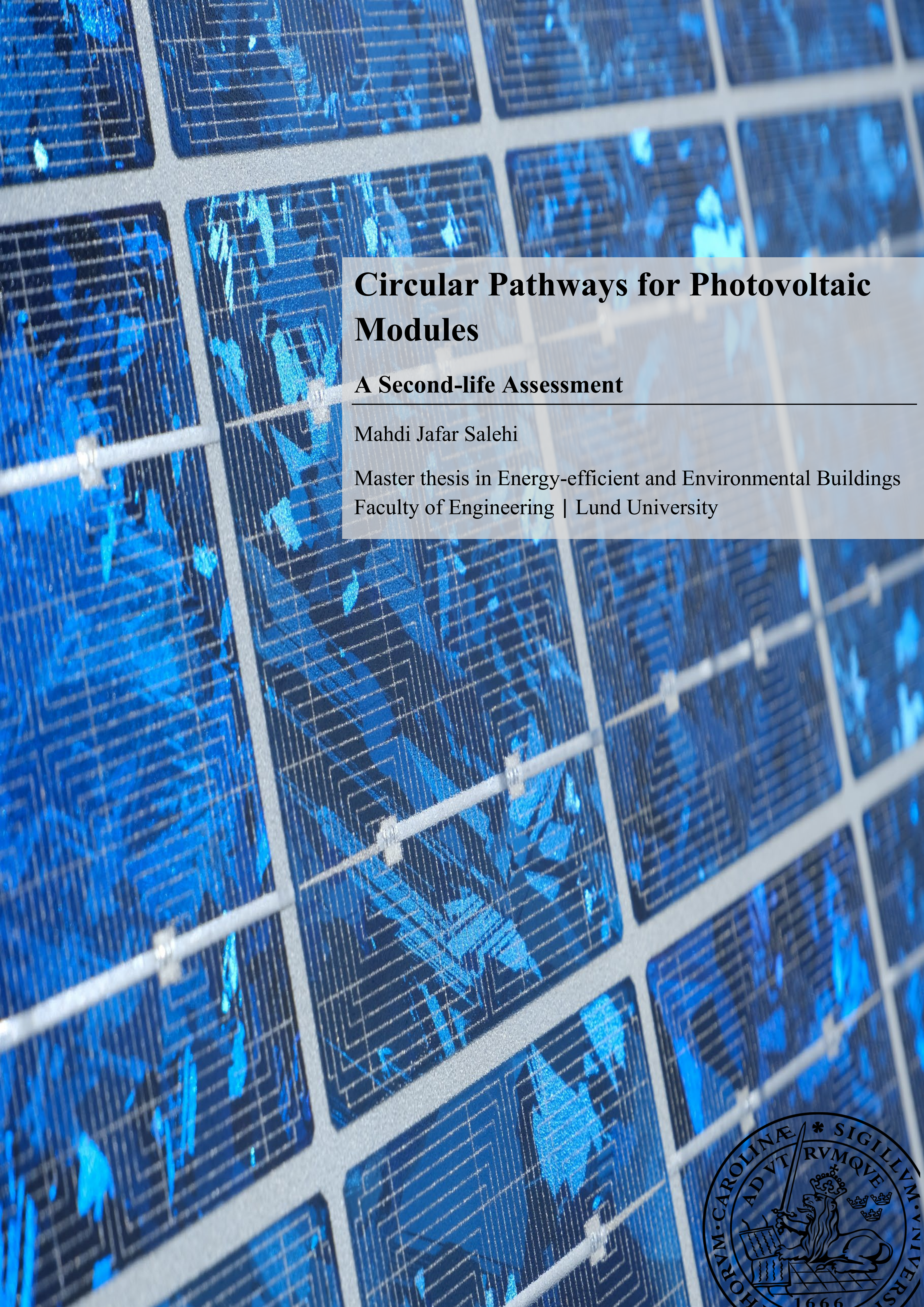

Circular Pathways for Photovoltaic Modules

A Second-life Assessment

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

The rapid growth of photovoltaic (PV) deployment has raised concerns about the management of end-of-life PV modules, particularly crystalline silicon (c-Si) technologies approaching the end of their service life. Although PV systems contribute to renewable electricity generation, the increasing number of ageing modules poses environmental, technical, and resource-related challenges regarding whether these modules should be reused or recycled. Since PV modules contain valuable materials, including classified critical raw materials under current regulations, circular end-of-life management requires greater focus. At the same time, the global PV supply chain remains dependent on energy-intensive manufacturing processes, raw material extraction, and geographically concentrated production, raising concerns about supply chain vulnerabilities and material security.

This study investigates reuse and recycling as two circular end-of-life pathways for first-generation PV modules in a Nordic climate context. Reuse criteria were established based on degradation science, field data and safety considerations, while a Life Cycle Assessment (LCA) was conducted in SimaPro using the Ecoinvent database in alignment with EN 15804+A2 and ISO standards. Due to the absence of an established LCA framework for PV module reuse, the study adapted the EN 15804 principles of polluter pays, end-of-waste state, functional equivalence, and substitution, to assess the reuse scenario.

The results of this study revealed that PV modules operating in cold climates generally degrade more slowly than those in other climates. Field evidence further suggests that many PV modules removed early from service still retain functional value and may qualify for second-life use. However, reliable reuse depends on structured testing capable of detecting safety-critical defects, and degradation mechanisms that may remain latent during operation but become important as modules approach the later stages of their service life.

The LCA results further show that the production stage dominates life cycle environmental impacts, accounting for approximately 90% of total emissions in both scenarios. Within this stage, the solar cell layer represents only 4% of module mass yet contributes 79% of production emissions, meaning that each 1% share of module mass associated with the solar cell corresponds to nearly 20% of production emissions. Glass and aluminium together make up 83% of module mass but account for only 13% of production emissions. Mechanical recycling targets these heavy and low-impact fractions, while the solar cell that carries the largest environmental footprint remains unrecovered. This mass-impact inversion is precisely what reuse addresses by extending the lifetime of functional PV modules, while recycling remains an important pathway for modules that can no longer be effectively reused.

The study concludes that reuse is not simply an environmental preference but a technically achievable pathway, as demonstrated by the reuse criteria established in this study based on degradation science and structured testing. However, the methodological and regulatory frameworks needed to support this at scale, such as standardised testing protocols, agreed performance thresholds, and economic incentives do not yet exist, and their absence is what prevents the circular potential identified in this study from being realised in practice.

Acknowledgement

I would like to express my sincere gratitude to my supervisors, Ilia Iarkov and Henrik Davidsson, for their guidance, encouragement, and support throughout this work. They believed in me even when I doubted myself and faced the challenges of this journey alongside me as though they were their own. Their support and dedication will never be forgotten, and I will always strive to give back whenever I can. I am also deeply grateful to them for consistently challenging me to think more critically, not only within the scope of this study but also in a broader sense. Their mentorship has encouraged me to become someone who never stops learning and questioning. I would also like to thank my examiner, Ricardo Bernardo, for his time, engagement, and valuable feedback throughout the thesis process.

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Finally, and most importantly, I would like to thank my family for their unconditional support, patience, and encouragement throughout this journey. Knowing that you were always there for me made all the difference and gave me the strength to keep moving forward.

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List of Abbreviations

BoS	Balance-of-System
c-Si	Crystalline Silicon
CRM	Critical Raw Material
EoL	End-of-Life
EPD	Environmental Product Declaration
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Mono-Si	Monocrystalline Silicon
Multi-Si	Multicrystalline Silicon
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
STC	Standard Test Conditions
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

Over the past decades, the global energy system has shifted toward sustainable solutions and away from fossil-fuel-based systems, largely due to the need to mitigate climate change and reduce greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC), global warming is the direct result of human influence primarily via GHG emissions, noting that current surface temperatures have already risen 1.1 °C beyond pre-industrial levels. As the energy sector remains the largest contributor of Global Warming Potential (GWP), the rapid scaling of renewable technologies is critical to achieving net-zero targets by 2050 [1].

Furthermore, global fossil energy reserves, such as oil and natural gas, are projected to decrease by 31% and 24%, respectively, by 2050. This increases the importance of developing renewable energy technologies as global energy demand rises [2].

However, the move toward an energy system dominated by renewables means trading dependence on fossil-fuels for dependence on raw materials [3]. This shift suggests that the environmental benefits of reduced emissions must be weighed against the life cycle impacts of the infrastructure itself. The rapid scaling required to replace fossil fuels creates linear take-make-dispose pressure on global resources, bringing the circularity of the PV life cycle into focus.

PV technologies are categorized into three main types: crystalline silicon as the first generation, thin-film as the second generation, and emerging solar cells as the third generation [4]. A large portion of first-generation deployed PV modules are reaching their expected end of service life. It is projected that PV waste could reach 1.7 to 8.0 million tonnes by 2030 and up to 78 million tonnes by 2050 worldwide [5].

Managing this growing waste volume requires a more detailed assessment of end-of-life (EoL) strategies. For first-generation crystalline silicon (c-Si) PV modules, two circular pathways are available to reduce the need for further raw material extraction while extending the use of resources already invested in. This aligns with the purpose of the present study, which assesses reuse and recycling as two alternative strategies.

1.1 Aim & Goal

The project aims to investigate two circular pathways, namely reuse and recycling, for the first generation of photovoltaic (PV) modules nearing the end of their service life. To support this, relevant data were collected and analysed to identify the opportunities and challenges associated with each pathway, providing a basis for evaluating their environmental performance. Therefore, the study seeks to answer the following research questions:

1. Which degradation mechanisms and performance thresholds determine whether first-generation c-Si PV modules are suitable for reuse rather than recycling?

2. How can reuse eligibility and remaining performance be translated into LCA assumptions in the absence of an established reuse LCA framework for second-life PV modules?

3. How do the environmental impacts of reuse and recycling pathways differ under these assumptions?

1.2 Background

1.2.1 PV growth

According to the International Renewable Energy Agency (IRENA), the global PV sector has experienced increasing momentum since the early 2000s, when cumulative installed capacity stood at 1 GW worldwide, increased to 100 GW by 2012 and surpassed 1 TW in 2022, with projections suggesting it will reach 2.8 TW by 2030, meaning nearly 2 800 times increase over roughly three decades [6], illustrated in Figure 1.

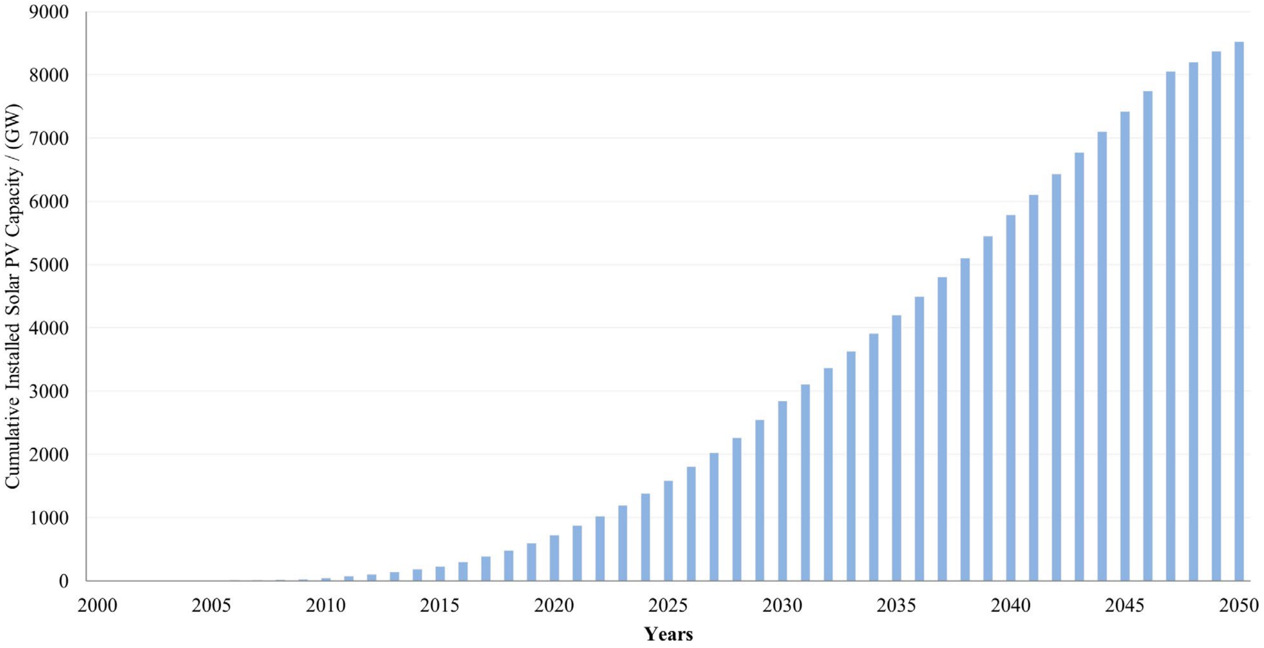

Figure 1. Global cumulative installed PV capacity, including projections. Adopted from IRENA [6], regenerated by the author

This rapid growth was supported by continuously declining costs, with PV module prices decreasing by 25% for every doubling of cumulative global production over the past 44 years, and an 82% cost reduction recorded between 2010 and 2019 alone [7]. This cost reduction started approximately in 1980. A study in 2006 identified that between 1980 and 2001, the expansion of manufacturing plant sizes that facilitated economies of scale, was the driver of cost reductions, accounting for an estimated 43% of the decline. During the same era, improvements in module efficiency and falling polysilicon costs contributed an additional 30% and 12% to cost declines, respectively [8]. Following this period, large investments rapidly expanded global manufacturing capacity across all stages of production. As PV supply started to exceed market demand, continual oversupply occurred and led to a steady decline in prices for products ranging from raw feedstock materials to finished modules [9].

Building on these, another study found that between 2005 and 2012, the traditional drivers of “learning-by-doing” and “economies of scale” became less impactful than the impact of upstream industries. The same source acknowledged that the increasing presence of Chinese manufacturers was a primary factor, as these companies achieved production costs 22.4% lower than international competitors through regional supply chain networks [10].

Supportive policy frameworks such as “Feed-in-Tariff” (FiT) also played a key role in driving this growth. This mechanism provided direct financial incentives to PV system owners by compensating them for electricity fed into the grid at rates above standard retail electricity prices, thereby making solar systems more economically attractive to consumers at the time [11]. Further module-level improvements also pushed this growth. PV modules began offering lower weight-to-power ratios, meaning that the amount of materials required in the manufacturing process was reduced and the adoption of advanced technologies maximised energy output per unit weight. This resulted in developments that contributed to both cost reductions and increased performance [5].

Together, these factors have contributed to solar energy becoming the fastest-growing renewable energy source. According to an IEA estimate, solar power is expected to surpass both wind and hydropower and will account for approximately 16.1% of total renewable electricity generation by 2030. This represents a substantial increase from only 3% in 2020, suggesting that long-term deployment targets may be achieved sooner than originally anticipated [12]. As a direct consequence of this rapid market growth with installed capacity increasing from 1 GW in the early 2000s to over 1 TW by 2022, a growing number of the modules deployed during this expansion are now approaching the end of their expected lifetimes, increasing the need for effective management of the resulting waste stream.

1.2.2 PV structure

Among the technologies driving the widespread deployment of PV modules, first-generation crystalline silicon (c-Si) has dominated the market since the early 2000s, as shown in Figure 2. This technology comprises two major types: monocrystalline (single-crystalline) and polycrystalline (multi-crystalline) silicon, both of which have a largely similar layer structure, as illustrated in Figure 3.

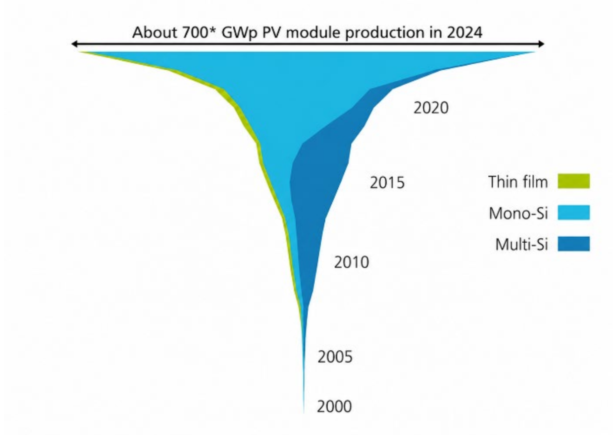

Figure 2. Market share of PV technologies from 2000 to 2024. Adopted from [7]

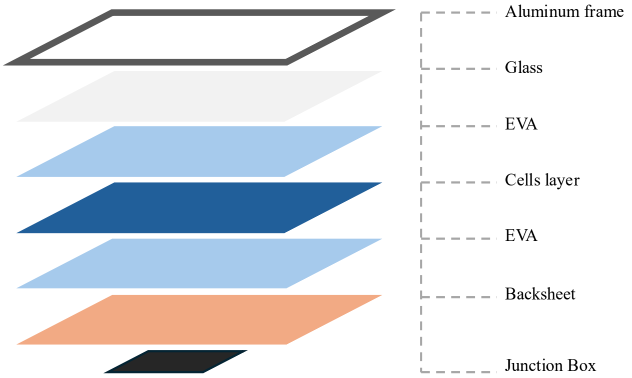

Figure 3. Cross-sectional layer structure of a c-Si PV module, adapted by the author from [7].

The power output of PV modules is measured under Standard Test Conditions (STC), which requires an irradiance of 1000 W/m², an air mass 1.5 (AM1.5) spectrum, and a cell temperature of 25 °C in a laboratory condition. The result defines the module's nameplate capacity and is expressed as Watt-peak (W_p) [13]. In addition, the module's ability to convert this irradiance into energy under STC is defined as its conversion efficiency [14].

C-Si PV modules have improved in efficiency over time. An efficiency range of 14% to 15% was reported for c-Si modules in 2010, and it reached 22% in 2024 due to further advancements, mostly in mono-Si PV. However, its twin technology had disappeared from the market by 2024, and mono-Si PV accounted for 98% of the total market share [7], [15]. Mono-Si became dominant primarily because its higher efficiency delivers the same power output from a smaller area, reducing land use, roof space requirements, and balance-of-system costs. It is reported that the output per module was below 200 W in 2010, rose to approximately 350 W by 2019, and reached between 550 W and 700 W for predominant mono-Si modules by early 2025 [16].

While both technologies are largely similar, the key difference lies in their cellular architecture. Multi-Si PV consists of multiple small crystals of different sizes and typically has slightly thicker wafers. In contrast, mono-Si PV has a single, uniform crystal lattice and thinner wafers. This difference directly affects their performance, as the electrical current encounters fewer obstacles in monocrystalline cells, resulting in higher efficiencies [17], [18], [19].

Understanding the layered structure of c-Si modules is important for EoL management because the different materials vary in terms of purpose, recovery potential, and environmental impact. In addition to the solar cells, which form the core of a conventional c-Si PV module, several other layers are laminated into a sandwich-like structure. While the solar cell layer is responsible for electricity generation, the remaining layers provide mechanical support, protection, and electrical insulation. A description of these layers is provided in Table 1.

Table 1. Material composition of the c-Si PV module

Key components	**Purpose**
Aluminum frame	Adds mechanical stability and rigidity to the whole module and keeps the different layers of the PV module together [20].
Tempered glass	Allows solar rays to penetrate while providing physical protection and mechanical strength, preventing the inner layers from being exposed to environmental stressors [21].
Solar cell layer	The core of a c-Si module is the solar cell, which generates electricity by absorbing photons and converting their energy into electrical current. Multiple cells are connected in series using interconnectors and arranged in rows. The interconnectors and busbar ribbons then act as an energy highway, carrying the collected current across the cells to the bussing ribbon, which directs it to the junction box [22].
Ethylene-Vinyl Acetate (EVA)	Ethylene-Vinyl Acetate (EVA) is the primary support layer for the solar cell. Two layers of this polymer, one positioned above and one below the solar cell layer, to encapsulate the cells and protect them from UV exposure, moisture ingress, and thermal cycling, all of which can cause damage to the cell layer. It also acts as an adhesive, binding the layers of the laminate together [23], [24].
Backsheet	Isolates internal layers by preventing leakage of live electrical current from inside the module to the outside, as well as moisture ingress and UV exposure from the outside to the inside [25].
Junction box	Consists of ribbons from the solar cell layer, bypass diodes, and cables. It serves as the interface between the ribbons that carry energy from the solar cells and the external cables connected to the system, while also protecting these components from moisture ingress by isolating them from direct environmental contact [25].

