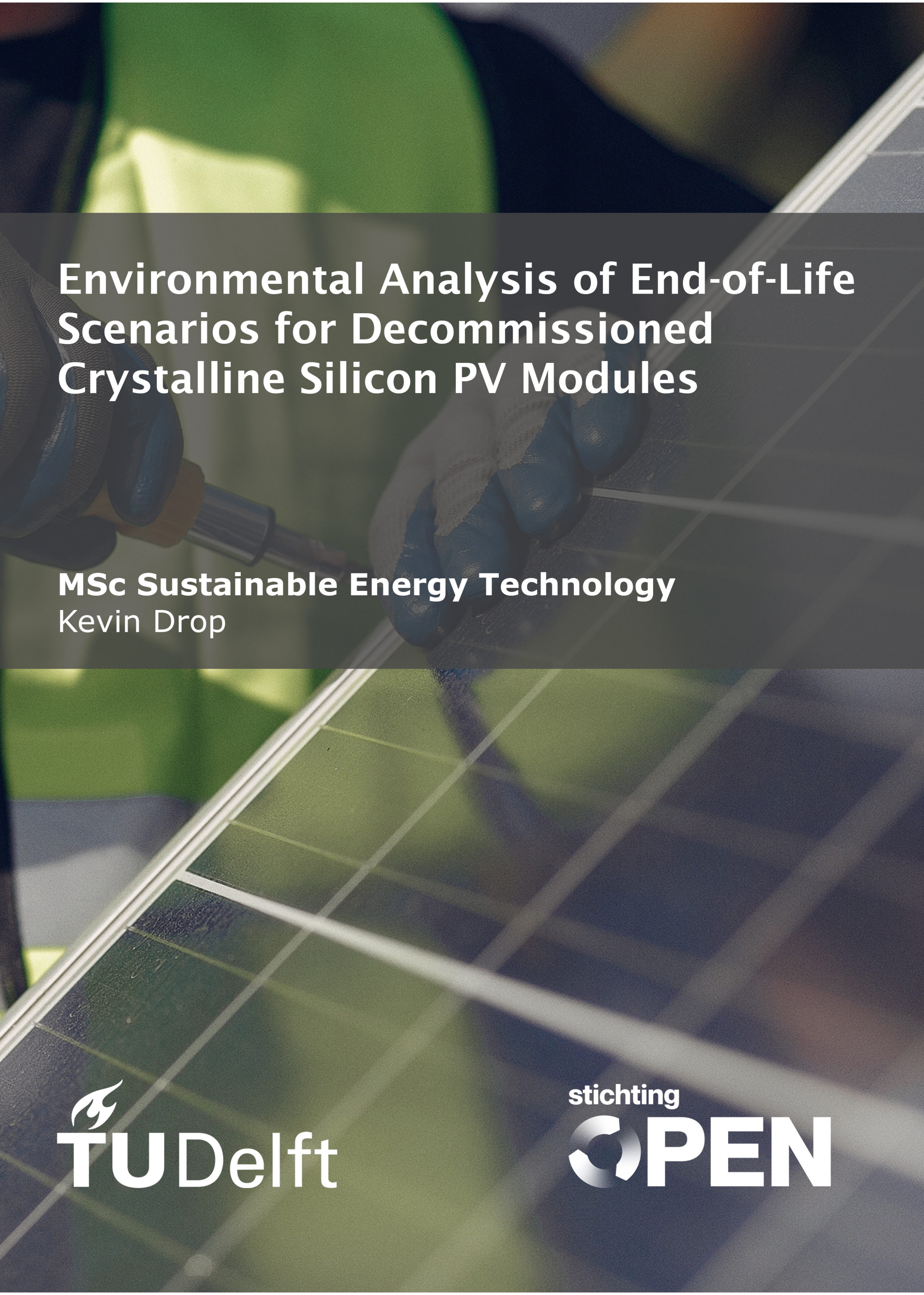

Environmental Analysis of End-of-Life Scenarios for Decommissioned Crystalline Silicon PV Modules

MSc Sustainable Energy Technology

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Environmental Analysis of End-of-Life Scenarios for Decommissioned Crystalline Silicon PV Modules

by

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ABSTRACT

Many functional photovoltaic (PV) modules are decommissioned prematurely, often due to the financially motivated repowering of PV systems. This study assesses under which circumstances there is an environmental incentive to reuse these modules as opposed to recycling and replacing them with new, more efficient modules. A life cycle assessment was conducted, covering the end-of-life treatment, manufacturing, transport and use phase of decommissioned and new modules. The decommissioned modules had an efficiency of 14.7% in 2011, the new modules have an efficiency of 19.79%. The analysis covers two different reuse scenarios (local and export) and two different replacement scenarios, based on the quality of the recycling and the manufacturing country of the new modules.

