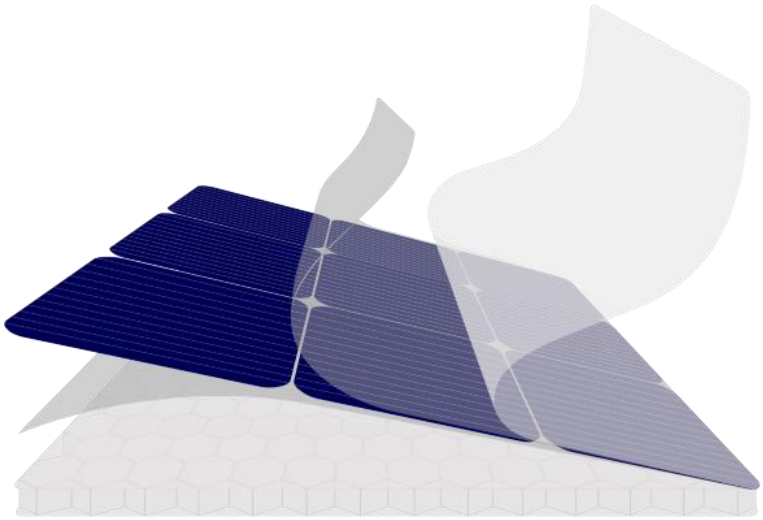

Figure 1.10 *Honeycomb structure of SOLO Ultra Low Carbon* [17]

Reuse

The reuse option is closely tied to the reparability of the technology. This approach emphasises the importance of extending the lifecycle of products and components, thereby reducing waste and conserving resources. If a component is too damaged to function effectively, the product should ideally be returned to the manufacturer for repair. This process ensures that the product can be restored to working condition and continues to provide value, minimising the need for new materials and reducing the environmental footprint. When repair is not feasible, the reuse strategy focuses on repurposing non-defective components. These parts can be harvested and used in the manufacture of new products, effectively closing the loop in the product lifecycle. This conserves valuable materials and reduces the demand for raw materials, thereby mitigating the environmental impact associated with their extraction and processing.

Implementing a successful reuse strategy necessitates establishing comprehensive "take-back" programs [18]. Such programs are designed to facilitate the return of defective products to manufacturers. By doing so, manufacturers can ensure that usable components are efficiently reclaimed and reintegrated into production. These take-back programs can be incentivised through financial rewards, making it more attractive for consumers and businesses to participate.

Moreover, the reuse strategy fosters a culture of sustainability and responsibility among consumers and manufacturers. Promoting the repair and repurposing of products encourages the development of technologies designed with durability and reparability in mind. This enhances the sustainability of the products and builds consumer trust and loyalty, as customers are more likely to support brands that demonstrate a commitment to environmental stewardship.

Recycle

As mentioned in previous sections, incorporating recycled materials into the composition of final products is essential for mitigating the environmental impact of PVT technologies and reducing the demand for raw materials. Utilising materials such as recycled aluminium, silicon, and glass can significantly decrease the ecological footprint of PVT collectors. For instance, recycled aluminium can be used for the frames and structural components, recycled silicon can be incorporated into the PV cells, and recycled glass can be employed for the protective layers.

Furthermore, integrating recycled materials sourced from previous PVT products into the supply chain offers additional benefits. It reduces the need for extensive processing of recycled components, which can be energy-intensive and costly. This approach facilitates establishing a closed-loop system, where materials are continuously recycled and reused within the industry. Such a system not only conserves resources but also minimises waste and the overall environmental impact.

Adopting a closed-loop recycling system enhances sustainability by ensuring that the materials from end-of-life PVT collectors are efficiently reclaimed and reintegrated into new products. This cycle promotes a more circular economy, reduces the carbon footprint associated with the extraction and processing of raw materials, and helps manage the growing volume of electronic waste. By prioritising the use of recycled materials and implementing innovative recycling practices during the design phase of PVT collectors, the industry can move towards more sustainable and environmentally friendly solutions.

2. Energy Label considerations

The Energy Label Directive and the Ecodesign Directive are two key policy instruments deployed in the EU to mitigate the environmental impacts of products throughout their life cycles. Energy labelling primarily focuses on energy consumption and other resources, while Ecodesign is more broadly focused on reducing environmental impact.

Currently, there are no regulations regarding the energy labelling of PVT technologies. However, by adhering to the principles of energy labelling, environmental impact can be minimised. Therefore, this section outlines some ideas for integrating energy labelling into ecodesign based manufacturing processes, emphasising the reduction of energy use during the manufacturing phase and maximising energy efficiency during the usage phase.