1.2.3 PV resources and supply chain

PV modules generate electricity with lower greenhouse gas emissions than fossil-fuel-based systems during operation. This transition, however, often shifts the burden from greenhouse gas emissions to resource depletion, as the manufacturing process remains reliant on raw material extraction and non-renewable energy reserves [26], and demand for critical materials and energy will increase accordingly as PV production expands.

C-Si PV modules typically require silicon and silver, depending on the type, and the use of each material carries its own concerns. The manufacturing phase of PV modules is typically energy-intensive, with solar cell production as the primary driver. Producing a solar cell involves several stages that require high temperatures, from the mining of silica sand and the extraction of metallurgical-grade (MG) silicon, through further purification and solidification into wafers, to final surface treatments. The purification of silicon into wafers for multi-Si applications alone requires temperatures of 1 100 °C to 1 200 °C in the Siemens process, which accounts for the highest energy use in PV manufacturing [27]. Although the total energy use during production is largely determined by the production process itself and remains broadly similar regardless of where modules are produced, the resulting emissions vary considerably depending on the carbon intensity of the local electricity grid, powering that process.

According to the International Energy Agency (IEA), China currently has the most competitive manufacturing costs for clean energy technologies globally. On average, production costs in other markets are higher, reaching up to 40% more in the United States, 45% more in the European Union, and 25% more in India than in China [28]. This makes China the global leader in providing a clean electricity generation technology. However, a study on China's electricity grid reported that its energy mix is heavily reliant on fossil fuels, with coal combustion accounting for 79% of its grid mix [29]. The effect of the energy source on production is further supported by another study that conducted an LCA of the production of two conventional PV modules in China, Germany, and the European Union. The researchers found that manufacturing in Europe reduces greenhouse gas emissions by 30% to 40% compared to China, reflecting the effect of a cleaner electricity grid [30].

In addition to the environmental impact associated with a fossil-intensive electricity mix, the extreme geographic concentration of PV manufacturing introduces supply-chain vulnerabilities. China currently hosts at least 80% of the world's manufacturing capacity across all segments of the solar PV value chain, encompassing processes from the initial purification of polysilicon to the final assembly of modules [28]. Because such a dominant share of the global PV production line is concentrated in a single region, global PV deployment has become highly vulnerable to trade restrictions, geopolitical tensions, or sudden policy changes affecting that region. In addition to the effects of fossil fuel combustion and supply chain vulnerability, resource depletion is also on the horizon. Silver used in interconnectors and as a front paste for solar cells [18] is at risk of shortages, as the PV industry's demand for silver is projected to reach between 29% and 41% of total global supply by 2030. At the same time, the silver supply may only meet two-thirds of total global requirements by that date [31].

In terms of resources, the European Union introduced the Critical Raw Materials Act in 2024 in response to expected growth in demand for critical rare earth elements and other key materials in the coming years. Critical Raw Materials (CRMs) are materials that are both economically important to the EU and at risk of supply disruption, largely because their production is concentrated in specific countries worldwide, making their supply chains vulnerable. The Act aims to achieve three main goals: expanding and diversifying the EU's supply of these materials, improving circularity through better recycling and recovery, and supporting research into more resource-efficient processes. The regulation also aims to reduce Europe's dependence on external suppliers for materials critical to its economy. In the context of c-Si PV modules, aluminium, copper, silicon, boron, and phosphorus are among the critical materials included in the CRM list [32], [33].

However, the Act does not define specific recovery targets for critical materials in PV modules, nor does it require the use of recycled materials in the manufacture of new modules. As a result, there is currently no regulatory framework to ensure the recovery of materials of sufficient quality from EoL modules.

Overall, the material composition of c-Si PV modules highlights the importance of effective EoL management. Nevertheless, current recycling practices and existing regulations do not fully address these resource-related challenges. The following section, therefore, explores how the dominant recycling approach deals with the recovery of valuable materials from EoL modules.

1.2.4 PV recycling

To address the growing volume of PV waste, recycling can offer a promising pathway to recover the valuable materials embedded in PV modules. Among continents, Europe is the only one to have established a structured regulatory framework to manage the PV waste stream. The European Commission expanded its Waste Electrical and Electronic Equipment (WEEE) Directive in 2012 to include PV modules. It introduced an extended producer responsibility (EPR) framework under which manufacturers are responsible for the logistical and administrative processes of their products at the end of life. In 2018, the directive further set targets and mandated a minimum total mass recovery of 85%, with at least 80% of module mass to be reused or recycled.

While this framework has provided the foundation for the expansion of recycling facilities across Europe, it has also directed European industry toward the currently dominant commercial approach: mechanical recycling. This approach, adapted from existing glass recycling industries in some countries, targets only bulk material recovery, such as glass and aluminium, which together account for more than 80% of a module's total mass, meaning that recycling these fractions alone is sufficient to meet legal requirements [34].

Although a large fraction of PV module mass is recovered through this approach, it does not yield high-quality recovery. Mechanical recycling heavily relies on shredding and crushing to break the PV module; therefore, different types of scrap metals are mixed and contaminated after the recovery [34]. This type of recycling frequently reduces the quality of materials compared to their original form and cannot be used in the same application again, a process known as downcycling [35]. The recycled fractions, such as aluminium, glass, and a portion of metals like copper from wires and junction boxes, can be sold to metals processors or aluminium recyclers. Still, the remaining fraction is typically incinerated for energy recovery or landfilled [36].

In terms of cost, the polymers, such as EVA and backsheet, that are burned for energy recovery carry a higher value within this fraction, but not these materials themselves. The solar cell layer, consisting mostly of a silicon wafer and silver trapped in the encapsulation, accounts for half of the PV module's economic value while representing only approximately 5% of its mass, reflecting the insufficiency of mechanical recycling in recovering a major contributor to the PV module's economic value [37]. In response, laboratory and pilot-scale studies explored more advanced recycling pathways, such as thermal and chemical processes, capable of recovering more materials and at higher purity levels.

The Full Recovery End-of-Life Photovoltaic (FRELP) process, developed under the European LIFE programme, exemplifies what is achievable at the pilot scale. The study examined one tonne of module waste; the process recovered at least 94% of non-polymer materials, with quality close to that of the original materials. A following life cycle assessment based on this process reported a 10% to 15% reduction across environmental impact categories, including global warming potential, ozone depletion, and ecotoxicity, relative to the impact reduction of conventional mechanical recycling [38]. These advanced approaches typically lead to upcycling, in which recovered materials retain qualities close to those of their virgin counterparts and can be reintroduced into their original supply chains [35].

However, these recovery yields represent only part of the picture, as thermal and chemical recycling typically involve high energy use and harsh chemicals. Thermal delamination or pyrolysis, for instance, requires temperatures of approximately 500 °C – 600 °C in an oxygen-free environment to decompose the EVA layers and access the solar cells, followed by chemical treatment with nitric acid to fully separate the cells from the polymer. This hybrid process can cause atmospheric emissions that contribute to acidification and lead to acid rain, in addition to specialised equipment requirements [39], [40].

In summary, while thermal and chemical recycling offer higher recovery rates and environmental benefits, the high upfront costs remain the primary barrier to large-scale adoption because these processes require high energy use, specific chemicals, and specialised equipment. Mechanical recycling, on the other hand, remains the state-of-the-art approach in the PV sector, particularly in Europe, while meeting legal requirements and costing less, even though it loses a valuable fraction of CRMs. Given these limitations, the possibility that modules entering the waste stream may still retain sufficient function for reuse rather than direct recycling deserves further investigation.

1.2.5 PV reuse potential

PV modules are typically warranted for 25 to 30 years, with guaranteed output thresholds of 90% of rated peak power in the first decade and 80% thereafter through year 25. However, many modules are decommissioned before their expected end-of-service life. It was estimated that, in recent years, 80% of the European PV waste stream consisted of modules that had been prematurely decommissioned, i.e., removed from service while still functional, either individually or as part of a larger system replacement [41]. This figure aligns with an earlier 2019 study, which estimated that approximately 45% to 65% of the PV waste stream at that time was still suitable for repair or reuse [42]. These estimates should nevertheless be interpreted with caution, and more studies are needed to support claims of reusability.

A 2018 study, conducted in collaboration with the European Commission, examined a 10 kW_p c-Si PV system in Switzerland, the oldest grid-connected PV system in Europe, installed in 1982. Researchers measured the PV modules' performance in 1982, 2001, 2010, and 2017 using indoor IV tracing, insulation resistance, visual inspection, and electroluminescence (EL) imaging. They further revealed that after 35 years of operation, 60% to 70% of the modules still met standard warranty criteria. The study concluded that a useful service life of 35 years or more is technically achievable for c-Si modules in temperate climates [43].

A second study conducted a global meta-analysis of degradation rates by analysing 80 datasets comprising approximately 70 000 modules installed worldwide since 1979. The researchers further concluded that c-Si technology exhibited the highest stability, and that modules in cold climates degraded much more slowly, with projected lifetimes of up to 47 years in installations with adequate ventilation [44]. These findings support the case for module reusability and raise the question of what pushes early decommissioning despite this technical potential. Several factors have been identified, the first of which is economic.

Economic reasons can drive revamping in some cases, when Balance-of-System (BoS) components, such as inverters or PV modules, are replaced. At the same time, the total installed capacity remains the same, but the use of newer, higher-efficiency modules results in less land use compared to the previous plant. In other cases, it occurs through repowering, in which components or modules are replaced with newer, higher-efficiency alternatives on the same ground area, resulting in higher energy generation per unit area than the previous installation [45].

Furthermore, the decline in PV module prices has transformed building renovations into a pathway to premature system retirement. Even when the existing plant is still functional, owners often find that the labour costs of remounting old equipment are not justified, especially since installers are typically unwilling to provide long-term service guarantees for a system they did not originally install. Consequently, building owners favour full system replacements that provide both higher efficiency and renew the warranties [46]. Moreover, data from the Australian PV sector reveal that the labour costs and time-consuming nature of field testing often outweigh the cost of a new system. According to these industry interviews, this leads manufacturers to favour the wholesale replacement of an entire string during warranty claims, even when a system failure is limited to a single panel. Whilst this is efficient for the manufacturers, it contributes to the premature decommissioning of functional modules that could otherwise remain in service [47].

Additionally, the PV sector is a global supply chain that typically involves long transportation, from the manufacturing gate to importers and to installation locations. Internal layers of a PV module are typically brittle and can lead to structural defects due to unavoidable mechanical stresses during transportation. Historical data from suppliers underlines this risk. A study involving a sample of 2 million PV modules reported that transportation damage alone accounted for 5% of early-life failures [48]. This risk persists through the installation phase, leading to waste generation before a system begins its operational life.

Beyond the reasons behind early decommissioning, another important question is how much remaining performance is sufficient for a module to be considered suitable for reuse. Researchers from the University of South Australia, for instance, proposed a certification system categorising decommissioned modules by State of Health (SoH): a Gold Tier for modules having above 80% of original performance are suitable for demanding applications such as residential rooftops, a Silver Tier for modules between 64% and 80% that are suitable for community or off-grid projects, and a Bronze Tier below 60%, where recycling is recommended [49]. However, this suggestion may conflict with existing legislation. NREL has noted that in certain territories, state and local electrical regulations restrict the reuse of PV modules on building rooftops due to fire safety [46].

A separate framework developed at UFSC in Brazil takes a different approach, adjusting the criteria based on how much is known about a module's history. For modules with no specific background, a minimum of 60% of rated power is required. In comparison, modules with a documented history are instead checked against a 10% margin of their expected degraded output. When tested on a group of 22-year-old modules expected to perform at 78% of their original rated power, a total of 68% of the PV modules qualified for reuse, which were then split into Class A and Class B based on how well they performed relative to expectations. The same study also notes that the TRUST PV project adopts a more lenient approach, accepting modules with as little as 50% of their original performance for reuse [16].

Furthermore, researchers from imec and the bifa Umweltinstitut suggest that a module retaining at least 70% of its original power can still be considered a product rather than waste. They argue that this limit makes sense, as it sits just below what a typical module delivers after 20 years in the field [50].

Even with the lack of a minimum performance threshold suitable for PV reuse, decommissioned modules have already been successfully deployed in real-world applications. One example of industrial-scale reuse is SOLARCYCLE's facility in Texas, which runs in part on a 500 kW_p system built from around 1 000 decommissioned panels. Modules were tested through IV and EL testing to confirm remaining performance without any physical repair. The system covers approximately 50% of the facility's electricity use, indicating that decommissioned modules can serve as a reliable energy source in commercial applications [51].

Overall, the evidence reviewed in the background section highlights a clear gap in current EoL practices for PV modules. Many modules are removed before reaching the end of their technical lifetime, while the most common recycling methods mainly recover material mass rather than preserving environmental value. At the same time, a considerable portion of decommissioned modules may still retain enough functionality for second-life use. These findings shape the core problem explored in this study and guide the methodological approach presented in the following chapter.

2 Methods

Due to the emerging nature of second-life applications of PV modules, this study adopts an exploratory mixed-methods approach, combining a literature review with a Life Cycle Assessment (LCA). The method is structured into two main phases, and the overall workflow is shown in Figure 4.

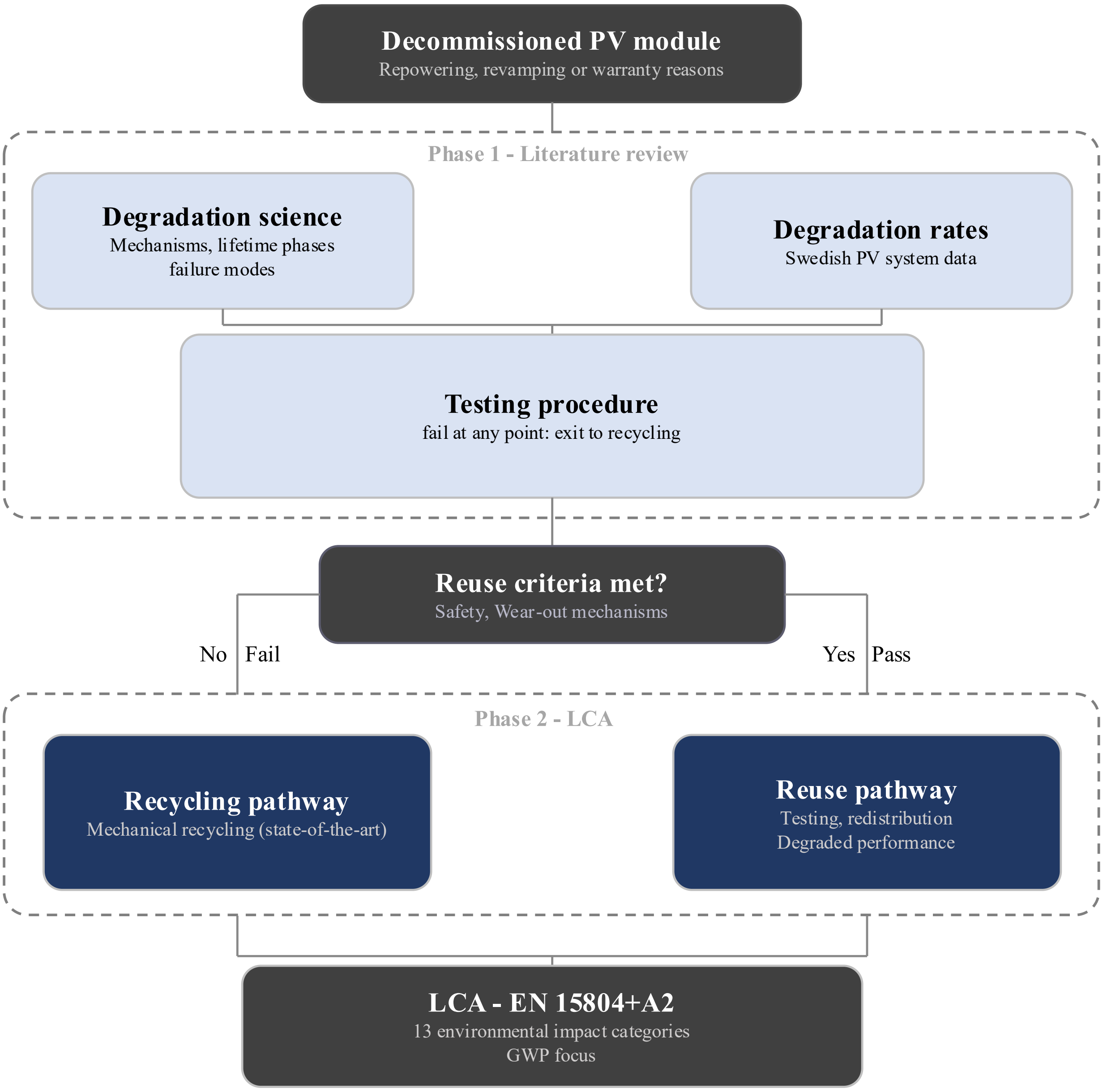

Figure 4. Overall workflow of the study.

In the first phase, a literature review was conducted to establish a reuse framework and assess the technical feasibility of PV module reuse for this study. It allowed the study to identify the conditions under which reuse may be preferred over recycling, whilst also considering recycling as an alternative pathway. Without understanding the degradation mechanisms, the ways of detecting failures, and the effect of those on module performance over time, it is not possible to define which modules are suitable candidates for reuse and which should be directed to recycling. The literature review therefore did not serve as a standalone phase, but as the direct source of the technical feasibility assessment and as the basis for the inputs that made the LCA reuse scenario possible.

In the second phase, a Life Cycle Assessment (LCA) of an aged multi-Si PV module at the end of its warranty period was conducted as a conservative scenario. This phase evaluates the environmental impacts associated with two EoL pathways: reuse and recycling. Key parameters identified in the literature review, particularly those related to performance degradation and reuse suitability, were used as input assumptions for the reuse scenario. Furthermore, as no established LCA framework exists for PV module reuse, this scenario was constructed by adapting the principles of the EN 15804 standard that is built upon ISO 14040 and 14044.

2.1 Literature review method

To assess the technical feasibility of PV module reuse and establish a reuse criterion for this study, a structured literature review was conducted primarily through Scopus, which served as the main database for identifying relevant publications. The search was performed using a combination of predefined keywords, including PV module degradation, crystalline silicon degradation rate, photovoltaic reuse, second-life PV, PV testing procedures, applied both individually and in combination to ensure broad coverage of the relevant literature.

The initial search returned a total of 54 articles. A screening process was then applied to narrow the scope to publications directly relevant to the goal of this study. Titles, abstracts, and conclusions were reviewed, and articles were excluded if they did not address c-Si PV module degradation at the module level, well-established testing methods, or field evidence. Following this screening process, 28 articles were identified as directly relevant and retained for full review.

The full review was structured around four main topics, each corresponding to the sections of the first phase. First, the degradation mechanisms affecting c-Si PV modules were examined, focusing on processes that cause performance loss over time. Second, reuse approaches and testing procedures proposed in the literature were reviewed to identify the conditions under which a decommissioned module may remain suitable for second-life use. Third, module-level degradation rates reported in field studies were analyzed, with particular attention to studies conducted in Sweden. Finally, the findings from these three areas were synthesised to define the reuse criteria that form the backbone of the LCA inputs in this study. The findings of each topic are presented in the Results section.

2.2 Life Cycle Assessment (LCA)

Based on the reuse criteria established in the first phase of the study, the EoL pathways diverge depending on the module's condition. Modules that pass the testing procedures proceed to reuse, while modules that do not are directed to recycling. A Life Cycle Assessment (LCA) was therefore conducted to model both pathways within the same framework.