The impacts are quantified in three categories: global warming potential, eco-cost of resource scarcity and total eco-cost. The findings indicate that, because of rapid technological advancements, the recycling and replacement of 10-year old decommissioned modules generally yield greater environmental benefits than local reuse: the net benefit in terms of global warming is greater after only 5 years. In addition, the calculations show that reusing decommissioned modules in a new PV system is only the preferred strategy from a global warming perspective if the modules are less than 5 years old, if that system is intended to have a (financial) lifetime of 10 years or longer. However, reuse in a selected European Union member state can provide greater benefits in the global warming potential and total eco-cost impact categories than recycling and replacement. The advantage of export is driven by higher annual irradiation as well as a higher emissions intensity of the electricity mix.

These results contrast the conventional belief that reuse is always environmentally preferable to recycling. Based on this research it can be argued that in most cases of premature decommissioning, there is no strong environmental incentive to reuse the modules, provided that new PV modules are widely available or that the materials go directly to the production of new modules. The annual efficiency increase of PV technology was identified as a key parameter for this outcome.

Preface

This thesis marks the end of my studies at Delft University of Technology. I am grateful to have had an opportunity to contribute to the scientific community, especially in an area that seems to be so commonly overlooked: although innovations within the sustainable energy sector gather considerable attention in academia, the end-of-life stage often appears to be an afterthought. I am pleased to have been able to shed some light on this interesting and essential component of the energy transition.

I would like to thank my daily supervisor René Eijsbouts, not only for offering me a graduation internship at the OPEN Foundation, continually supporting me in my research and having faith in my competences, but also for giving me the feeling of involvement within the company. The visits to a recycling plant, the Solar Solutions trade fair and the TNO Energy Research Centre were great opportunities to become acquainted with the solar energy sector and are among my most cherished memories of my time at the OPEN Foundation.

I would also like to express many thanks to my supervisor Dr. Malte Vogt for his seemingly endless knowledge of PV energy and close involvement in the thesis, and foremost his ability to instill a positive and solution-oriented attitude in me during our meetings. Regardless of how much I seemed to get stuck in the research or started doubting myself, I would leave the meetings with a sense of relief and new motivation to continue my research.

Hopefully, this research will inspire others to critically evaluate the waste hierarchy and realize that the concept of reduce, reuse, recycle is not set in stone.

Kevin Drop
Zoetermeer, December 2023

CONTENTS

List of Figures

List of Tables

Acronyms

3D Three-dimensional

6N 99.9999%

AC Alternating Current

BoS Balance of System

c-Si Crystalline Silicon

CdTe Cadmium Telluride

CIGS Copper Indium Gallium Selenide

CO_2 Carbon dioxide

CO_2-eq Carbon dioxide equivalent

CRM Critical Raw Materials

Cz Czochralski

DC Direct Current

EoL End-of-Life

EU European Union

EVA Ethylene-vinyl Acetate

FRELP Full Recovery End of Life Photovoltaic

GR Greece

GWP Global Warming Potential

HQ High-quality

IEA International Energy Agency

ISO International Organization for Standardization

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LQ Low-quality

MASC Methyl Aluminium Sesquichloride

MG-Si Metallurgical Grade Silicon

NL The Netherlands

PET Polyethylene Terephthalate

PRO Producer Responsibility Organization

PV Photovoltaic

PVDF Polyvinylidene Fluoride

PVF Polyvinyl Fluoride

PVPS Photovoltaic Power Systems Programme

RPT Replacement Payback Time

SoG-Si Solar Grade Silicon

SRM Strategic Raw Materials

TMAl Trimethylaluminium

WEEE Waste Electronic and Electrical Equipment

Wh Watt-hour

Wp Watt-peak

1 Motivation and Background

In an effort to mitigate climate change, sustainable energy technologies are being installed on a large scale as an alternative to the use of fossil fuels. One of the most prominent of these technologies is solar photovoltaic (PV) energy, which has the highest potential generation capacity of any renewable energy technology [1]. While the projected amount of cumulative installed PV capacity varies between studies, estimates reach up to 70 TWp (terawatt-peak) in 2050 [2], with the average between studies published from 2017 to 2020 falling at 25 TWp in 2050 [3]. Based on these results, it can be assumed that billions of PV modules will be installed in the following decades. Due to the exponential increase in the use of PV modules for the production of electricity, up to 78 million tonnes of cumulative PV waste are expected by 2050 [4], [5]. In the Netherlands, the total amount of installed PV capacity amounts to approximately 1.2 million tons [6]. Although PV modules typically have an assumed lifetime of 25 years or 30 years [7], many modules are decommissioned before reaching the end of this designated lifetime [6].