2.1. Manufacturing phase

Solar technologies are developed to decrease dependence on fossil fuels by harnessing renewable energy from sunlight. However, the manufacturing process of these technologies is not without environmental impact. Significant greenhouse gas emissions are produced during this phase, primarily because fossil fuels are often used to power manufacturing facilities and processes. This reliance on fossil energy contributes to the carbon footprint of solar technologies. To mitigate the environmental impact and enhance the sustainability of solar energy, it is crucial to adopt measures that minimise energy consumption during manufacturing. This can be achieved by utilising renewable energy sources to power production facilities, improving energy efficiency in manufacturing processes, and investing in advanced technologies that reduce the overall energy demand. Additionally, optimising supply chains and developing more efficient production techniques can further reduce the carbon emissions associated with producing solar technologies, ultimately contributing to a more sustainable and environmentally friendly energy solution.

Electricity consumption constitutes a massive portion of the global warming potential associated with the manufacture of PV technologies, primarily due to the frequent use of electricity sourced from fossil fuels, especially in regions like China. By manufacturing most components in Europe, we have the potential to reduce greenhouse gas (GHG) emissions by 30% to 40% [19]. As shown in **Figure 2.1**, Scandinavian countries could be a great option when selecting local manufacturers due to their low carbon intensity of electricity.

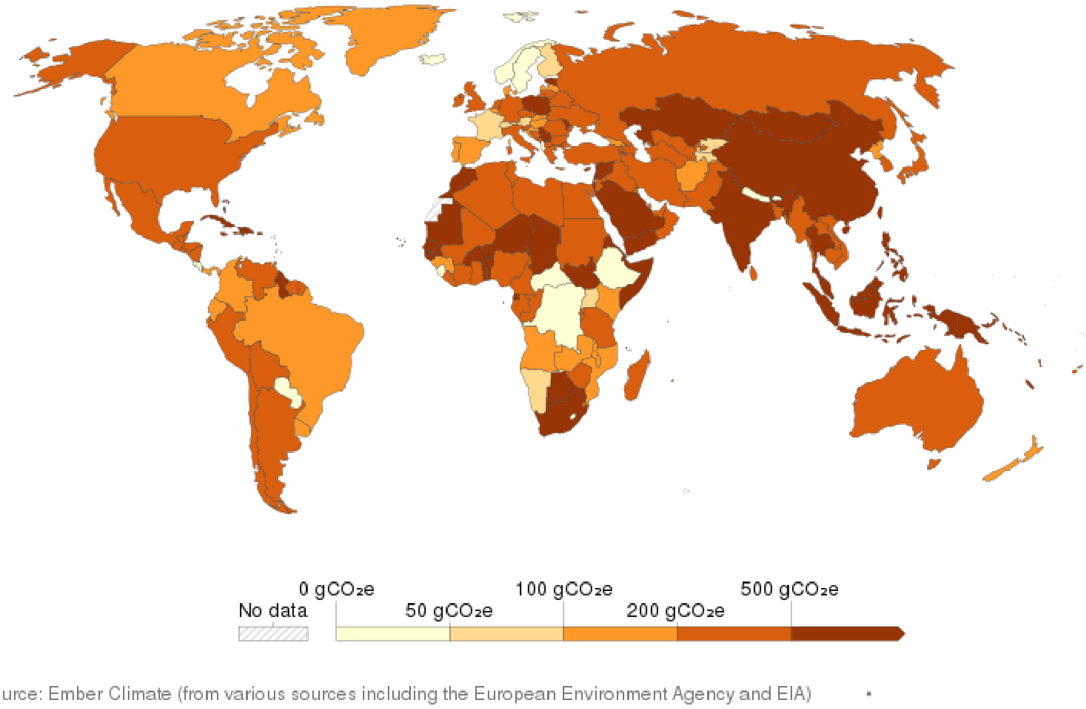

Figure 2.1 *Carbon intensity of electricity in 2021, in grams of CO2-equivalents per kWh* [20]

Additionally, relocating production lines to Europe facilitates a decrease in transportation requirements. Nevertheless, the cost-effectiveness of this approach should also be evaluated, considering that, in the last decade, one of the main barriers for PVT manufacturers has been to reach economies of scale and deliver technologies that are competitive with conventional ones. Local incentives should be put in place to encourage the production of these technologies in the region.

2.2. Using phase

Ensuring the efficiency of solar energy systems is essential for maximising their electricity output, directly impacting their economic viability and returns on investment. Additionally, improving efficiency helps reduce the environmental footprint of solar installations by minimising resource consumption and land use. Moreover, enhancing solar energy efficiency enhances energy security by reducing dependence on finite fossil fuels and mitigating risks associated with climate change and energy market volatility.