LCA is a structured methodology for quantifying the environmental consequences of a product or service through all stages of its life cycle, from raw material extraction to EoL treatment. By covering the full lifespan rather than isolated stages, the method helps identify burden shifting, i.e., reducing environmental impact at one stage such as the production phase, may lead to increased impacts at another such as EoL treatment. In this way, LCA supports more transparent and complete environmental decision-making [52].

Furthermore, ISO 14040 defines a framework consisting of four different phases as illustrated in Figure 5. In the first phase, the goal and scope of the assessment should be clearly defined, where the system under study and its boundaries are established. The second phase accounts for all relevant inputs and outputs, such as materials and energy flows, through an inventory that fulfils the goal and scope of the assessment. The third phase translates the inventory results to the environmental impact categories to facilitate interpretation. In the fourth phase, the LCA results are interpreted to evaluate consistency with the preceding phases. Conclusions are drawn to spot the trade-offs, based on the contribution of each inventory result to the selected environmental impact categories [53].

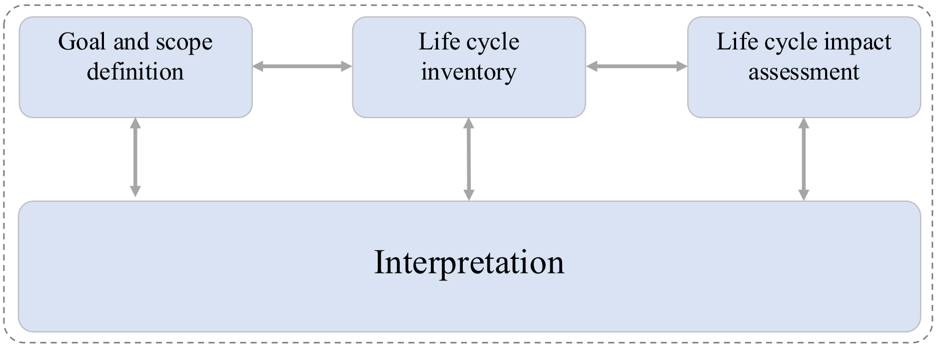

Figure 5. The phases of an LCA study according to ISO 14040, adopted by the author from [53].

While ISO lays the foundation for an LCA study, different products and systems require specific benchmarks for assessment. To identify the most appropriate framework for this study, three existing LCA guidelines applicable to PV modules were reviewed and compared: the IEA PVPS guidelines, the PEFCR for PV, and EN 15804 with its corresponding PCR. The following sections briefly describe each and justify the selection made for this study.

2.2.1 IEA LCA guideline

The IEA PVPS guidelines for LCA of PV systems are primarily aimed at quantifying the environmental impacts of PV and enabling comparison with other electricity generation technologies. This methodology focuses on electricity generation, with the functional unit recommended as kWh of electricity produced over the service life to reflect electricity delivered to the grid and account for performance-related parameters such as efficiency and system losses.

The system boundary includes raw material extraction, manufacturing, installation, operation, and EoL stages of both PV modules and BoS components, enabling a system-based comparison between technologies. EoL aspects are covered through allocation in accordance with ISO 14044, and the methodology supports the use of avoided-burden approaches for recycling and material recovery. However, no explicit framework is provided for modelling second-life use of PV modules [54].

2.2.2 Product environmental footprint category rules for PV (PEFCR PV)

The Product Environmental Footprint Category Rules (PEFCR), structured within the Environmental Footprint (EF) method, are designed to support regulatory applications, particularly under the Ecodesign Directive. This methodology focuses on calculating the carbon footprint of PV modules. The functional unit is defined as 1 kWh of total electricity generated over the service life of the PV module, accounting for efficiency, degradation, lifetime, and geographic conditions, and enabling comparison with other electricity generation technologies.

The system boundary focuses on manufacturing stages, including raw material extraction, silicon processing, cell and module production, and transportation to the market (cradle-to-EU). All EoL aspects are addressed through the Circular Footprint Formula (CFF), a mathematical bridge that applies allocation factors to distribute burdens and credits across product systems. However, no specific framework for assessing reuse scenarios was identified [55].

It should be noted that the information extracted for this methodology is based on the harmonised rules proposed as an adaptation of the PV PEFCR. At the time of this study, the final accepted version was not yet available, and the 2024 version was used.

2.2.3 EN 15804 and Product Category Rules (PCR)

EN 15804, which defines core Product Category Rules (PCR) for construction products, together with the relevant PCR for PV modules, provides a framework for conducting LCA of PV modules. The main purpose is to set a consistent guideline for developing Environmental Product Declarations (EPD) to ensure transparent and comparable results [56]. In this framework, the system boundary is structured into modular stages that cover manufacturing, use phase, end-of-life, and benefits and loads beyond the system boundary. For PV modules, the PCR specifies that only the module itself is included, while balance-of-system components are excluded. The functional unit is defined as 1 W_p of a manufactured PV module, based on the nameplate capacity. This allows environmental impacts to be expressed relative to rated power under standard test conditions, avoiding variability related to location-dependent electricity generation. EoL modelling requires the inclusion of relevant waste treatment and disposal scenarios in compliance with the European Waste Framework Directive (2008/98/EC), while useful output flows, such as recycled materials, are accounted for using substitution for primary materials.

Based on this comparison, it was found that while all three methodologies provide detailed approaches to conducting an LCA of a PV module, none offer an explicit, structured framework for modelling the reuse scenario of PV modules. Additionally, the IEA methodology is not suitable for the goal and scope of this assessment, as it provides a system-based LCA. In contrast, the PEFCR method focuses primarily on the manufacturing stage, whereas this study focuses on EoL alternatives. Therefore, EN 15804 and the corresponding c-PCR were selected as the reference and guideline for this LCA.

In addition, while the purpose of this study is not to develop an EPD, which is most often used for commercial purposes, the modular structure and the ability to account for benefits and loads beyond the system boundary in EN 15804 help this study assess these scenarios more consistently. With EN 15804 as the methodological framework, the LCA was conducted in SimaPro using the Ecoinvent 3 database as the primary source of background data [57].

2.2.4 SimaPro and Ecoinvent

To conduct the LCA of this study, SimaPro software was used. SimaPro is a professional LCA software developed by PRé Sustainability that models and calculates the environmental impacts of products and systems across their life cycles. The "Ecoinvent 3 - unit" library was also used for background data; this database was developed through a collaborative effort among several Swiss institutions. In addition, an Editorial Board assesses the quality of data by reviewing, validating, and editing all new datasets before their inclusion in the database [58]. Two types of processes are available in SimaPro:

1. A unit process which represents a single, isolated step within a production system. It contains only the emissions and resource inputs directly associated with that specific process, while referencing other unit processes that supply inputs to it. This structure keeps the entire supply chain visible and traceable, so that each upstream process can be examined and understood individually. When a unit process is selected in SimaPro, all linked upstream processes are automatically incorporated into the calculation.
2. A system process which is a pre-aggregated version of the same production chain. Rather than referencing individual upstream processes, it already includes the combined emissions and resource inputs from all stages of the production system in a single process record. As a result, the internal structure of the supply chain is not visible to the user, which is why a system process is commonly described as a “black box”.

Material flows, energy needs, and associated waste streams were first collected and modelled in SimaPro, based on their respective geographical scopes, using unit processes to trace and cross-check the individual upstream data. Finally, the EN 15804+A2 methodology was used in this software to assess the study's impact.

2.2.5 Goal and scope definition

In this section, the goal and scope of the LCA study are defined in accordance with ISO 14040. This step establishes the purpose of the LCA study, as well as the system boundaries and methodological framework applied throughout the assessment [53]. The key requirements of the goal definition are shown in Figure 6 and answered below.

Figure 6. Goal definition requirements of the LCA study, adapted by the author from [53]

The intended application is to evaluate the environmental impacts of alternative EoL strategies for conventional PV modules, namely reuse and recycling. The reason is to assess and compare the environmental benefits and loads of these two EoL pathways. The intended audience could be academic researchers, policymakers, and stakeholders in the PV sector and waste management. The study includes two alternatives as reuse and recycling scenarios; however, the results are not intended for public comparative assertions.

The requirements of the scope definition are shown in Figure 7 and described below.

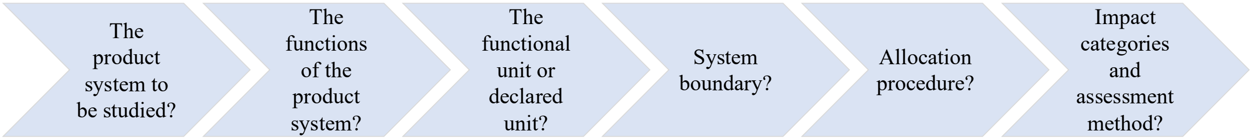

Figure 7. Scope definition requirements of the LCA study, adapted by the author from [53].

The product system is a multi-Si PV module. The system's function is electricity generation. Declared unit is defined as 1 Watt-peak (W_p) of PV module capacity. The system boundary is set to cradle-to-gate with options. No allocation at the foreground level; substitution is applied for stage D. Impact categories, and methodology of impact assessment follow EN 15804+A2.

The system boundary of the study is illustrated in Figure 8, which follows the modular structure defined in EN 15804. The figure presents the included life cycle stages, from production to EoL processes, as well as potential benefits and loads beyond the system boundary. In addition, while the study focuses on the EoL stage, the production stage is modelled to align with the EN 15804 framework, which states that the minimum system boundary to be included covers modules A1-A3, C1-C4, and D [56].

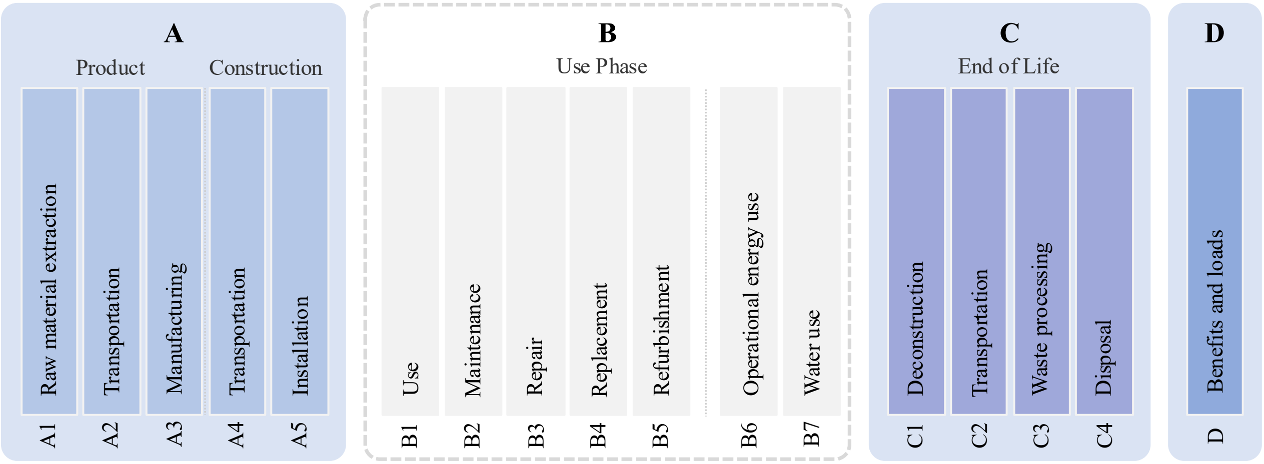

Figure 8. LCA stages, included phases are highlighted with blue. Generated by the author in accordance with [56]

For a PV module assessed under EN 15804, the use phase represents energy consumed by the product during operation. Since a PV module generates rather than consumes energy during use phase, this stage carries negligible operational energy burden, and its exclusion does not affect the results. The selection of 1 W_p as the declared unit requires further explanation, given the two-scenario structure of this study, as described in the following section.

2.2.6 Functional unit and declared unit

In life cycle assessment, a reference unit is required to normalise material flows and environmental impacts, ensuring consistency in reporting results. According to EN 15804, this reference may be defined as either a functional unit or a declared unit. The functional unit represents the quantified performance of a product system and allows comparisons between systems that fulfil the same function. It is applied when the product's specific function and typical application scenario are clearly defined [56].

In contrast, when typical functions and scenarios are multiple or not specified, the declared unit is used as a measurable reference for reporting environmental impacts. The choice between a functional unit and a declared unit is also linked to the scope and system boundaries of the study: a functional unit is generally required for full life cycle assessment, such as “cradle-to-grave”, whereas a declared unit is appropriate for only part of a product's life cycle, such as “cradle-to-gate” or “cradle-to-gate with options” [59].

In this study, the assessment considers two EoL scenarios and does not rely on a single application context. Consequently, the conditions for applying a functional unit are not fully established. Therefore, 1 W_p of manufactured PV module was chosen as the declared unit for this study in accordance with the PCR requirements. In addition, selecting 1 W_p as the reference unit is justified because it represents the module’s rated power, defined under Standard Test Conditions (STC) according to IEC 60904 and corresponding to the module's maximum power output. Therefore, differences in module design, such as solar cell efficiency and physical dimensions, can be normalised to the rated power. This enables the evaluation of environmental impacts based on rated capacity under identical standard conditions and provides a consistent, product-level basis for assessment across module designs.

In contrast, alternative reference units, such as energy output (kWh) or module area (m^2), require additional assumptions about operational conditions or performance characteristics. As a result, they introduce scenario-dependent variability and do not provide a stable basis for product-level comparison for this study. This methodological difference is widely discussed in the literature; a synthesised summary of the advantages and limitations of commonly used reference units in PV LCA is presented in Table 2.

Table 2. Advantages and disadvantages of common reference units in PV LCA

Reference units	**Advantages**	**Disadvantages**
Rated capacity (W_p)	Reflects the rated capacity of the PV module under STC and provides a consistent basis for product-level comparison.	Does not account for the actual electricity fed into the grid, which can vary between technologies.
Energy output (kWh)	Represents the electricity delivered by the PV system and is useful for system-level comparison.	Requires assumptions on location, irradiation, lifetime, degradation, and BoS, which reduces comparability across studies.
Module area (m^2)	Useful for quantity-based LCA and building-related applications such as building-integrated PV (BIPV).	Does not capture performance differences between modules and is therefore not appropriate for comparing technologies with different efficiencies.

2.2.7 Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) is the second phase of an LCA, building upon the system boundary defined in the scope definition phase to achieve the study's goal. It involves the collection and quantification of all relevant inputs and outputs linked with the product system throughout its life cycle. The inventory is structured as a set of connected unit processes, where each process transforms inputs into outputs. These inputs can be broadly categorised as raw materials, intermediate products, energy, and ancillary materials. At the same time, the outputs can be products, co-products, waste, and emissions to air, water, and soil [53]. In this way, the inventory captures resources taken from nature, material and energy exchanges between processes, and the resulting waste streams and emissions released to the environment, all within the product system.

In this study, specific manufacturing data for PV module production were not directly available. Therefore, the PV module inventory, mostly lamination process and end of life recycling was structured using secondary data from the IEA [39], [60]. These databases represent the most complete publicly available datasets for PV module manufacturing and recycling. The foreground unit processes were cross-checked against additional literature before being modelled in SimaPro. The inventory framework was subsequently adapted according to the assumptions and module specifications defined in this study. This approach is consistent with EN 15804, which permits the use of generic representative datasets where specific data are unavailable.

2.2.7.1 Production phase (A1 - A3)

The production phase refers to all processes required to deliver the product up to the factory gate, ready for sending to relevant markets. This phase includes the supply of material and energy inputs, their transport, product manufacturing, and the treatment of process-related waste generated during this stage. Following the modular principle based on EN 15804 [56], the product stage consists of three different modules that include all "cradle-to-gate" activities:

Module A1 (Raw material supply) accounts for the extraction and processing of all primary resources. It also includes processing secondary material inputs and products reused from previous systems. Additionally, A1 includes the generation of energy, such as electricity, steam, and heat, from both primary resources and secondary fuels, including their extraction, refining, and transport.

Module A2 (Transport) covers transportation involved in the delivery of raw materials and intermediate pre-products to the manufacturing site.

Module A3 (Manufacturing) includes the production of ancillary materials and the final assembly of the product. It also encompasses the management of all manufacturing residues and waste generated during production.

In this study, due to the limited public availability of disaggregated data for specific raw material extraction processes, the A1-A3 modules were modelled as a single aggregated unit process. In this approach, transportation to the factory and the final assembly processes were derived from IEA and modelled at the foreground level. At the same time, for raw material supply (stage A1), the study relied on background data from the Ecoinvent database to bridge the data gap.

For the transportation phase of the production stage, it was assumed that solar cell manufacturing takes place in China. This reflects the industry standard of the 2000s, when cells were typically produced in Asia and then transported to Europe for final module assembly [13].

The transportation route was modelled in three sequential steps. First, solar cells were transported by ocean freight from Shanghai, China, to the Port of Rotterdam, the Netherlands, using IEA data for standard shipping distances. Second, from Rotterdam, the cells were transported by road to Bonn, Germany, where final module assembly takes place, with the road distance obtained from Google Maps. Third, transportation distances for the remaining components required for final assembly in Bonn were sourced from IEA standard distances. To reflect the historical context of this stage, Euro 3 vehicles were selected for road transport within Europe to align with the emission standards of that era. The specific distances used for the A2 stage are presented in Table 3.

Table 3. Transport distances for production stage (A2)

Components	**Transport**
Solar cell	Shanghai to Rotterdam, sea freight: 19994 km Rotterdam to Bonn, lorry: 286 km
Laminations	Freight, lorry: 600 km Freight, rail: 600 km

The life cycle of a c-Si solar cell begins with the extraction of silica from quartzite or quartz pebbles, which is then processed through carbothermic reduction in an electric arc furnace to yield metallurgical-grade silicon. To achieve the solar-grade purity necessary for high-efficiency cells, the material undergoes further refinement; while the Siemens gasification process remains the industry standard, other methods such as fluidised-bed reactors (FBR) or the upgraded metallurgical-grade (UMG) route are also employed. Following purification, the silicon is cast into multicrystalline ingots, which are precision-sliced into wafers and thoroughly cleaned. These wafers are then transformed into functional cells through a sequence of chemical and physical treatments, including surface texturing, doping, and etching. The process concludes with the application of conductive contacts, typically utilising aluminium for the rear surface and silver paste for the electronic connections [61]. However, to produce a ready-to-use PV module, several additional components and processes are still needed. Once the cell layer is prepared, individual cells are connected in series using tin-coated copper ribbons and lead-tin solder to form strings of solar cells. Additionally, the layering process takes place. First, a tempered low-iron glass is used for the front of the module. Next, a layer of EVA is applied as a transparent adhesive to bind the solar cell layer to the front glass. A backsheet layer, typically consisting of pressed layers such as polyvinyl fluoride (PVF) and polyethylene terephthalate (PET), is added and adhered to the cells using a second layer of EVA [40], [62]. Once the internal layers are laminated, the final assembly occurs. An aluminium frame is sealed to the lamination using silicone rubber, and a junction box is fixed to the back of the module as the final step. This box is constructed from injection-moulded thermoplastics, such as glass fibre-reinforced plastic (GRP) for the outer casing and contains copper wiring internally [7], [62].

Since this study models a PV representative of the early 2000s, a multi-Si solar cell with an efficiency of 13.5%, produced via the Siemens method, was selected in SimaPro. This dataset represents a unit process that encompasses the entire production chain of a solar cell and accounts for all inputs, waste, and emissions exchanged between the technosphere and nature.

The IEA database reports inventory data in different units, such as weight and area; therefore, two conversion factors were derived to express all material flows and energy inputs in the assessment's declared units. The parameters used to calculate these factors are summarised in Table 4.

Table 4. Conversion factors for scaling inventory data to the declared unit

Parameter	**Value**	**Unit**	**Source**
Module Efficiency	13.5	%	Assumption / Literature
Power Density	135	W_p/m^2	Calculated
Specific Mass (With frame)	13.2	kg/m^2	IEA
Area Scaling Factor	0.0074	m^2/W_p	Calculated (1/135)
Mass Scaling Factor	0.0978	kg/W_p	Calculated (13.2/135)

Based on these conversion factors, the material flows for the production stage were quantified per declared unit and are presented in Table 5. In addition, RER, GLO, and RoW dataset designations refer to European, global, and rest-of-world averages, respectively.