There is currently no cost-effective method to recover the critical materials inside the PV modules in high quality, as the waste volume is still too low for the PV recycling industry to benefit from economies of scale [8]. Therefore, most PV modules are coarsely shredded and only a small fraction of the materials is recovered [8]. The reuse of prematurely decommissioned modules represents an alternative strategy to the low-quality recycling that is the current practice in the Netherlands. However, significant technological advancements have been achieved with respect to the performance of PV modules: the typical efficiency of PV modules has seen a relative increase of over 40% between 2010 and 2020 [9], [10]. Replacing the decommissioned modules with new, more efficient modules might therefore be a strategy that holds a greater environmental benefit.

Considering the scale of the PV industry, it is paramount to establish which strategies are available to manage prematurely decommissioned PV modules and to determine the environmental implications of each strategy. Additionally, it is important to examine the future possibilities for high-quality recycling of the modules and to identify the environmental benefits of a circular PV energy sector.

1.1. PV MODULES

PHOTOVOLTAIC modules convert light coming from the sun into electricity using semiconductor materials inside the modules [11]. There are various semiconductor materials that are used in PV modules on a commercial scale, such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) [9], but crystalline silicon (c-Si) is by far the most common semiconductor material. The market share of silicon PV modules has hovered around 90% for the last 25 years and was about 95% in 2020 and 2021 [4], [12]. For this reason, proper management of decommissioned c-Si PV modules is the most pressing issue and this study is focused on c-Si PV modules specifically.

1.1.1. PV MODULE COMPONENTS

Crystalline silicon PV modules consist of several layers of high-quality materials such as silicon, silver, copper, solar glass and aluminium [5]. The aluminium frame and glass cover provide structural stability and help to protect the PV cells. The silver and copper inside the PV modules are used to conduct electricity. Besides the metals, glass and silicon, PV modules consist of different polymers. The solar cells are encapsulated by two layers of ethylene-vinyl acetate (EVA) which protect the cells from moisture and physical damage, and boost the longevity of the cells [13]. The backsheet layer of the module is commonly manufactured using polymers such as polyvinyl fluoride (PVF) or polyvinylidene fluoride (PVDF), but glass can also be used as a backsheet layer. This study focuses on PV modules that have a polymer backsheet. In figure 1.1, the components of a typical PV module, excluding the junction box, are shown in a 3D model.

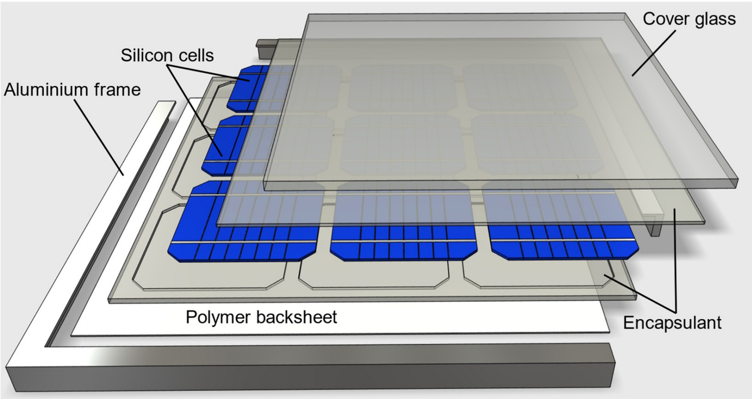

Figure 1.1.: Exploded view of a typical glass-backsheet silicon PV module [14].

1.1.2. PV MODULE OUTPUT & (MATERIAL) EFFICIENCY

The efficiency and power output of commercial PV modules have increased significantly over the last decades. In 2010, the typical efficiency of commercial crystalline silicon-based PV modules in the United States was 14% for both mono c-Si and multi c-Si modules [9]. In comparison, the average module efficiency of modules installed in the United States in 2020 was approximately 19.7% for mono c-Si and 17.5% for multi c-Si [15]. A typical mono c-Si PV system in 2020 therefore generated 40.7% more energy per square meter than a typical mono c-Si system in 2010, even without taking the degradation of the PV modules from 2010 into account. This is one of the factors that complicate the business case for the reuse of PV modules.

Another issue with respect to reusing old PV modules is the increased material efficiency of newer modules. For example, between 2004 and 2018, the peak power produced per gram of silicon has tripled [16]. This could mean that it might be more sustainable to, if possible, opt for high-quality recycling instead of reuse and produce a higher number of new modules with the silicon and silver extracted from old modules.

1.1.3. Safety & Quality Degradation

After years of use, PV modules generally experience a degradation in terms of performance and increased safety hazards [17], [18]. As PV modules age, they are prone to a range of defects that can occur due to factors such as exposure to the elements and mechanical stresses.