On the other hand, PVT technologies provide significant advantages over traditional PV and solar thermal systems by generating both electricity and heat from the same surface area, leading to higher overall efficiency, and maximised use of space, particularly in urban environments (**Figure 2.2**). The cooling effect on PV cells enhances electrical efficiency, while the dual output reduces dependence on fossil fuel-based heating systems, offering a comprehensive renewable energy solution. PVT systems also contribute to more significant energy savings and reduced greenhouse gas emissions through year-round utilisation, lower embodied energy, and support for decentralised energy generation, making them a powerful tool for enhanced decarbonisation and sustainability.

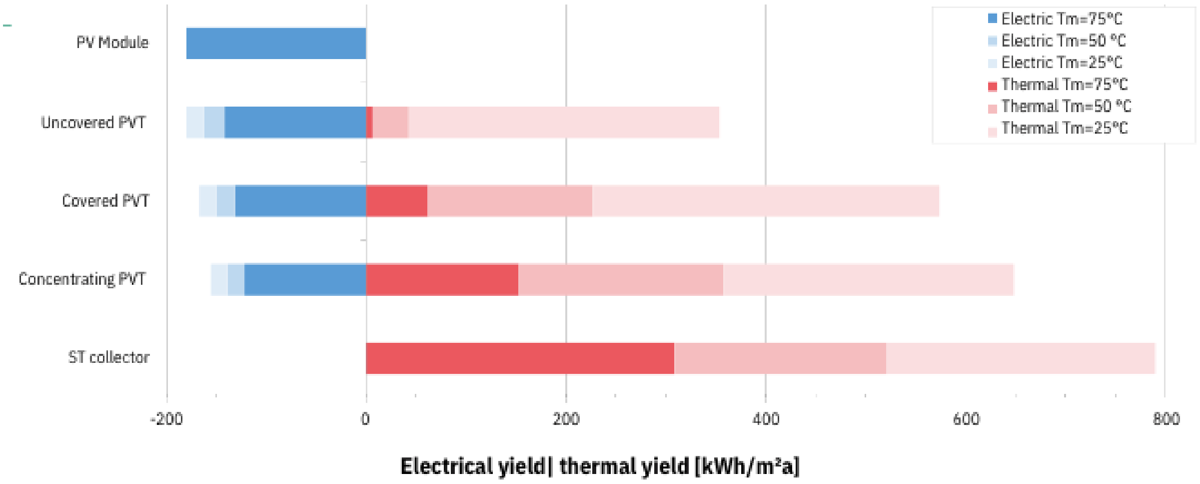

Figure 2.2 Specific energy yield of solar technologies [21]

3. Certification for solar technology

After applying ecodesign principles, certification can be obtained to validate the action taken to reduce the environmental impact of the product during the conception phase. Labels and certifications assure quality, build consumer confidence, ensure regulatory compliance, facilitate market access, and can provide a competitive advantage in the marketplace. Consequently, obtaining certification not only demonstrates a manufacturer's commitment to social and environmental causes but also enhances brand image and distinguishes products in a crowded market. Moreover, it allows a fair comparison between different technologies available in the market.

3.1. EPEAT Photovoltaic Modules

EPEAT (Electronic Product Environmental Assessment Tool) is a global ecolabel that helps purchasers evaluate the environmental attributes of electronic products. Initially developed for IT products, EPEAT provides a comprehensive rating system that considers multiple environmental criteria, including energy efficiency, recyclability, reduction of hazardous substances, and design for end-of-life management. For solar products, EPEAT is expanding its scope to include PV modules and inverters. EPEAT for Solar is a comprehensive ecolabel designed to simplify the procurement of sustainable, low-carbon PV modules. By adhering to transparent ESG criteria and undergoing rigorous third-party verification, EPEAT for Solar enables buyers to reduce their scope 3 carbon emissions and supports the growth of domestic PV manufacturing.

EPEAT evaluates products according to seven environmental performance criteria: materials selection, supply chain GHG emissions reduction, design for circularity and product longevity, energy conservation, end-of-life management, and corporate responsibility. First Solar's Series 6 module is the world's first PV product to be rated in the Electronic Products Environmental Assessment Tool (EPEAT) registry for sustainable electronics.

All EPEAT Photovoltaic Modules and Inverters Products must meet, at a minimum, the following required criteria:

(5.1.1) List of declarable substances
(5.1.2) List of declarable substances used in manufacturing
(5.2.1) Disclosure of substances on the European Union REACH Regulation Candidate List of Substances of Very High Concern (SVHC)
(5.2.5) Avoidance or reduction of high global warming potential (GWP) gas emissions
(5.2.6) Conformance with provisions of European Union RoHS Directive
(6.1.1) Declaration of recycled content in a product
(7.1.1) Conducting LCA
(8.1.4) Weighted efficiency reporting

3.2. SOLERGY Label

The SOLERGY Label is a voluntary label for solar thermal collectors that gives an easy-to-read performance rating ranging from A- to AAA. This rating system indicates the energy produced per unit area for different climates. This label was established in response to the absence of solar thermal collectors in the EU Energy Efficiency labels. Instead of indicating device consumption, the SOLERGY Label quantifies the amount of heat energy a solar thermal collector can generate across multiple geographic locations. The difference between the EU Energy Efficiency label and the SOLERGY Label are depicted in **Figure 3.1**. The SOLERGY label provides information on the temperature level and the corresponding application that the collector is most suitable for.