Table 5. Material flows for multi-Si PV module production stage (A1-A3)

PV components	Material flows	Weight per DU / (kg/W$_p$)
Frame	Aluminium alloy, AlMg3 {RER}| Cut-off, U	0.0158
Glass	Solar glass, low iron {RER}| Cut-off, U	0.0653
Interconnect ribbons	Copper, cathode {RER}| Cut-off, U Lead {RER}| Cut-off, U Tin {RER}| Cut-off, U	0.0008
Solar Cells	Photovoltaic cell, multi-Si wafer {RoW}| Cut-off, U	0.0036
EVA	Ethylvinylacetate, foil {RER}| Cut-off, U	0.0064
Backsheet	Polyethylene terephthalate, granulate {RER | Cut-off, U Polyvinylfluoride, film {RER} | Cut-off, U Polyethylene, HDPE {RER} | Cut-off, U	0.0027
Junction box	Glass fibre reinforced plastic, polyamide, injection moulded {RER}| Cut-off, U Silicone product {RER}| Cut-off, U wire drawing, copper {RER}| Cut-off, U Diode, market for diode {GLO}| Cut-off, U	0.0029

The electricity use for the lamination process, reported as 14 kWh/m² of module area, was normalised to the declared unit using the same scaling approach. The energy use is shown in Table 6. In addition, the database reports solid waste outputs generated during PV module manufacturing. These waste fractions were first summed on a mass basis, resulting in a total of 0.064 kg per m^2 of PV module. The value was subsequently normalised to the declared unit using mass scaling factor, resulting in a total manufacturing waste flow of 0.0063 kg/W$_p$.

Table 6. Energy input for the lamination process

Process	Energy use per DU / (kWh/W$_p$)
Electricity, medium voltage {ENTSO-E| Cut-off, U	0.1

2.2.7.2 Construction process phase (A4 - A5)

The construction process phase refers to the actions required after the product leaves the factory gate and enters the relevant market. In accordance with EN 15804, this phase includes two stages: A4, i.e., transportation of the product to the construction site, and A5, i.e., use of any energy, water, and ancillary materials during installation. All relevant activities between these two stages are included, such as product storage and the energy required for this scenario at storage, including heating, cooling, and humidity control. This phase also accounts for the additional manufacturing required to replace any products lost during these steps. Furthermore, the assessment includes the treatment of packaging waste from the transport stage. In this study, only transportation (A4) and packaging waste treatment (A5) were modelled. Storage energy, humidity control, and on-site energy use were excluded as no data were available, and their contribution was expected to be negligible relative to transportation.

For transportation, a EURO 3 vehicle was considered. The destination was assumed to be from Bonn to Malmö, with an additional 500 km added per the PCR recommendation for imported PV modules, which applies when the distance from the storage location to the relevant market is not specified. The total mass needed to calculate the transportation for the multi-Si PV module and additional packaging was extracted from the IEA inventory. The total mass was then scaled to the study's declared unit using the mass scaling factor and is presented in Table 7.

Table 7. Transportation data from the manufacturing gate to the relevant market (A4)

Product	**Transport**	**Total weight per DU / (kg/W_p)**
Multi-Si PV module	Bonn to Malmo, Freight, lorry: 810 km Standard distance, Freight, Lorry: 500 km	0.1
Corrugated board box {RER} | Cut-off, U		

For the installation stage, mounting materials, inverters, wiring, switches, battery banks, battery chargers, and all electrical components required to connect the PV module to the system, as well as personnel transportation and activities at the construction site, are excluded per PCR specification [59]. Packaging waste is assumed to be sent to municipal incineration for energy recovery, and no further waste is generated at this stage. The installation of the PV module is assumed to be carried out manually using screwdrivers, and the energy consumption for this activity was neglected.

2.2.7.3 End-of-life phase (C1 - C4)

EoL phase is the final stage of a product's life cycle, when it is considered waste after replacement, dismantling, or deconstruction. According to EN 15804 [56], this phase includes four different stages: module C1, which represents the dismantling, deconstruction, or demolition of the product, module C2, which covers the transportation of deconstructed products or materials from the site to waste treatment facilities, module C3, which includes waste processing for potential reuse, recovery, or recycling, and module C4, which represents the final stage for products or material fractions that are not reused, recovered, or recycled, including physical treatment and disposal site management.

The EoL stage was modelled separately for the recycling and reuse scenarios. The processes and input flows within the stages vary by scenario. Stage C1 is assumed to be identical and negligible in both scenarios, as modules are assumed to be dismantled manually in the same way as during installation in stage A5, with no energy or equipment use. Additionally, Euro 6 vehicles were selected for transportation related to stage C2 within Europe to align with the current emission standards.

In the recycling scenario, C2, C3 and C4 stages were modelled to represent the typical EoL treatment of the PV module, including transport, mechanical recycling, and final disposal.

C2, which includes the transport of the module to the recycling facility, was extracted from the PCR, which recommends considering 50 km if no specific recycling facility is known. A freight lorry was selected for this scenario, and the transportation weight follows the assumptions in stage A4, excluding packaging from the total mass. For stage C3, mechanical recycling was selected as the state-of-the-art approach for current recycling practices, as the scenarios considered for waste processing should be realistic in terms of their economic and technical feasibility, in accordance with EN 15804+A2. The data and information needed for this stage were obtained from the IEA [39].

The recovery rates were obtained from a separate IEA database than the one used for the manufacturing stage (A1-A3). The database represents a mechanical recycling facility for c-Si PV modules with a nominal treatment capacity of 4 200 tonnes of PV waste per year, where recovered outputs are reported as percentages of the total incoming module mass.

Since the recycling inventory was developed independently of the manufacturing inventory, the reported recycling outputs were not directly linked to the production inventory presented in the manufacturing stage in section 2.2.7.1. To bridge the two inventory models within the same framework, the reported output fractions were converted to kg/W_p using the mass scaling factor derived from the manufacturing inventory, as presented earlier in section 2.2.7.1.

The normalised output flows were subsequently assigned to EoL scenarios based on the nature of each fraction and the conditions set by EN 15804. Aluminium and glass fractions were linked to material recycling processes, where the fraction is processed into a secondary material and reaches the end-of-waste state. Polymer fractions, mainly representing EVA and backsheet materials with the solar cell layer within, were directed to incineration for energy recovery, as these materials were assumed to meet the EN 15804 requirement that energy recovery credits are only assigned where the recovery process exceeds 60% efficiency. Dust fractions were assigned to landfill disposal and accounted for in stage C4. The remaining fractions were directed to municipal incineration without additional credits in stage D. This assumption was made because the recycling database does not provide sufficient detail for these streams, which makes individual substitution modelling uncertain, and because their heating value and recovery efficiency could not be confirmed to meet the 60% threshold required by EN 15804.

The selected routes for aluminium, glass, and polymers together account for approximately 89.5% of the total reported recycling output, while the remaining fractions directed to incineration without credit may result in an underestimation of the potential environmental benefits of the mechanical recycling scenario. Fractions reaching the end-of-waste state through either material recovery or energy recovery are credited in stage D, and the detailed output flows and assumed scenarios for each fraction are shown in Table 8.

Table 8. Recovery fractions and assumed end-of-life scenarios for mechanical recycling (C3-C4)

Material	**Recovered output / %**	**Output flow / (kg/W_p)**	**Assumed scenarios**
Aluminum frame	11.5	0.0112	Recycled
Glass	64	0.0625	Recycled
Polymers	14	0.0137	Energy recovery
Ferrous metals	0.2	0.0002	Incineration
Non-ferrous metals	1.2	0.0012	Incineration
Junction box	0.35	0.0003	Incineration
Cables	0.65	0.0006	Incineration
Mixture of glass, foil and metals	6.6	0.0064	Incineration
Dust	1.5	0.0014	Landfilled
Total	100	0.097	-

For this mechanical recycling process, an electricity consumption of 60 kWh/tonne is reported in the source. This was scaled to the declared unit by multiplying by the mass scaling factor and dividing by 1000 kg/tonne, resulting in the energy use shown in Table 9.

Table 9. Energy input for the mechanical recycling process

Process	**Energy use per DU / (kWh/W_p)**
Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U	0.0054

In the reuse scenario, the EoL stage includes pre-processing activities required before the PV module's second-life use. This approach is interpreted within the EN 15804 framework, using its own principles for the EoL phase, particularly the polluter-pays principle and the concept of the end-of-waste state.

The EoL stage begins when a product no longer delivers its intended function. At this point, all outputs from deconstruction and associated processes are first considered as waste. The polluter-pays principle states that responsibility for waste processing remains with the system that generated the waste until the end-of-waste state is reached [56]. This reflects the fact that reused modules are not immediately considered as products suitable for reuse but must first undergo testing procedures to verify their suitability for second-life use. These processes are therefore included within the EoL stage of the system boundary.

A freight lorry was considered for transportation in Stage C2, a distance of 100 km to the testing and sorting facility and an additional 50 km from the facility to the reuse site was assumed. Packaging is included in the transport mass in this scenario, as modules are assumed to be repackaged for redistribution to the second-life site, unlike in the recycling scenario, where modules are transported as loose waste.

Stage C3 of this scenario includes the testing procedures. During the literature review five testing approaches were identified that are described in 3.2 and among these various tests, only electroluminescence (EL) testing is identified as having considerable energy use. The EL testing process involves powering the module until it reaches thermal saturation. Based on the literature, this process takes 30 minutes and requires an electrical power supply of 264 W/m² [63]. To include this data in the LCI, the process energy was first calculated in kWh/m² and then scaled to the study's declared unit using the area conversion factor, and the result is shown in Table 10.

Table 10. Energy input for electroluminescence testing

Process	**Energy use per DU / (kWh/W$_p$)**
Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U	0.001

It should be noted that the source used a mono-Si PERC module for this measurement. Since PERC is a cell architecture applied to both mono and multi-Si technologies, and the study does not specify which variant was tested, it was assumed here to represent a multi-Si configuration for consistency with the rest of the model.

2.2.7.4 Benefits and loads beyond the system boundary (stage D)

Benefits and loads beyond the system boundary, or stage D, provide information on the environmental burdens and benefits resulting from reusable and recyclable materials and energy recovery, leaving the product's system, which typically result in a negative flow.

This stage only accounts for and receives credit when the output flows reach the end-of-waste state. To reach the end-of-waste state, flows leaving the product's system must comply with the following criteria, in accordance with EN 15804. The end-of-waste state is reached when a recovered output has an identified downstream application, satisfies the technical and regulatory requirements for that application, has positive market value, and does not pose environmental or human health risks. Only once these conditions are met can the output be considered a product rather than waste, and credited as a benefit in stage D [56].

The same regulation also acknowledges that the waste state ends for the considered material or product, as it provides a useful output under these conditions. Furthermore, this useful output can be calculated as a potential benefit to the system under study, where the output flow that has reached the end-of-waste state, such as secondary material or recovered energy, substitutes another material or energy in the following product system. The standard specifies that, this benefit as an avoided environmental burden, should have a defined scenario and should be based on average current technology and practices. Additionally, the substitution should maintain functional equivalence between the materials, and if the output flow does not meet that equivalence, a value-correction factor should be applied.

In this study, stage D was also modelled separately for the reuse and recycling scenarios, reflecting the different approaches used to avoid the burdens. The following sections describe the modelling approach applied to each scenario.

In the recycling scenario, recovered glass and aluminium were considered for material substitution, while the remaining fractions were directed to incineration for energy recovery. For material recovery, the outputs from mechanical recycling were modelled as secondary materials available for substitution. As described, such processes often result in downcycling, where recovered materials are used in alternative applications, such as glass cullet used in insulation or foam production [62]. Given the absence of detailed data on the exact quality and applications of these secondary materials, no additional value-correction factor was applied; instead, representative secondary material datasets from Ecoinvent were used directly to model the substitution in SimaPro and shown in Table 11. In terms of energy recovery, only materials that have an efficiency rate of 60% can be approved as suitable for energy recovery, and their waste state ends [56]. In essence, the materials must achieve an energy recovery rate exceeding 60% of their heating value [64].

Table 11. Inputs for stage D of recycling scenario

Material	**Recovered flow / (kg/W_p)**	**Secondary application**
Aluminium frame	0.0112	Aluminium scrap
Glass	0.0625	Glass cullet
Polymers	0.0137	Electricity grid

For this study, stage D credit for energy recovery was applied only to polymers that are primarily encapsulant and backsheet layers, as these materials meet the required efficiency threshold, and the resulting energy is assumed to be fed into the electricity grid. No credit was given to other materials sent for incineration to account for uncertainty in their efficiency rates and to avoid overestimating the environmental benefits.

In the reuse scenario as discussed, no standardised framework was identified for modelling the reuse scenario for stage D, specifically for calculating avoided burdens. However, the general principles defined in EN 15804 can be applied to a given scenario by considering product-level substitution. In the reuse scenario, environmental benefits beyond the system boundary were modelled by assuming that the reuse of a PV module avoids producing a new module for the following application within the system boundary of this study. In essence, if reuse did not occur, a new PV module would be required to provide the same function.

To represent the substituted product and current average technology, the manufacturing stage of a mono-Si PV module was considered. The same inventory structure described in section 2.2.7.1 was applied for the mono-Si module and is therefore not repeated here, instead, is reported in Appendix A. Since the selected IEA datasets report identical material inventories per unit area for both mono-Si and multi-Si technologies, the same area-based inventory structure and foreground modelling assumptions were applied in this section. However, due to the different power density assumptions applied for the modules in this study that are 224 W_p/m^2 for mono-Si and 135 W_p/m^2 for multi-Si, the normalised inventory values per declared unit differ between the two models.

Since a reused module does not perform at the same level as a newly manufactured one, a value-correction factor of 0.88 was applied to the mono-Si model output in SimaPro to account for the reduced functional output of the aged multi-Si module relative to a new mono-Si module. This factor was derived by applying the Swedish module-level degradation rate of 0.5% per year over a 25-year first-life service period that is described in section 3.3, resulting in a remaining performance of 87.5%, rounded to 88%. Accordingly, the reuse scenario was assumed to avoid 88% of the environmental impacts associated with manufacturing new mono-Si PV capacity under the declared unit framework. The other two degradation rates were not considered for this value-correction factor: the second Swedish field study reported a total decrease over 21 years, with the first five years of data unavailable, making it less suitable as a consistent annual rate; and the third study represented a global average in which hot and humid climates were also included, meaning it was not representative of Swedish or cold temperate conditions.

2.2.8 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is the third phase of an LCA. In this phase, the environmental impact categories are assigned to LCI inputs and outputs to assess their contribution to each environmental consequence caused by the system under study. The core environmental impact categories were selected for this stage in accordance with EN 15804 [56], and are described in Table 12.

Table 12. Environmental impact categories in accordance with EN 15804+A2, with description adapted from [65].

Impact category	**Unit**	**Name**	**Description**
AP	mol H^+ eq.	Acidification Potential	Causes the degradation of coniferous forests and increased fish mortality through the deposition of these emissions in soil and water bodies. Driven by acid-forming emissions released through combustion processes in electricity generation, heat production, and transportation.
GWP - Total	kg CO_2 eq.	Global Warming Potential	Potential increase in the average global temperature due to the combustion of fossil fuels such as natural gas, oil, and coal.
GWP - Fossil			
GWP - Biogenic			
GWP - land use and land use change (LULUC)			
ODP	kg CFC 11 eq.	Ozone depletion potential	Causes risks to both human health and ecosystems, including a rise in skin cancer incidence and adverse effects on plant life, driven by the depletion of the ozone layer, which increases harmful ultraviolet radiation (UV-B).
EP - fresh water	kg P eq.	Eutrophication potential for fresh water, marine and terrestrial	All occur when excessive nitrogen or phosphorus compounds are introduced into ecosystems, accelerating algal overgrowth and disrupting ecological balance. Driven by sewage treatment, agricultural runoff, agricultural fertilisers and combustion processes.
EP - Marine	kg N eq.		
EP - Terrestrial	mol N eq.		
POCP	kg NMVOC eq.	Photochemical ozone creation potential	Unlike stratospheric ozone, which serves a protective function, ground-level ozone present in the troposphere is harmful to both living organisms and ecosystems. Causes degradation of organic compounds in animals and plants and contributes to the formation of photochemical smog (Summer smog), increasing the incidence of breathing problems in urban populations.
ADP - Mineral & Metal	kg Sb eq.	Depletion of natural fossil reserves, minerals and metals	Cause scarcity of finite resources for future generations and force them to rely on lower-grade or lower-value reserves. Driven by the extraction of non-renewable energy resources such as coal, oil, and natural gas, and the extraction of high-concentration mineral and metal deposits.
ADP - Fossil	MJ		
WDP	m^3	Water depletion potential	Causes water scarcity by depleting available freshwater resources through extraction from lakes, rivers, or groundwater reserves.

2.2.9 Life cycle interpretation

The final phase of an LCA is the interpretation of findings from the inventory analysis and the assessment of the environmental impacts resulting from the system under study. This phase helps to conclude, which may lead to recommendations and facilitate decision-making [53].

2.3 Limitations

When interpreting the results of this study, several limitations should be taken into account:

- The study adopts the EN 15804 framework, which does not provide an explicit procedure for modelling PV module reuse. The reuse scenario in stage D was therefore constructed by applying the standard's substitution principles at the product level, treating the reused module as a substitute for producing a new module, which represents an interpretation rather than a defined process within the standard.

- Due to the limited availability of specific manufacturing data, the life cycle inventory is based on literature sources and secondary datasets. As the LCA input is data-sensitive, the results may not fully represent manufacturing processes.

- This study did not include a detailed sensitivity or uncertainty analysis due to time and resource constraints. Therefore, the results should be interpreted as scenario-based estimates rather than definitive outcomes.

- Due to the limited public availability of disaggregated data for specific raw material extraction processes, the A1 stage relied on background data. Transportation distances of materials to the factory and final assembly processes (A2-A3) were derived from secondary database as standard distances, and typical manufacturing processes of c-Si PV modules. These modelling choices introduce uncertainty at the inventory level.

- The inventory for both multi-Si and mono-Si modules was derived from secondary database, which reports identical material quantities per unit area for both technologies. While this is consistent with the source data used in this study, actual mass may vary between module technologies and manufacturers, meaning the inventory may not fully reflect the material reality of every decommissioned module entering the EoL stream.

- Thermal and chemical recycling processes offer higher material recovery rates and greater environmental credits, sufficient LCI data for these pathways were not available to include them in the model. As a result, the environmental benefits associated with advanced recycling are not captured in this study, which may lead to an underestimation of potential stage D credits in the recycling scenario.

- Stage D credit for energy recovery of recycling scenario was applied only to polymers, specifically the encapsulant and backsheet layers, as these materials meet the required energy recovery threshold, and the resulting energy is assumed to be fed into the Swedish electricity grid. No credit was given to other materials sent for incineration, to account for uncertainty in their heating value and to avoid overestimating the environmental benefits.

- The value-correction factor applied in stage D to account for the reduced functional output of the reused module was derived from a Swedish field degradation rate of 0.5% per year over a 25-year first-life period. The substituted product was assumed to be a new mono-Si module representing current average technology. However, in practice, a reused module may substitute a range of applications and system types where the performance benchmark differs, meaning the avoided burden in stage D is sensitive to both the assumed degradation rate and the choice of substituted product, introducing uncertainty into the reuse scenario's environmental credit.

- The assessment of reuse feasibility is based on literature-derived degradation mechanisms and does not include experimental validation or field testing of modules. Therefore, the actual suitability of individual modules for reuse may vary.

- This study is limited to environmental assessment using LCA and does not include a life cycle cost analysis. The economic feasibility of reuse and recycling, therefore, remains outside the scope of this work and represents an area for further research.

- The results are scenario and mostly assumption-specific and should not be generalized to all PV systems without considering differences in technology, climate, and system configuration.

3 Results

This section presents the findings of the study in two parts. The first part reports the outcomes of the literature review, covering the degradation mechanisms identified in field studies, establishing a reuse criterion based on mechanisms, and the module-level degradation rates reported for c-Si PV systems, with particular focus on Swedish field data. The second part presents the LCA results, including normalisation and global warming potential analysis for the reuse and recycling scenarios.

3.1 Degradation mechanism

PV modules are generally designed to operate under varying environmental conditions because the module's core, or solar cells, is placed between several protective layers. However, PV modules are continuously subjected to a combination of environmental stressors, including UV radiation, thermal cycling, humidity, and mechanical loads from wind and snow [66]. The cumulative effect of these stressors typically results in a decline in the module's performance over time, known as degradation. Degradation is typically defined as the “gradual deterioration of the characteristics of a component or system, which may affect its ability to operate within the limits of acceptability criteria and which is caused by operating conditions” [67].

Previous studies in this field that investigated this phenomenon and collected data from outdoor exposure observations have shown that degradation mechanisms vary across different climates, and environmental conditions can dictate the failure modes of PV modules. Research indicates that in snowy or polar regions, mechanical loads from wind and heavy snow are the leading causes of physical damage, specifically solar cell cracks, bent frames, and front glass breakage [68]. At the same time, encapsulant discolouration (browning and yellowing) results from exposure to intense UV radiation and high operating temperatures [69]. The differences between types of this phenomenon become more apparent when the nature of PV module degradation is examined. PV modules over their lifetime experience three phases: “infant mortality,” “intrinsic” or “midlife” failures, and “wear-out” failures, in terms of durability and reliability [70], [71]. Durability is defined as “the ability of a product to perform its required function over a lengthy period under normal conditions of use without excessive expenditure on maintenance or repair”, and reliability can be defined as “the measure of unanticipated interruptions during customer use” [71], [72]. In the meantime, these two share the same phases, but their behaviours differ slightly.

The first phase is the “infant mortality”, this early-stage failure in PV modules typically happens due to defects that occur during the manufacturing process, as well as damage that arises during transportation, and installation, which can result in breakage of glass or solar cells, meaning that some PV modules do not even reach operation. Therefore, failure rates are typically high during this phase [73], [74]**.** In terms of power loss, this can occur within the first year of operation, when the power output decreases rapidly due to the module's initial exposure to the environment, triggering Light-Induced Degradation (LID). However, this does not result in permanent failure; after the initial power loss, performance stabilises [48]**.**

The second phase is the “intrinsic” or “midlife failure”. In this phase failures are typically random and may result from internal defects in metallization and interconnections, component failures in the junction box or bypass diodes, or failures from sudden environmental events, such as lightning strikes and hailstorms. There, PV modules typically experience gradual degradation mechanisms including glass coating degradation, encapsulant discolouration, delamination, cell cracks, potential-induced degradation (PID), bypass diode failure, and interconnection degradation, all of which generally result in an almost linear and steady power loss that continues until the wear-out phase [48], [70], [74], [75], [76].

The final stage of a module’s operational life is known as the “wear-out” phase. During this period, operational life is typically deemed at an end when a critical safety risk is identified or when the electrical output diminishes past a standard benchmark, generally 70% to 80% of the module’s initial rated power. Unlike the relatively stable midlife period, the wear-out phase is marked by an increase in the activity of existing degradation mechanisms, resulting in non-linear power losses and an increased probability of total system failure [48], [77]. These three phases together form what is known as the “bathtub” curve [74]. The simplified schematic of this curve is illustrated in Figure 9.

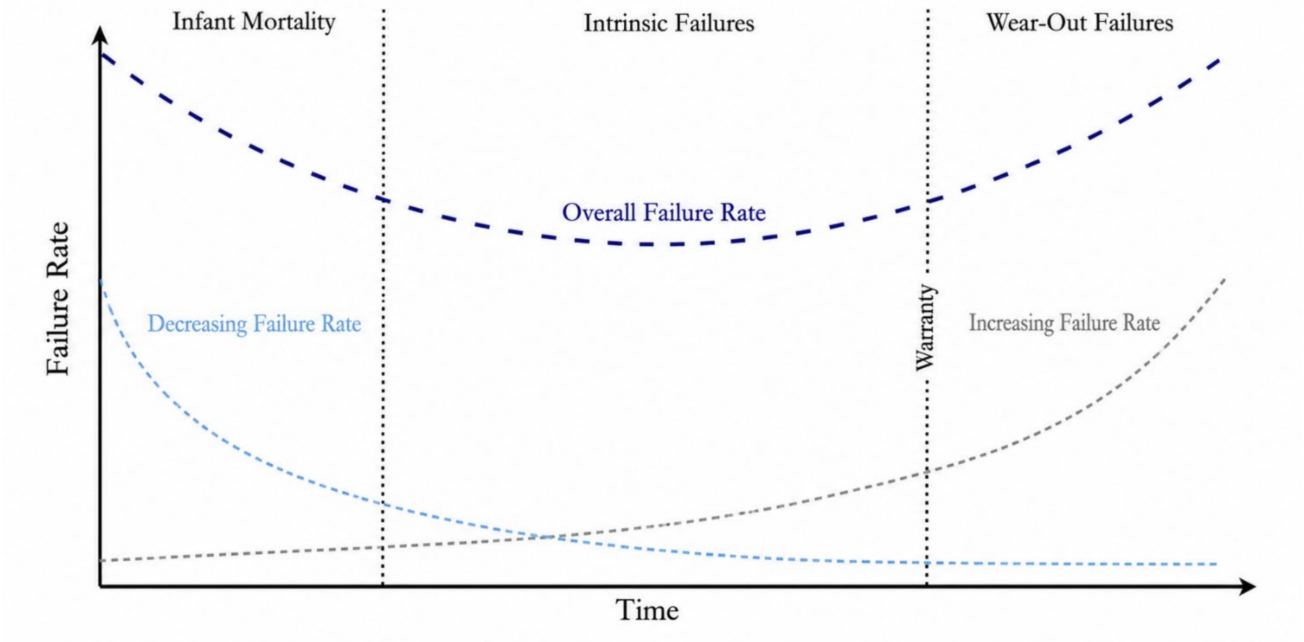

Figure 9. Simplified schematic of the PV module "bathtub" curve. Adapted by the author from [74]

3.2 Reuse criteria

Drawing on the lifetime phases described in previous studies, it becomes possible to differentiate between modules that may still be suitable for reuse and those that should instead be directed to recycling. Since the wear-out phase typically occurs through the gradual increase in degradation mechanisms during midlife operation, modules that have already passed the infant phase are the most suitable candidates for reuse. However, this does not mean that all modules in their midlife are automatically suitable for such applications.

Modules experiencing a stable, gradual performance decline may still maintain sufficient functionality to continue operating. In other cases, certain degradation mechanisms may already be accelerating performance loss or increasing the probability of failure, even if the module has not yet reached the wear-out stage in terms of age. Such modules may pose a higher risk of failures during their second life. Therefore, considering these active degradation mechanisms during the midlife phase is important for modules that should be excluded from reuse criteria before their condition worsens further. The following mechanisms are typically observed during the midlife phase: glass coating degradation, encapsulant discolouration, delamination, cell cracks, potential-induced degradation (PID), interconnection degradation, and failures involving the junction box [70].

EVA discolouration is common in c-Si PV modules and is caused primarily by continuous exposure to ultraviolet (UV) radiation and high temperatures. EVA is widely used as an encapsulant due to its strong adhesion to glass and backsheet, weather resistance, and high light transmittance. However, as this material is positioned between the front glass and the cells, its degradation has a direct impact on energy yield. Research indicates that continuous exposure to high operating temperatures and UV radiation triggers a chemical shift in the EVA, causing it to lose its initial transparency. This transition which visually progresses from yellowing to a dark brown state creates an optical barrier that limits light transmittance, resulting in performance declines due to optical losses [67], [78].

Delamination refers to the separation between module layers, particularly between the polymer-glass interface and the backsheet. Moisture infiltrating the module is typically what drives this degradation phenomenon, which increases the likelihood of hotspots. The ingress and accumulation of moisture resulting from delamination can further accelerate degradation processes, including the corrosion of metal components and metallisation layers, such as interconnectors within the affected areas [79], [80].

Cell cracks are a degradation issue that can occur at different stages during the operational lifetime of PV modules. One of the primary causes stems from the production phase, where operations such as soldering may apply too much mechanical stress to the solar cells. Cracks may also develop further due to additional mechanical agitation during transport or operational stresses under extreme weather loads, such as snow and wind [78], [80].

Interconnector degradation in PV modules affects both electrical performance and reliability. While multiple solder bonds are used in a PV module, the failure of several bonds increases power losses and localised heating, which can lead to further solder degradation. Common failure modes include solder bond issues, cell cracks, and physical or chemical decay of the ribbons. These defects are mainly caused by thermal and mechanical stresses during soldering, as well as by improper joint design or poor solder compatibility, which lead to increased series resistance and reduced module performance [25].

The aforementioned degradation mechanisms can drive the module into the wear-out phase. However, other mechanisms can go beyond performance loss and can pose direct safety risks that are critical to identify before any reuse decision is made.

Glass breakage is the clearest example of this principle. This failure can lead to performance loss over time by providing a pathway for moisture and oxygen to reach the laminate's interior, causing corrosion of the cells and interconnectors. Glass fractures can also trigger the formation of hotspots and potentially cause parts of the PV module to burn, while during a rainstorm the module may lose its insulation properties [48].

Potential-induced degradation (PID) is considered one of the more severe degradation mechanisms affecting PV modules because leakage currents can develop between grounded module frames and solar cells under high potential differences. Studies have shown that long-term outdoor exposure can increase the likelihood of PID, particularly when modules already exhibit other degradation phenomena, such as cell cracking, bypass diode failure, or encapsulant deterioration. These interacting failure mechanisms may further affect module reliability and electrical safety, and could lead to fire risks from electrical arcs, short circuits, and hotspots [66], [78].

Fractures in the backsheet layer are also hazardous, as these defects allow moisture to penetrate the module's interior, gradually degrading its insulation properties. A study has shown that this loss of insulation can contribute to system-level failures, including ground faults and inverter malfunctions and, in severe cases, may lead to burning of affected areas or even module combustion [81]. Moreover, backsheet integrity is vital because its failure can exacerbate internal issues. When the layer cracks, moisture can reach the sensitive internal circuits, accelerating the progression of existing problems such as corrosion, delamination and PID. This is more than a performance issue and constitutes a primary safety hazard, as compromised insulation can lead to dangerous leakage currents and accidental electrocution [82].

Failures involving the junction box are particularly critical because they often progress internally without immediate visual indicators until a hazardous event occurs. Studies indicate that deterioration of the adhesive bond between the junction box and the backsheet can result in complete separation of the housing, exposing high-voltage internal conductors to environmental elements. Furthermore, the failure of integrated bypass diodes presents an additional safety threat, as these components can undergo thermal runaway or arcing when compromised [66], [70]. In summary, the high electrical current passing through the junction box components means that any degradation in these components poses a safety risk.

To identify which modules fall within the reuse criteria, a testing process is typically required, as not all failures are immediately visible, and not all performance losses affect reliability in the same way. The testing procedures used for this purpose relate directly to the degradation and failure mechanisms discussed earlier, and together, these assessments provide a basis for deciding whether a module remains suitable for reuse. Five testing approaches are commonly reported for this purpose.

Visual inspection functions as a preliminary triage to immediately disqualify modules with catastrophic failures such as shattered front glass, damaged backsheet, or failures in junction box, and direct them toward recycling. By focusing only on these critical, severe defects, inspection time can be reduced, ensuring that no further labour is wasted on non-viable units [16].

Insulation resistance testing applies a DC voltage to measure the resistance of the module’s insulation under various load conditions to prevent the risk of fire or electric shock in its second life. Because safety is the primary rejection criterion, an insulation-resistance failure results in immediate recycling, regardless of the module's power output [16].

Thermal imaging maps the distribution of operating temperature across the module at the cell level, which cannot be identified by the naked eye, detecting hotspots that indicate bypass diode failures, resistive interconnectors, or cell damage. It can be performed using a handheld infrared camera for module-level analysis or a drone-mounted camera for system-level mapping [83].

Current-voltage (I-V) curve measurement is used to determine a module’s state of health. Researchers trace the module’s current-voltage relationship to calculate the remaining maximum power output. While laboratory flash testing is the gold standard, outdoor field measurements conducted are also increasingly used as a cost-effective alternative for large-scale decommissioning [16]. Finally, comparing the measured output against the module's original nameplate power output sets the primary basis for confirming performance suitability for second-life approval.

Electroluminescence (EL) imaging is a final predictive measure. EL imaging provides an X-ray view of the cells by applying a forward bias and capturing the emitted near-infrared light. This is the only reliable method for detecting underlying microcracks that might not yet affect but pose a high risk of rapid degradation or failure in the future. Researchers suggest that the high labour cost of manual EL analysis can be mitigated by using AI and machine learning for automated defect classification [16].

The testing procedures established in this section provide the practical means for applying the exclusion criteria. Since this study does not specify the ages of the modules under assessment, the criteria are designed to apply to modules across all three life phases. Modules presenting midlife degradation mechanisms that show signs of accelerating toward wear-out, modules already in the wear-out phase, and modules showing safety failures are all directed to recycling. Those that pass the full testing procedures are considered suitable for reuse and are then subjected to performance-based evaluation in this study.

3.3 Degradation rate

Passing the tests shows that a module does not pose a safety issue or failure and can therefore be considered a potential candidate for reuse. However, it does not mean that the module has retained its original performance. Like all operating PV modules, it continues to experience gradual degradation over time, and some performance loss persists even when the module remains functional. Quantifying this remaining decline is important for estimating how much useful output the module can continue to provide in a second-life application. This is commonly evaluated through degradation rates and will be discussed in the following section. As established, degradation mechanisms differ depending on the climate in which the PV modules operate; this phenomenon often leads to a decline in performance over time, which is defined as a rate expressed as an annual percentage.

Among the degradation rates reported in the literature, some are measured at the system level and others at the module level. The differences become more apparent when the reported rates are compared. For instance, in one study conducted in Utah, USA, degradation rates per module were reported to be 0.5%/year, whereas the same rate was reported to be 2.5%/year at the system level for c-Si modules [84].

This difference between system-based and module-level degradation rates can be due to the presence of BoS components at the system level, where losses from components such as inverters can affect overall system performance. Another contributing factor is mismatch; this phenomenon can arise from module-level problems, as PV modules do not degrade at the same rate or through the same mechanisms, thereby affecting the entire string in system-level measurements [85]. A mismatch can also result from several other factors, such as shading from direct sunlight, degradation of the glass coating, glass breakage, or soiling, which prevent solar rays from passing through the glass and generating the intended electricity output [70]. It is also reported that this could result from other, more severe degradation mechanisms, such as cell cracking, encapsulant discolouration, and delamination [69], [78].

I-V tracing of individual modules was identified in the reviewed literature as the primary method for calculating module-level degradation rates. While I-V curve measurement was introduced earlier as part of the testing process for reuse approval, it also serves as the main method for estimating module degradation rates. Here, the focus is on how the power output declines throughout the operational lifetime and how exactly it can be measured.

IV tracing can be an ideal method for identifying module-level defects, as it allows different degradation mechanisms to be traced by isolating three key electrical parameters of the PV module, such as the short-circuit current (I_{sc}), representing the module's maximum current output; the open-circuit voltage (V_{oc}), representing the maximum voltage the module can generate; and the maximum power point (P_{max}), which defines the peak power output of the module [86], [87]. Studies on c-Si PV modules, for instance, have shown that power degradation is driven primarily by losses in short-circuit current rather than other I-V curve parameters. These losses are frequently linked to encapsulant-related issues such as yellowing/browning and delamination between the cells and the EVA layers, along with mechanical damages like glass breakage. I-V curve analysis often reveals rising series resistance caused by failing interconnectors and solder joints [87].

This method can be conducted under either outdoor or indoor conditions. However, both methods should follow the Standard Test Conditions (STC) described in section 1.2.2. In both cases, a measurement setup typically requires controlled illumination, temperature control, and instrumentation capable of recording electrical performance. During the measurement, an external load or power supply is used to vary operating conditions while the corresponding current-voltage response is collected and analysed [48]. Each condition, however, differs in its approach and equipment as outlined below.

Outdoor measurements typically utilise portable I-V tracers and pyranometers to capture data under natural sunlight. However, because field conditions rarely align perfectly with STC, researchers must apply mathematical corrections to the resulting curves to account for fluctuations in temperature and irradiance. In contrast, indoor testing using solar simulators offers precision. By employing reference modules with matched spectral responses and maintaining a strictly regulated environment, the transition of measured electrical parameters to STC can be achieved with higher accuracy. The results are also compared with the module's nameplate power [48]. Given these findings, two Swedish field investigations that assessed the degradation rates of c-Si PV modules using outdoor I-V tracing, and one global meta-analysis were identified as global representative and selected for further analysis.

In the first study, a 3.2 kW_p grid-connected PV system installed in 1994 on the rooftop of Dalarna University in Borlänge, Sweden, was examined. The system consists of 72 crystalline silicon PV modules manufactured in 1992, each with a rated power output of 45 W. I-V tracing was conducted at two time points in 2016 and 2024 using a handheld I-V tracer, with a minimum irradiance of 800 W/m^2 and an irradiance fluctuation of no more than ±1%. The results were then compared to the nameplate capacity of the modules from 1992. The period between 1992 and 1994 was excluded from the measurements because the PV modules were not yet operational and were stored in a warehouse. Furthermore, this study reported an average annual degradation rate of 0.5% [88]. It should be noted that the source does not explicitly clarify the reason for initially reporting 72 modules, even though measurements were applied to only 53 modules. Based on the available information, it can be inferred that, because the system changed in 2013 and 2014, during which additional modules were integrated into the existing array, the study likely considered only the original 53 modules installed in 1994. However, this is not explicitly stated in the source and remains the author's interpretation.

In the second study, the first Swedish PV system, consisting of 20 c-Si modules was examined. The system was originally installed in 1981 on the façade of a building in Årsta, south of Stockholm. After six years of operation, the system was dismantled and reconfigured in 1988 as a stand-alone system in Stockholm. In May 2006, after 25 years of outdoor exposure, the modules were dismantled once more as the island became connected to the mainland electricity grid. The performance of the modules was assessed by comparing the 1985 and 2006 I-V curve testing. Visual inspection of the remaining modules revealed only gradual degradation mechanisms, such as interconnector corrosion and encapsulant bubbling, with no cracked cells and only one instance of minor delamination. Further, the study revealed a 3.8% performance loss over 21 years, corresponding to an annual degradation rate of approximately 0.17%/year [89].

In the third study, conducted by NREL, a meta-analysis of nearly 2 000 individual degradation rates was performed and reported, drawing on the global literature from field testing over the preceding 40 years. To identify trends, the researchers partitioned the data by technology type, distinguishing between c-Si and thin-film technologies. The analysis revealed a global median degradation rate of 0.5%/year and an average rate of 0.8%/year. Ultimately, the study concluded that current field experience supports typical 25-year commercial warranties, as the average degradation rate is generally sufficient to ensure reasonable performance throughout the module's intended service life [84]. The performance curves for these three degradation rates are shown in Figure 10. Based on the degradation rates identified through this review, a module that has completed a 25-year first-life service period under the Swedish rate of 0.5%/year is assumed as the representative input for the LCA conducted in the second phase. This assumption reflects the Nordic field context of the study and results in a remaining performance of 87.5% relative to the original nameplate capacity.