Adopting the SOLERGY Label helps consumers choose products that best enable them to enjoy a sustainable and cost-effective heat supply. The principal requirement for obtaining this optional label is holding a valid Solar KEYMARK certificate. Although the label was initially developed for solar thermal collectors, it has been extended to PVT collectors. Manufacturers of PVT collectors, such as DualSun, Abora, and Naked Energy, have already received the label. To date, a total of 25 manufacturers and distributors of flat plate, evacuated tube, and PVT collectors in Europe have received the SOLERGY Label.

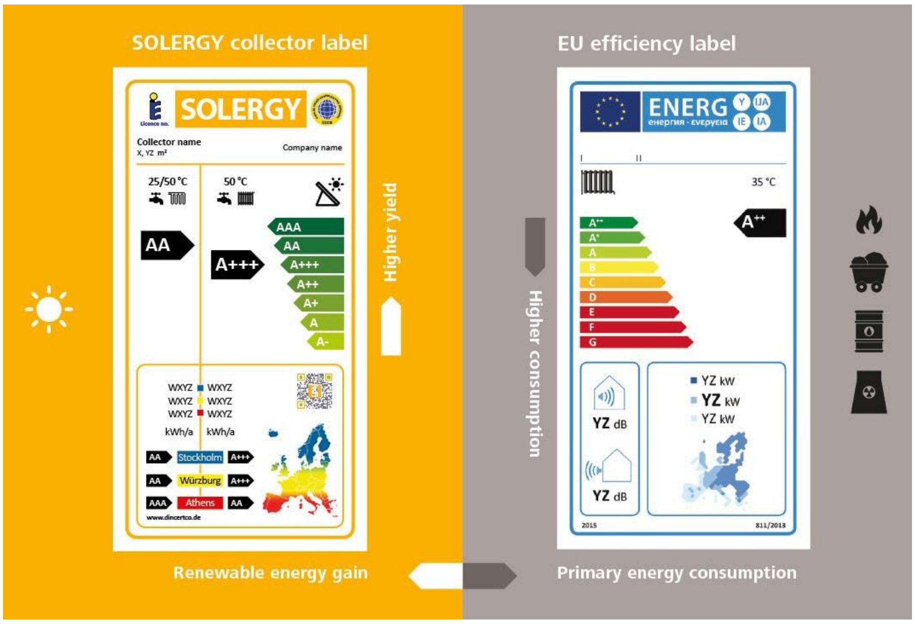

Figure 3.1 *Comparison of SOLERGY collector label and EU efficiency label* [22]

4. Conclusion

This report provided environmental considerations for designing PVT technologies. Ecodesign considerations focus on four key strategies that are integrated into the life cycle of the product: Material Selection, Reparability, Recyclability, and Circular Economy. For each strategy, environmental considerations were applied to PVT technologies to reduce the environmental impact of each stage of the product.

When selecting materials, it is important to give preference to durable and sustainable materials, avoid rare metals, and give preference to components made from natural fibres. In addition, reparability and recyclability must be an integral part of the product development process to ensure that products can be disassembled without damaging parts. This means avoiding components that are difficult to replace and the use of adhesives that could interfere with disassembly. Finally, consideration of the principles of the circular economy with the 3Rs principle ensures the use of recycled materials and the optimisation of material consumption. Consideration was also given to energy labelling in order to reduce energy consumption in the manufacturing phase and optimise the energy efficiency of the technology. Lastly, two examples of solar energy certification were proposed to demonstrate the manufacturer's commitment to social and environmental issues as well as to improve the brand image and make the products stand out in a crowded market.

Ecodesign and energy labelling considerations are essential for minimising the environmental impact of PVT technologies. However, technical and economic aspects must also be considered in order to develop a competitive product. Ecodesign recommendations need to be tailored to each product according to its specific characteristics. As the PVT4EU project introduces new types of PVT technologies with unique shapes and complex components, these recommendations become even more critical. To assist designers in making decisions aligned with ecodesign principles, a comprehensive life cycle assessment (LCA) should be conducted to identify hotspots. Identifying these hotspots is crucial for prioritising ecodesign decisions and enhancing the overall sustainability of PVT technologies. By implementing these recommendations, the PVT4EU project can improve the sustainability of PVT technologies, reduce their environmental impact, and support the broader transition to renewable energy. This approach ensures that PVT technologies not only meet environmental standards but also remain economically viable and technically robust.

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