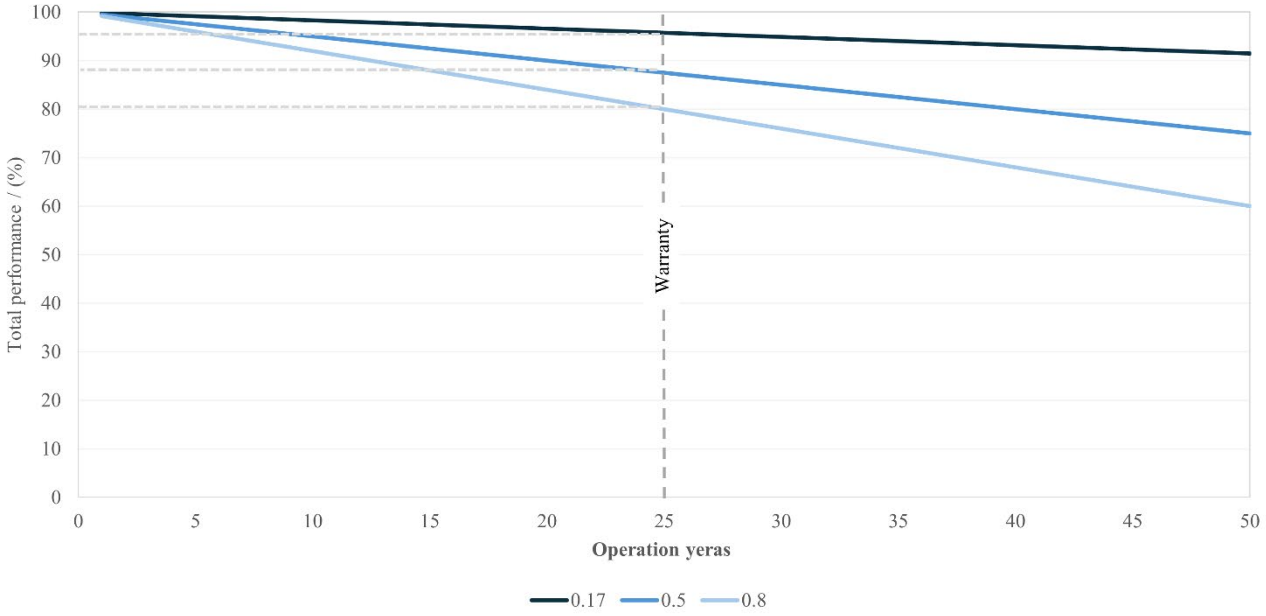

Figure 10. Three degradation rates and their respective performance decline over time.

The degradation rates and performance thresholds identified in this review form the basis for the reuse scenario modelled in the following LCA, which evaluates the environmental impacts of reuse and recycling.

3.4 LCA

As each life cycle stage addresses different phases, each life cycle impact categories also address distinct burdens. To report the results for the core environmental impact categories required by EN 15804+A2, a normalisation approach by following ISO 14044 was applied. Since each impact category is measured in a different unit, numerical comparison across categories is not directly possible. Therefore, within each impact category, the life cycle stage with the highest environmental impact was identified and assigned a reference value of 100%, with all other life cycle stages expressed as percentages relative to this reference. In addition, Global Warming Potential (GWP) was selected as an additional basis for analysing the results in a more direct manner. While this normalisation approach is outlined in the ISO standard, its application in this study was first inspired by another study [90]. All results are expressed based on the declared unit of the study, namely 1 W_p.

3.4.1 Normalisation

Figure 11 shows the normalised environmental impact contributions of the production and construction process stages (A1-A5) across all 13 impact categories. The manufacturing stage (A1-A3) dominates across all categories, reflecting the energy-intensive nature of solar cell production, and module assembly. Transport to the market (A4) represents the second-highest contributor in most categories, while installation-related activities (A5) contribute the smallest share. One exception is the GWP biogenic category, in which both A1-A3 and A4 are assigned a value of zero. This is because packaging materials such as corrugated board that is used in the inventory contain biogenic carbon, which is sequestered during the growth of the source material and is therefore reported as a negative value in stages A1 to A4. Once the packaging is incinerated at stage A5, this stored carbon is released as CO_2 and recorded as a positive biogenic emission, making A5 the sole contributor to this category.

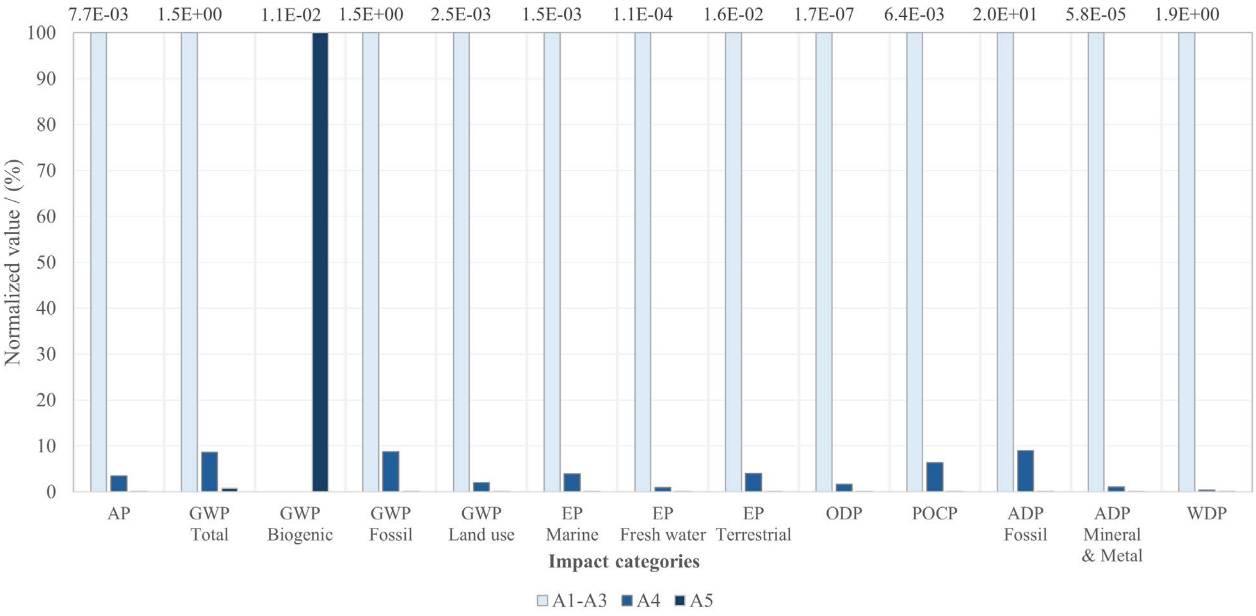

Figure 11. Normalised environmental impact contributions of the production and construction process phases (A1-A5) across 13 impact categories

In Figure 12, which represents the EoL phase for the recycling scenario, transportation is the driving factor, contributing to 8 of 13 environmental impact categories, underscoring the importance of distance and vehicle type. On the other hand, waste processing, where recycling activities such as mechanical recycling and incineration for energy recovery take place, accounts for the remaining five impact categories. Waste processing makes the largest contribution in the GWP biogenic category, here due to the presence of the backsheet and the stored carbon it contains, which is released during incineration. Disposal is relatively low compared to other stages, as most materials are either recycled or recovered for energy, which results in the distribution of impacts across prior stages.

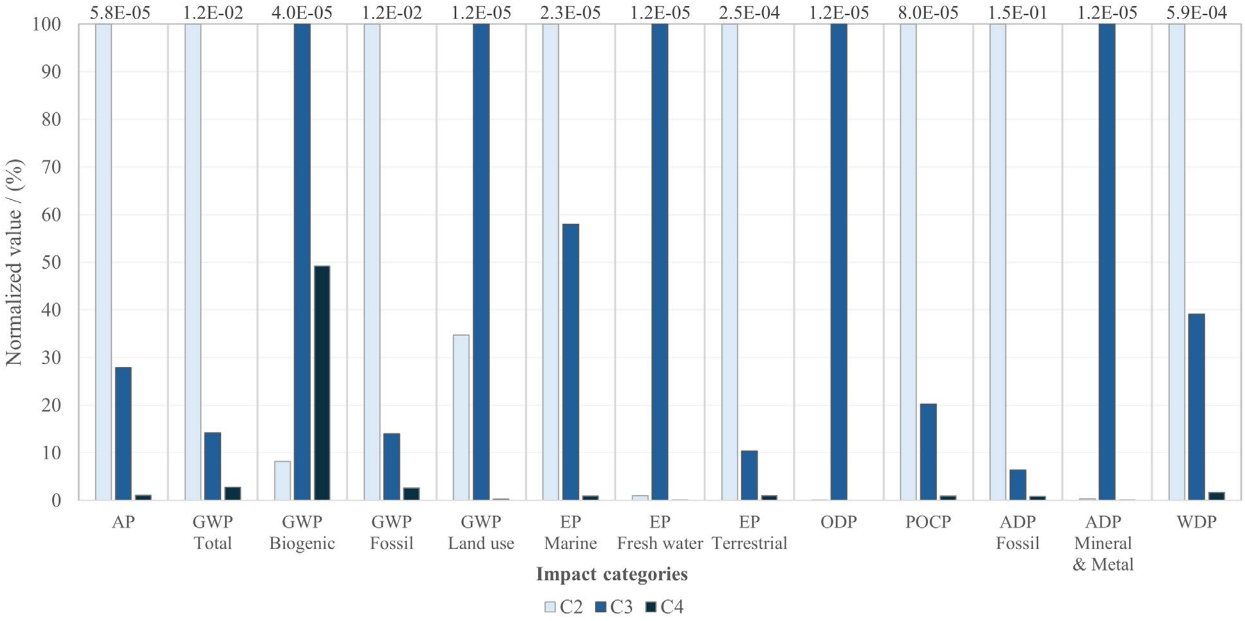

Figure 12. Normalised environmental impact contributions of the end-of-life stages (C1-C4) for the recycling scenario across 13 impact categories

Figure 13 shows the normalised environmental impact contributions of the EoL stages (C1-C4) for the reuse scenario. Transport (C2) is the highest contributor and serves as the reference point across all 13 impact categories. This reflects the longer assumed transport distance in the reuse scenario compared to 50 km assumed for the recycling scenario. Waste processing (C3), which includes electroluminescence testing and incineration of repackaging materials, remains low relative to transport across all categories. No disposal stage (C4) occurs in the reuse scenario, as the module itself enters second life rather than being broken down into fractions.

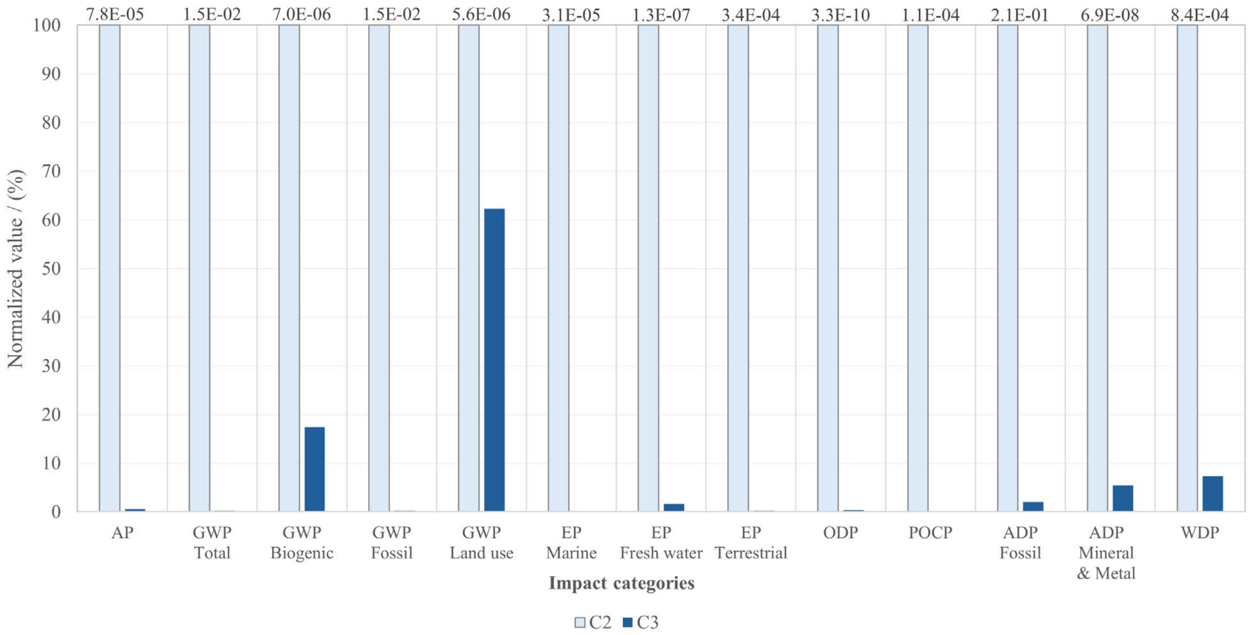

Figure 13. Normalised environmental impact contributions of the end-of-life stages (C1-C4) for the reuse scenario across 13 impact categories

Figure 14 illustrates the environmental benefits of the reuse and recycling pathways, which were normalised relative to the maximum benefit achieved within each impact category. The benefits are represented as negative values at the top of each bar to indicate the real avoided burden. The results show that the reuse scenario might offer a clear environmental advantage by avoiding the energy-intensive stages of raw material extraction and module manufacturing. In contrast, while mechanical recycling shows only a fraction of the benefit in each category, its magnitude is marginal, reflecting the limitations of mechanical recovery and its insufficiency to recapture the emissions initially used to manufacture the module.

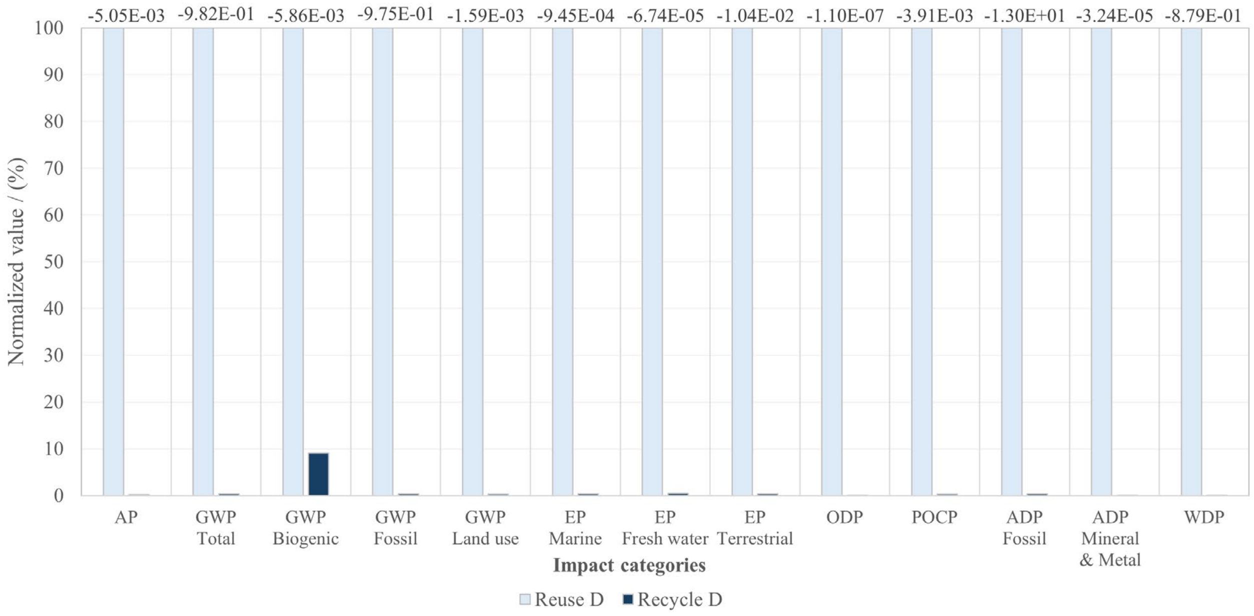

Figure 14. Normalised avoided burdens in stage D for the reuse and recycling scenarios across 13 impact categories

3.4.2 Global Warming Potential analysis

Among the 13 impact categories assessed, GWP total was selected for detailed numerical analysis. This decision is justified by the fact that climate change is recognised by the Intergovernmental Panel on Climate Change (IPCC) as a fundamental risk to the health of both humanity and the planet [1]. Consequently, GWP was used as the primary metric for detailed interpretation due to its strong relevance to global climate objectives. All results are expressed based on the declared unit of the study, namely 1 W_p.

Figure 15 shows the total life cycle GWP contributions for both scenarios across all life cycle stages. Since both scenarios use the same module and share identical A stages, the differences between scenarios are confined to the EoL (C) and beyond-system-boundary (D) stages. The manufacturing stage contributes 1.51 kg CO_2 eq, representing approximately 90% of total life cycle GWP in both scenarios. Transport and installation (A4-A5) together contribute approximately 0.14 kg CO_2 eq, or roughly 8% of total GWP. The EoL stages (C2-C4) account for less than 2% of total GWP in both scenarios. In stage D, the reuse scenario achieves an avoided burden of -0.98 kg CO_2 eq, while the recycling scenario achieves -0.017 kg CO_2 eq. These figures reflect the substitution of new module manufacturing in the reuse scenario and the recovery of glass, aluminium, and polymer energy in the recycling scenario, respectively.

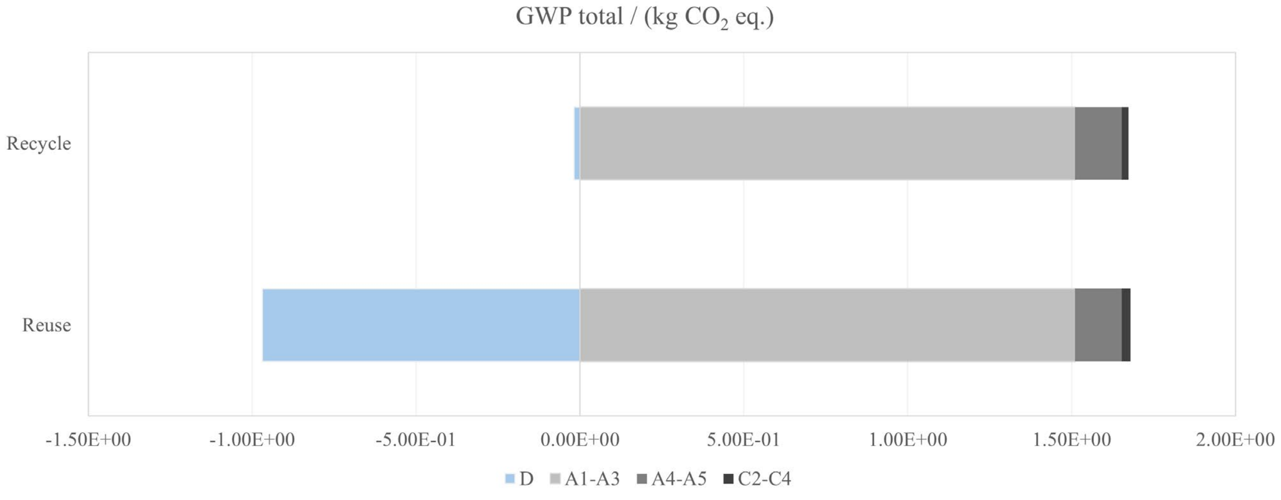

Figure 15. GWP total across the entire life cycle stages of both reuse and recycling scenarios

Table 13 provides a numerical breakdown of the GWP contributions from each life cycle stage. By calculating the relative percentage of each stage against the total scenario impact, the environmental "profile" of each pathway is more clearly defined. While stages A1-A5 remain identical in absolute terms for both scenarios, their relative percentages are slightly different due to the differing totals created by the EoL stages. In the reuse scenario, transportation (C2) and waste processing (C3) account for 0.9% and 0.7% of the total impact, respectively. Conversely, the recycling scenario shows a distinct shift in environmental burden: transportation (C2) drops to 0.3%, while waste processing (C3) increases to 1.1%. The disposal stage (C4) does not occur in the reuse scenario, its value for recycling is also negligible, reflecting the avoidance of waste generation even in the mechanical recycling approach.

Table 13. Impact distribution throughout the life cycle of each scenario

	A1-A3	**A4**	**A5**	**C2**	**C3**	**C4**	**Total**
Reuse / (kg CO_2 eq.)	1.51E+00	1.30E-01	1.19E-02	1.49E-02	1.20E-02	-	1.68E+00
Relative to total GWP / (%)	89.9	7.8	0.7	0.9	0.7		100
Recycle / (kg CO_2 eq.)	1.51E+00	1.30E-01	1.19E-02	4.99E-03	1.81E-02	3.42E-04	1.67E+00
Relative to total GWP / (%)	90.1	7.8	0.7	0.3	1.1	< 0.1	100

By identifying that the manufacturing stage dominates the total life cycle GWP, this phase is further analysed at the component level. Table 14 presents the mass share, GWP contribution, and intensity ratio for each component and process within the manufacturing stage (A1-A3), where the intensity ratio expresses the GWP contribution relative to mass share, a value above 1 indicates a component contributes disproportionately more to emissions than its physical mass would suggest, while a value below 1 indicates the opposite. Assembly energy use and module transportation are included as process-level contributions and are therefore not assigned a mass share.

The results reveal a marked discrepancy between mass and environmental impact across the module components. Glass dominates the module by mass at 67%, yet contributes only 5% of manufacturing GWP, yielding an intensity ratio of 0.07, meaning glass generates less than one tenth of the emissions that its mass share would proportionally suggest. The aluminium frame follows a similar pattern, representing 16% of module mass while accounting for 8% of GWP, with an intensity ratio of 0.50. The solar cell layer presents the opposite extreme at only 4% of total module mass, it is responsible for 79% of manufacturing GWP, producing an intensity ratio of 19.75. This means the solar cell generates nearly 20 times more emissions per unit of mass than its physical weight in the module would suggest. Assembly energy use and transportation of components together contribute a further 3.5% of manufacturing GWP and represent the only process-level contributions not tied to a specific material fraction.

Table 14. Impact contribution and emission intensity ratio of PV module components in the manufacturing stage (A1-A3)

Component	**Mass share / (%)**	**GWP total / (kg CO_2 eq.)**	**GWP contribution / (%)**	**Intensity ratio / (-)**
Frame	16	1.19E-01	8	0.50
Glass	67	7.60E-02	5	0.07
EVA	6	2.42E-02	1	0.17
Solar cell	4	1.20E+00	79	19.75
Interconnector ribbon	1	2.60E-03	0.1	0.10
Backsheet	3	1.57E-02	1	0.33
Junction box	3	2.13E-02	1.5	0.50
Assembling energy use	-	3.64E-02	2.5	-
Transportation	-	8.17E-03	1.9	-
Total	100	1.51E+00	100	-

Figure 16 shows the GWP contributions of the EoL stages (C2-C4) for both scenarios. The reuse scenario shows a higher C2 impact than the recycling scenario, reflecting the longer assumed transport distance of 150 km for reuse compared to 50 km for recycling. This higher transport burden is partially offset at C3, where the reuse scenario shows a lower impact than recycling, as the testing procedure avoids the energy use of mechanical shredding and incineration. The reuse scenario produces no C4 impact, as no material fraction is sent to disposal, and in the recycling scenario, C4 captured the lowest emission between C stages.

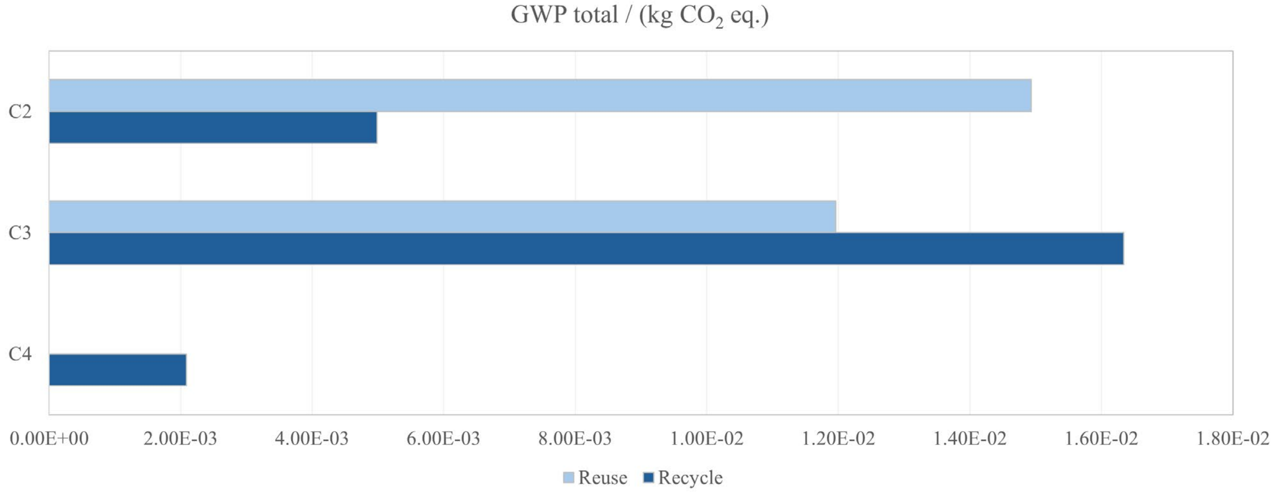

Figure 16. Impact contribution of end-of-life stages (C2-C4) for the reuse and recycling scenarios

Benefits and loads beyond the system boundary for the recycling scenario, illustrated in Figure 17, show that the highest benefit from mechanical recycling comes from the energy recovered through the incineration of the backsheet and encapsulant, which is assumed to be fed into the electricity grid. Recycled glass and aluminium from mechanical recycling led to downcycling, resulting in lower benefits.

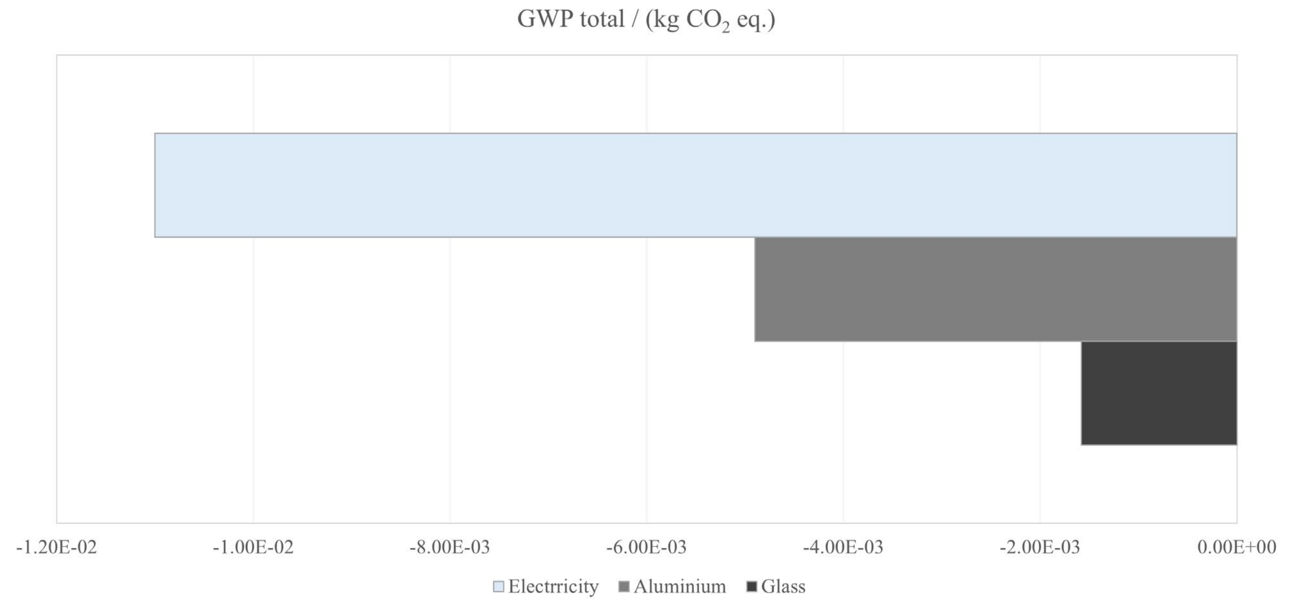

Figure 17. Avoided burdens in stage D for the recycling scenario

In Table 15, the benefits of recycled and recovered materials relative to their initial production impacts are shown. Recycling aluminium through mechanical recycling only accounts for 4% of its initial production impact, meaning that 94% of the emissions from producing an aluminium frame remained as emissions to nature. Glass also does not provide any better benefits, as it becomes glass cullet through the same recycling approach and only results in 3.8% of the initial emissions associated with producing this material. On the other hand, less than 1% of the emissions from manufacturing solar cells, backsheet, and EVA are compensated for, through energy recovery, as these materials are incinerated together and the solar cell is kept within the encapsulation. The benefit from energy recovery, which showed the highest among other recovery approaches, is relatively low when compared to the emissions caused by manufacturing the incinerated materials.

Table 15. Impact distribution of individual recovered components relative to production impact in recycling scenario

Components	**Production impact / (kg CO_2 eq.)**	**Avoided impact / (kg CO_2 eq.)**	**Avoided impact relative to production impact / (%)**
Frame	1.19E-01	-4.90E-03	4.10
Glass	4.18E-02	-1.58E-03	3.83
EVA	2.42E-02	-1.10E-02	0.89
Solar cell	1.20E+00		
Backsheet	1.57E-02		

The avoided burden for the reuse scenario follows a fundamentally different logic from that of recycling. Whereas recycling recovers material and energy, reuse preserves part of the function embedded within the module and thereby reduces the need for new module production. A value-correction factor of 0.88 was applied to account for the lower performance of an ageing module relative to a new replacement product. Derived from an annual degradation rate of 0.5% over a 25-year first-life operation period under Swedish field conditions, the factor represents the share of functionality retained by a multi-Si module at the end of its warranty period. Rather than corresponding to a specific number of additional service years, it represents the share of functionality assumed to remain available for second-life use, provided the module satisfies the testing and reuse criteria defined in this study. As shown in Figure 18, the reused module is therefore assumed to substitute 88% of the functionality of a new mono-Si module, resulting in a credit equivalent to 88% of the manufacturing impacts of the substituted product. The new mono-Si module carries a total manufacturing GWP of 1.11 kg CO_2 eq. and applying the 0.88 factor yields an avoided burden of 0.98 kg CO_2 eq., shown earlier as a negative flow in Figure 15. This avoided burden is sensitive to the module's actual second-life performance. For a module retaining only 50% of its original performance, the value-correction factor would be 0.50 and the avoided burden would decrease to approximately 0.54 kg CO_2 eq., illustrating the direct relationship between remaining functionality and the environmental benefits of reuse.

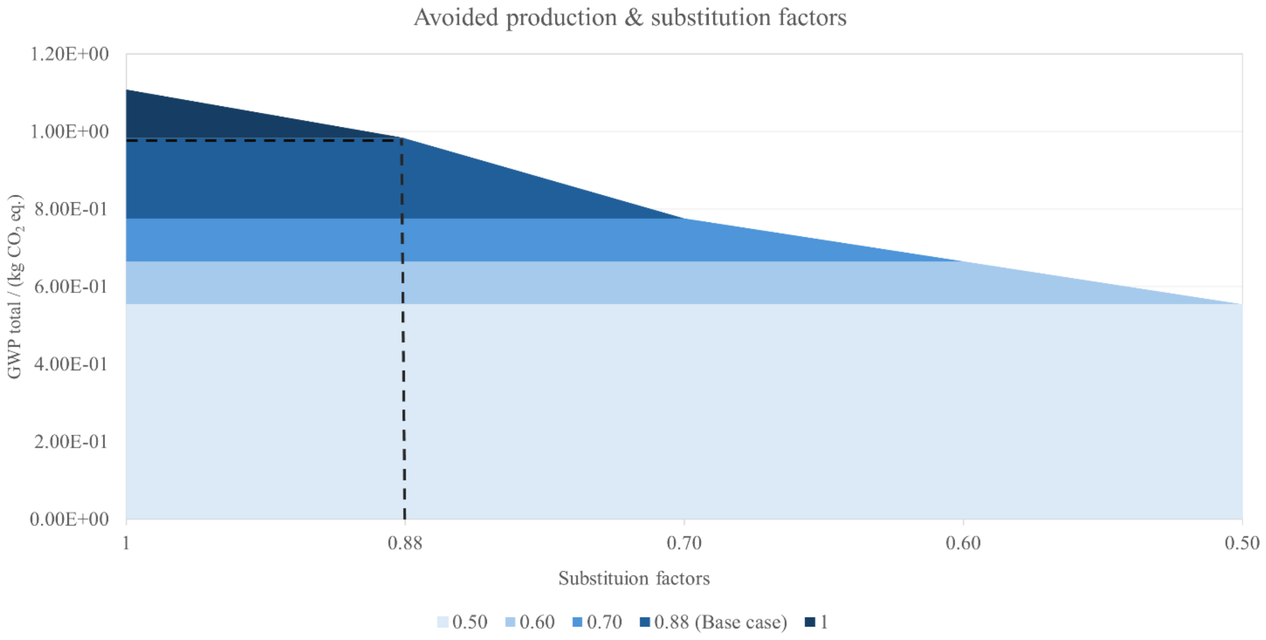

Figure 18. Avoided burden in stage D for the reuse scenario based on value-correction factors

Figure 19 presents a component-level breakdown of the 0.98 kg CO_2 eq. avoided burden in the reuse scenario. Solar cell manufacturing represents the largest driver of environmental benefit in this scenario. This is consistent with the manufacturing stage analysis in Table 14, which identified the solar cell as the most GWP-intensive component. It is important to note that the proportional contribution of each component to the avoided burden remains constant regardless of the value-correction factor applied, because all components scale proportionally together. Therefore, under any performance level, whether 50% or 88%, solar cell production avoidance remains the dominant environmental benefit of the reuse pathway.

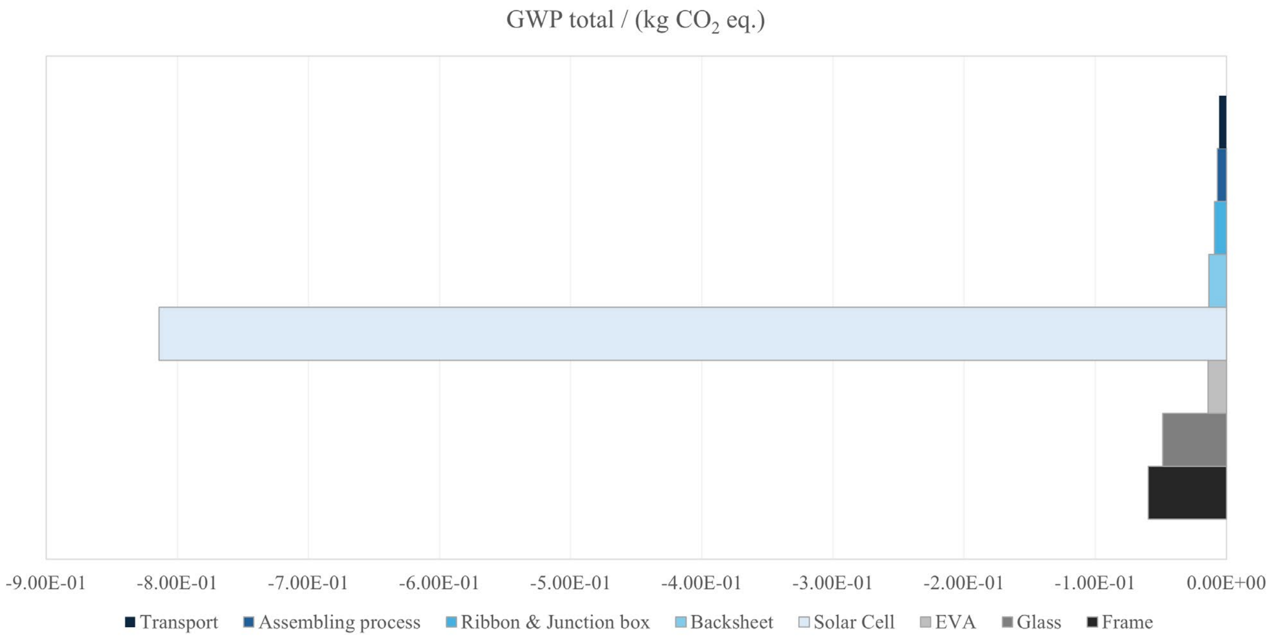

Figure 19. Component-level breakdown of the avoided burden in the stage D of reuse scenario

By comparing the impacts created in EoL scenarios with those avoided in Stage D, a recovery efficiency ratio can be calculated to determine how much avoided impact is gained relative to the cost of processing the module at end of life. This comparison is presented in Table 16. As shown, the reuse scenario achieves a recovery efficiency of 66, meaning the avoided burden in Stage D is 66 times greater than the EoL processing cost in Stage C. The recycling scenario, by contrast, results in a ratio of 0.75, indicating that the environmental cost of mechanical processing exceeds the credits gained through material recovery, either via recycling or energy recovery. In other words, for every kg of CO_2 eq. emitted during EoL treatment to bring the module or its fractions to the circular pathways, the reuse scenario provides 66 kg CO_2 eq. of avoided burden once the module enters its second life. For recycling, this ratio falls below 1, meaning that the emissions caused to bring material fractions into a useful output, exceed the environmental credits gained after the waste state is ended.

Table 16. Recovery efficiency ratio of reuse and recycling scenarios

	Total C / (kg CO_2 eq.)	**Total D / (kg CO_2 eq.)**	**Recovery efficiency / (-)**
Reuse	1.49E-02	-9.82E-01	66
Recycling	2.34E-02	-1.75E-02	0.75

4 Discussion

This thesis developed a decision framework that links PV module degradation behaviour, reuse suitability, recycling, and LCA into a connected whole, with particular attention to Nordic climate conditions. Whereas previous work has addressed second-life preparation [16], [49], [91], this study treats reuse and recycling as two pathways within the same circular-economy problem: reuse when a module remains functional and safe, and recycling when it does not. Cold-climate degradation rates and Nordic field evidence inform both the reuse suitability criteria and the LCA modelling, translating what is technically knowable about an aged module into an EoL decision. The findings suggest that EoL decisions for PV modules should not be based solely on age, warranty expiration, or material recovery potential. Instead, they require consideration of degradation behaviour, remaining functionality, safety, and environmental impacts simultaneously. The following sections interpret the results from this perspective.

4.1 Reuse potential

The literature reviewed in this study sets the backbone of the work and challenges the assumption that PV modules should automatically be treated as waste once their warranty period expires. While a 25- to 30-year lifetime is commonly assumed, the evidence suggests that this reflects commercial practice rather than technical reality. Studies have shown that c-Si PV modules do not always follow the assumed degradation and can remain functional well beyond their expected service life. This is evident in cold climates, where low degradation rates show that modules can stay functional for years beyond their warranty period. The field findings support this: a noticeable portion of systems still met typical warranty performance thresholds after their expected operational lifetime had passed.

It is also well established that PV modules do not always degrade linearly or uniformly; rather, they often follow a bathtub curve shape characterised by three phases. Understanding where a module sits on this curve is important for approving its reuse potential. Modules that have passed the first phase without critical failure can demonstrate a degree of reliability, and those in the midlife phase show a gradual, almost predictable decline. As such, several decommissioned modules from a typical PV system may still be in their midlife phase rather than approaching wear-out, meaning they likely have years of useful life remaining, and their future performance can still be measured and relied upon.

It is also worth questioning how well this pattern applies to individual modules. The bathtub curve is based on groups of modules, and any single module can behave differently depending on its conditions. While the curve can provide a useful guide, making decisions about individual modules based on it alone has limitations. This is where testing becomes particularly important in the context of reuse, since a reused system is only as good as its individual modules; each module, therefore, needs to be assessed on its own qualities.

At the same time, remaining power output alone is not a sufficient indicator of reuse suitability. A module may still satisfy common performance thresholds while containing degradation mechanisms that increase the likelihood of future failure. The reuse criteria developed in this study therefore combine performance assessment with degradation-based exclusion criteria. Safety-critical failures such as glass breakage, backsheet cracking, junction box failures, and PID require immediate exclusion from reuse regardless of remaining power output. In addition, degradation mechanisms such as encapsulant discolouration, delamination, cell cracks, interconnection degradation, and glass coating deterioration may indicate that a module is transitioning from a stable midlife phase towards accelerated wear-out. When these defects accumulate, they can also increase the likelihood of failure during the final stage of the module's service life. Although these defects do not always cause immediate failure, their presence increases uncertainty regarding future reliability and service life. This highlights the importance of the five-stage testing framework, which shifts reuse decisions away from age or power output alone and towards a more comprehensive assessment of module condition. In this sense, the main challenge of reuse is not identifying modules that are still functioning today, but identifying modules that are likely to remain functional throughout their second life.

Another aspect to consider is LID, a common mechanism in c-Si PV modules that occurs during the first few light exposures. Among the studies considered, it was found that the typical approach to measuring the degradation rate and performance threshold is to compare the measured output current or voltage at specific time intervals after years of operation with the nameplate capacity of the PV modules. However, in this approach, the performance drop over the years of operation is attributed to LID, which may overestimate the real degradation rate and output decline by including the initial rapid decline caused by this mechanism. Therefore, it may be more accurate to measure performance against the post-LID output. It is also possible for manufacturers to anticipate this phenomenon through laboratory tests due to newer policy requirements; however, in the context of reuse, this remains an important consideration, where some PV modules may be older than the policy changes.

The 0.5% per year degradation rate used in this study was taken from field studies that measure performance loss relative to the original nameplate capacity. This means the initial drop caused by LID is included in that rate. If performance were measured from the stabilised post-LID output instead, the degradation rate over the actual service life would be lower, and the remaining performance after 25 years would be slightly higher than 88% of the initial capacity. This can be interpreted as a sign that PV modules degrade even less than expected in cold climates.

4.2 LCA adaptation and challenges

This study faced a methodological challenge that is not explicitly addressed in current LCA standards: there is no established framework for assessing PV module reuse. Standard LCA practice for EoL scenarios assumes that waste enters well-defined processes such as recycling, energy recovery through incineration, or landfill disposal. Reuse does not fit this structure because the product itself remains in use and retains part of its functional value, thereby avoiding or delaying the need for new module production, rather than creating benefits through the recovery of material fractions. Assessing these benefits and loads therefore required the development of a methodological approach based on the principles of EN 15804, including the polluter-pays principle, end-of-waste state, functional equivalence, and substitution, and adapting them to a context that is not explicitly addressed by the standard.

This also reflects a broader limitation found in the reviewed literature: current LCA standards remain largely aligned with linear product systems and do not effectively meet circularity requirements. Although LCA is a well-established tool for recognising environmental hotspots and informing design decisions, it is still important to provide clearer guidance for scenarios where circularity, and reuse in particular, are the preferred solutions. EN 15804 already provides a foundation for expanding toward more circular assessment through principles such as the polluter pays principle and the end-of-waste state, but further adjustment is certainly needed. In addition, PV reuse remains a relatively novel scenario; however, as the reuse market grows and the PV waste stream expands, more consistent ways to communicate its environmental benefits and burdens will likely become necessary.

4.3 Reuse and recycling, benefits and loads

The results clearly show that the manufacturing stage dominates the total life cycle environmental impact across all assessed impact categories and accounts for approximately 90% of total GWP in both scenarios. At this stage, the solar cell layer is the dominant contributor to manufacturing GWP, despite accounting for only around 4% of the total module mass. The component-level analysis quantified this inversion through the intensity ratio, where the solar cell yields a value of 19.75, meaning that for every 1% of module mass the solar cell uses, it is responsible for nearly 20% of manufacturing GWP. By contrast, glass at 67% of module mass produces an intensity ratio of only 0.07, and the aluminium frame at 16% mass yields 0.50, confirming that the two heaviest components by mass are among the least emission-intensive per kilogram. This has a direct effect on how the two EoL pathways in this study should be interpreted. When manufacturing accounts for approximately 90% of total life cycle GWP, the environmental difference between pathways is driven mainly by how much of that manufacturing impacts each one avoids or recovers, rather than by differences in the efficiency of EoL processing itself, which contributes only a small fraction of total life cycle impact in this study.

Reuse addresses this directly by substituting new module production and avoiding the most environmentally costly stage of the entire life cycle. Mechanical recycling by contrast, targets glass and aluminium that are two heaviest constituents of the module by mass, yet neither ranks among the top contributors to manufacturing GWP. Glass, despite forming 67% of module mass, contributes only 5% of manufacturing GWP. Aluminium, at 16% of mass, accounts for 8% of GWP. Together they represent 13% of manufacturing emissions while making up 83% of module mass, this is the structural mismatch on which mechanical recycling is built, yet it does not reflect where environmental value is actually concentrated. For the solar cell layer, recovery via the mechanical pathway is effectively zero, as cells remain encapsulated in EVA and are directed toward incineration with the backsheet, and energy recovery primarily comes from burning polymers due to their high heating value. Even the energy recovery credit from incinerating these polymer fractions amounts to less than 1% of the combined impact on encapsulation production. It is worth noting that the electricity grid mix assumed for energy recovery in recycling is the Swedish grid mix, which is among the cleaner grids in Europe. In countries with coal-heavy grids, the GWP credit from incinerating polymers would be favourable. Also, if China's electricity grid were to decarbonise, the absolute stage D benefit of reuse would decrease, because the new module being substituted would carry a lower carbon footprint. But this would apply equally to both pathways. Cleaner manufacturing would narrow the absolute gap between reuse and recycling, but it would not reverse the ranking. The logic holds as long as manufacturing remains the dominant contributor to life cycle GWP, which is unlikely to change in the near term, given the material and energy requirements of solar cell production.

Moreover, the recovery efficiency ratio represents the environmental return on investment for each pathway. For the reuse scenario, this ratio is 66, meaning the avoided burden in Stage D is 66 times greater than the environmental cost of transport and testing, and the emissions invested in bringing the module to its second life are recovered 66-fold through the substitution of new module production. For mechanical recycling, the ratio is 0.75, meaning the environmental cost of EoL processing exceeds the credit from recovered materials; in GWP terms, mechanical recycling does not recover even the environmental cost of its own waste processing. In absolute terms, the Stage D avoided burden from reuse (-0.982 kg CO_2 eq.) exceeds the total stage D credit from mechanical recycling (-0.0175 kg CO_2 eq.) by a factor of approximately 56, meaning reuse avoids approximately 56 times the GWP impact that recycling avoids beyond the system boundary.

As interpreted, mechanical recycling captures a negligible fraction of the environmental value embedded in a PV module, despite meeting the WEEE Directive's legal mass recovery targets, indicating that current practice is characterised as circular mass management rather than actual circularity. This does not simply mean that reuse outperforms recycling in this study; rather, mechanical recycling is fundamentally misaligned with the distribution of environmental impacts across PV module components. However, this misalignment could be explained by the fact that mechanical recycling is not specifically developed for PV modules but is adapted from other recycling industries, where the waste streams might not experience this kind of mass-impact inversion.

Additionally, the EU Critical Raw Materials Act designates silicon, aluminium, boron, and phosphorus as critical raw materials for its economy, but does not yet translate this into separate recovery requirements that would support advanced recycling approaches or reuse over bulk mechanical processing. In addition, extended producer responsibility frameworks assign responsibilities for EoL management but do not currently link producer fees to the quality of recovery. As a result, there is no financial motivation to pursue reuse or high-value material recovery over cheaper mechanical recycling that meets the same legal threshold at lower cost. Closing this gap requires regulatory frameworks that reflect environmental value rather than mass. Producer fees structured around the quality of material recovery rather than mass alone, or mandatory requirements for recycled PV-grade silicon in new module manufacturing, could create the financial push needed to shift the industry toward higher-value EoL pathways and accelerate circularity in the PV sector, but without such, the industry has no reason to move beyond an approach that meets legal requirements while resulting in minimal environmental return.

4.4 Market potential and supply chain

The scale of reuse opportunities is supported by estimates that up to 80% of the European PV waste stream consists of prematurely decommissioned modules, with earlier assessments indicating that 45% to 65% of modules entering the waste stream were still suitable for repair or reuse. The environmental benefits modelled in this study, therefore, do not depend solely on future market development; they are available now for modules already being decommissioned. A fully developed second-life market for PV modules does not yet exist at a commercial scale. Current reuse activity happens mostly through individual resellers, community projects, and off-grid applications. The absence of standardised testing protocols, globally applicable PV performance thresholds suitable for reuse, and warranty criteria hinders broader market development.

In addition to its direct environmental benefit, the reuse pathway may also have strategic value. Given that the PV industry is heavily dependent on global supply chains and critical raw materials, disruptions in manufacturing or international trade could directly affect the availability and cost of new modules. Under such conditions, keeping functional modules rather than directing them to recycling could increase resilience, particularly for off-grid, emergency, or low-demand applications where performance requirements are less strict.

The findings also suggest that policy measures could play an important role in developing reuse pathways. Subsidies or regulatory incentives for testing, certification, and redistribution of second-life modules could help offset some of the additional labour and logistical costs that currently make reuse economically unattractive relative to replacement. Without such instruments, market conditions will continue to require repowering or revamping with newer modules, even where older modules provide sufficient function and environmental value to justify a second life.

5 Conclusion

The aim of this study was to investigate whether reuse can represent a viable circular end-of-life pathway for ageing crystalline silicon photovoltaic (PV) modules and under what conditions such an approach may be possible, while considering mechanical recycling as the conventional treatment pathway for end-of-life PV modules in Europe. To address this, a literature review was conducted to identify the main degradation mechanisms affecting PV modules, evaluate existing testing approaches, and establish criteria for second-life use. These findings were subsequently integrated into a Life Cycle Assessment (LCA) conducted according to EN 15804+A2, in which the environmental footprint of reuse and recycling was assessed. The main findings of the project are summarised through the three research questions that guided this study.

1. Which degradation mechanisms and performance thresholds determine whether first-generation c-Si PV modules are suitable for reuse rather than recycling?

Reuse suitability is determined by both safety-critical failures and performance thresholds, evaluated together rather than independently. Failures such as glass breakage, backsheet cracking, junction box detachment, and Potential Induced Degradation (PID) pose electrical and fire hazards that disqualify a module from reuse and direct it to recycling, regardless of remaining power output. In addition, degradation mechanisms such as glass coating degradation, encapsulant discolouration, delamination, cell cracks, and interconnection degradation can increase failure rates as modules progress from middle age towards the later stages of their service life. Although these mechanisms may not always cause immediate failure, they should be identified through testing, and modules exhibiting them should be excluded from reuse criteria where such mechanisms indicate an elevated risk of future performance loss and reliability issues. The five-stage testing framework provides a structured basis for this purpose. In terms of performance, proposed thresholds range from 50% to 95% of original nameplate capacity, but there is still no agreement among studies, and the appropriate threshold depends on the intended application. From an environmental perspective, most modules provide meaningful avoided burden even at 50% of original capacity. Field evidence shows that c-Si modules in cold climates can retain at least 80% of their original performance after 25 years, keeping them above typical warranty thresholds. Where critical failures do not occur, modules in well-ventilated conditions can remain functional well beyond their expected service life.

2. How can reuse eligibility and remaining performance be translated into LCA assumptions in the absence of an established reuse LCA framework for second-life PV modules?

Reuse eligibility was assessed using performance thresholds derived from field degradation data, while the remaining functionality of decommissioned modules was incorporated into the LCA through a substitution approach based on the stage D principles of EN 15804+A2. Since no dedicated LCA framework currently exists for second-life PV module reuse, this study adapted the modular structure and avoided-burden logic of EN 15804 to assess the environmental benefit of extending module service life and avoiding the production of a new PV module. Degradation rates were used to assess how much functionality a reused module could still provide relative to the new module it might replace under the system boundary of this study. A further contribution of this approach was that both reuse and recycling were modelled within the same system boundary and declared unit, with the two pathways diverging only at the end-of-life and stage D phases. This means the environmental difference between pathways is directly attributable to the substitution logic, making the comparison transparent and consistent in a way that is not always achieved in existing PV LCA studies. Although this approach does not address the lack of a standardised reuse methodology, it offers a transparent and reproducible way to incorporate second-life scenarios into environmental assessment until more specific frameworks become available.

3. How do the environmental impacts of reuse and recycling pathways differ under these assumptions?

Based on the assumptions applied in this study, reuse and recycling differ fundamentally in how they recover environmental value. The manufacturing stage dominates the life cycle Global Warming Potential (GWP) of both scenarios, accounting for approximately 90% of total emissions. Within this stage, component-level analysis revealed a mass-impact inversion. The solar cell layer accounts for approximately 79% of manufacturing GWP while representing only around 4% of module mass, resulting in an intensity ratio of 19.75. This means for every 1% of module mass occupied by the solar cell, nearly 20% of manufacturing emissions are generated. In contrast, glass constitutes approximately 67% of module mass but has an intensity ratio of only 0.07, while the aluminium frame represents 16% of module mass and yields an intensity ratio of 0.50. Together, glass and aluminium account for approximately 83% of module mass but only 13% of manufacturing GWP. These findings show that environmental impacts are concentrated in a relatively small and highly impact-intensive fraction of the module, whereas the heaviest components contribute comparatively little to manufacturing emissions.

Reuse addresses this imbalance by extending the module's operational life and avoiding the need for new manufacturing. As a result, the reuse scenario achieved an avoided burden approximately 56 times greater than mechanical recycling and yielded a recovery efficiency ratio of 66, revealing that the environmental impacts required to transition a PV from waste status to a second-life product were recovered 66-fold through the avoidance of new module production. In contrast, mechanical recycling achieved a recovery efficiency ratio of only 0.75, revealing that the environmental benefits obtained from recovered materials and energy were lower than the impacts generated by the recycling process itself. These findings suggest that, as long as PV manufacturing remains the dominant contributor to life cycle impacts, end-of-life strategies that do not offset, reduce, or avoid new production are likely to provide limited environmental benefits, regardless of how efficiently PV waste is processed. The results nevertheless suggest that the decision between reuse and recycling is not solely a matter of technical recovery efficiency but rather depends on where environmental impacts are concentrated across the life cycle, and which strategy is more effective at retaining or recovering that environmental value. Lastly, the results remain dependent on the degradation assumptions and substitution approach adopted in this study and should therefore be interpreted as indicative rather than absolute.

The gaps identified in this study are a clear sign that the development of the reuse market is being prevented and addressing this misalignment is possibly the most important policy challenge facing the PV waste sector. Recovery targets defined by material-value fraction rather than mass, and economic instruments that reflect the value of critical material recovery, will be necessary to drive the transition from bulk mechanical recycling toward high-value end-of-life pathways at the scale demanded by the expanding PV waste stream. The absence of a defined performance threshold further underlines that, without mandatory standards, the boundary between a reusable and a non-reusable PV module remains uncertain.

6 Future research

While this study answers its research questions, it also raises further questions that warrant further investigation. Future research could examine the repairability of degraded modules, specifically whether defects can be reliably repaired without introducing safety risks, and whether repaired modules can meet the same reuse criteria as unrepaired ones. Standardised testing procedures and certification frameworks for repaired modules would also be needed to support this direction.

Degradation behaviour beyond linear annual rates also requires deeper investigation, particularly into how mechanisms accumulate and accelerate during the transition from midlife to the wear-out phase, and how climate-specific stressors in Nordic conditions affect this progression relative to global averages. Long-term field studies tracking module-level degradation across different climates, and different system types such as ground-mounted and Building-Integrated Photovoltaics (BIPV) would provide a stronger evidence base for reuse decisions.

The potential interaction between second-life PV deployment and the ongoing heat pump-based energy transition also could be an investigation. As electrification of heating through heat pumps increases electricity use in Nordic countries, distributed second-life PV systems could contribute to lowering this demand at the building or district level. Research examining the alignment between the seasonal electricity generation profile of reused PV systems and the electricity use patterns of heat pumps would help quantify this potential.

The environmental and economic viability of closed-loop recycling deserves further investigation, particularly for advanced pathways such as thermal and chemical processes that allow upcycling and reintroduction of recovered materials into their original supply chains. Special attention should be given to the solar cell layer, which this study identified as responsible for the largest share of manufacturing GWP despite representing only a small fraction of module mass. The energy required to recover it at high purity through advanced recycling may still be substantially lower than that needed for virgin material production. The same assessment could be extended to other components such as glass and aluminium, examining whether the energy, emissions, and cost related to thermal or chemical recycling are justified by the quality of recovered fraction compared to their original material, or whether it is more effective to spend the energy and cost toward recovering only the solar cells layer and its silver content and treat the other fractions via mechanical recycling where they still have economic value and a market demand, even though these fraction are downcycled. This could be addressed by integrating LCA with life cycle costing (LCC) into a combined framework, sometimes referred to as Integrated Life Cycle Assessment (ILCA), which would provide a more complete basis for decision-making by manufacturers, recyclers, and policymakers. Additionally, the electricity grid mix can play a critical role in such assessments, as the carbon intensity of the electricity grid directly affects the environmental impacts of advanced recycling pathways, and accounting for different grid scenarios could influence the conclusions of such a study.

From a systems perspective, the role of second-life PV modules in supporting energy security deserves attention. Decommissioned modules that retain sufficient performance could serve as a decentralised energy resource in contexts where supply chain disruptions limit access to new modules, a concern that is particularly relevant given the current concentration of PV manufacturing as discussed in this study. Investigating the logistics, regulatory requirements, and technical standards needed to organise such a reserve would be valuable.

Finally, real-world cases of reused PV modules deserve much more documentation and analysis. While examples such as the SOLARCYCLE could validate the technical feasibility of deploying decommissioned modules at scale, systematic studies tracking the performance, reliability, and environmental outcomes of second-life systems across different applications and geographic contexts are still lacking. Such studies would also help improve the performance thresholds and certification criteria currently proposed in the literature.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT in order to improve grammar, readability, and rephrasing. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published work.

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Appendix A

Table A1. Mass of materials and components used in manufacturing stage of multi-Si and mono-Si PV modules.

Component	kg/m²
Aluminum frame	2.13
Solar glass	8.81
Interconnector ribbon	0.12
Solar cells / Multi-Si	0.49
Solar cells / Mono-Si	0.47
EVA foil	0.88
Backsheet	0.37
Junction box and cables	0.40

Table A2. Conversion factors for scaling inventory data of mono-Si PV to the declared unit (Wp).

Parameter	Value	Unit	Source
Module Efficiency	22.4	%	Assumption / Literature
Power Density	224	W_p/m^2	Calculated
Specific Mass (With frame)	13.2	kg/m^2	IEA
Area Scaling Factor	0.0044	m^2/W_p	Calculated (1/224)
Mass Scaling Factor	0.0589	kg/W_p	Calculated (13.2/224)

Table A3. Material flows for mono-Si PV module production stage (A1-A3).

PV components	Material flows	Weight per DU / (kg/W_p)
Frame	Aluminium alloy, AlMg3 {RER}| Cut-off, U	0.0095
Glass	Solar glass, low iron {RER}| Cut-off, U	0.0393
Interconnect ribbons	Copper, cathode {RER}| Cut-off, U Lead {RER}| Cut-off, U Tin {RER}| Cut-off, U	0.0005
Solar Cells	Photovoltaic cell, multi-Si wafer {RoW}| Cut-off, U	0.0021
EVA	Ethylvinylacetate, foil {RER}| Cut-off, U	0.0039
Backsheet	Polyethylene terephthalate, granulate {RER | Cut-off, U Polyvinylfluoride, film {RER} | Cut-off, U Polyethylene, HDPE {RER} | Cut-off, U	0.0016
Junction box	Glass fibre reinforced plastic, polyamide, injection moulded {RER}| Cut-off, U	0.0017

	Silicone product {RER}| Cut-off, U wire drawing, copper {RER}| Cut-off, U Diode, market for diode {GLO}| Cut-off, U	

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