Two of the most common PV module degradation modes are delamination and backsheet defects [18]. Delamination is the separation of layers within a module, often due to exposure to moisture or other environmental factors. Delamination can result in reduced performance [18]. Most PV modules have a polymer backsheet, which can degrade over time, particularly if exposed to high temperatures or humidity. The degradation due to environmental stress can eventually lead to delamination and/or backsheet cracking. Backsheet cracking is another major problem that can lead to impaired electrical insulation, ground faults and current leakage. Both delamination and backsheet cracking can pose safety hazards by allowing penetration of moisture into the module. The PV cells can also develop cracks due to thermal stress or mechanical damage, which can lead to reduced power output and hot spots. Hot spots can create burn marks on the module and further reduce power output and in some cases even lead to fires [19].

The decrease in power output over time, which one can typically expect to be between 0.5% and 1% per year depending on the vintage of the module [17], further increases the difference in performance between old and new modules and further weakens the business case for used modules.

In this study, it assumed that the decommissioned PV modules have been tested and are functional. The modules have a decreased efficiency due to degradation over time, however they do not exhibit any defects that would prevent the modules from being reused.

Figure 1.2.: Examples of backsheet degradation and failure: cracking (left) and delamination (right) [18].

1.1.4. PV MODULE TESTING

The electrical properties of (decommissioned) modules can be determined using a flash test [20]. This method allows a comparison between the expected performance degradation forecasted by the module manufacturer and the actual performance of the module.

In a flash test, a sun simulator provides illumination with similar characteristics to natural sunlight while a variable resistive load is applied to the terminals of the PV module [20]. The test yields an I-V (current vs. voltage) curve that can be examined to assess the performance of the module. Flash testing is a fast testing procedure, since the duration of a flash is in the order of thousandths of a second [20].

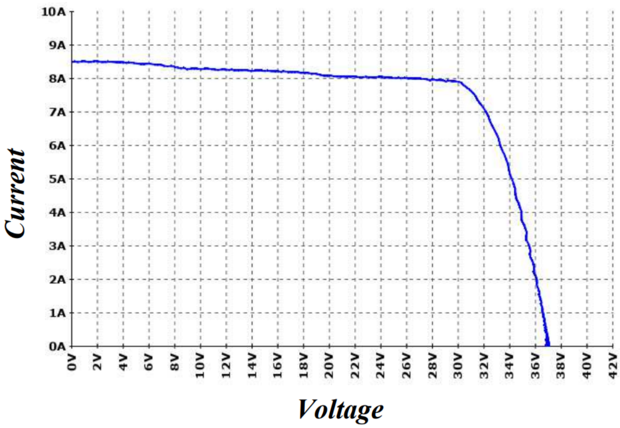

Figure 1.3.: I-V curve of a 'flawless' PV module [20].

Figures 1.3 and 1.4 show the I-V curves of a 'flawless' PV module and a PV module that exhibits delamination. The I-V curves were obtained through a flash test using a sun simulator [20]. In this particular case of delamination, the output of the module was only 32% of the output of the module in perfect operation [20]. The

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performance of the module is far below the expected degradation of the module, which in the case of the study by Kozsely et al. [20] was 5.1%. The delaminated PV module should therefore not be considered for reuse.

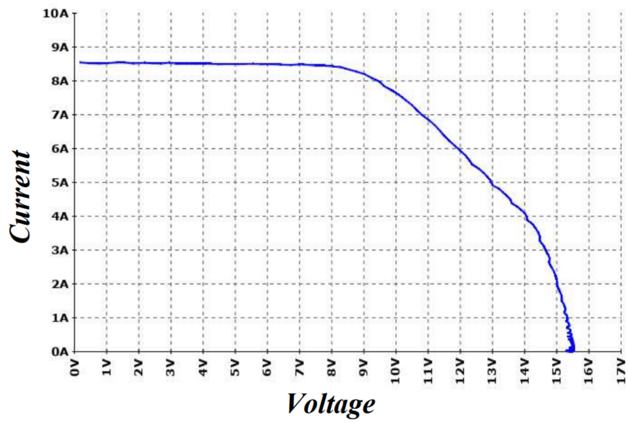


Figure 1.4.: I-V curve of a delaminated PV module [20].

1.2. BALANCE OF SYSTEM

THE balance of system (BoS) encompasses all components of a PV system aside from the PV modules. The BoS is essential to the functioning and safety of a PV system. The PV system discussed in this study is visualized in a simplified diagram in figure 1.5, with the singular PV module representing an array of modules. The BoS typically consists of an inverter, mounting system, lightning protection, a fuse box and cabling.

Of the BoS components, the inverter and the mounting system are of most interest in this study, as those typically have the highest environmental impact in a PV system after the PV modules [21]. The inverter transforms direct current (DC) from the PV modules into alternating current (AC), in order to connect the PV system to the electric grid. The mounting system is used to safely fix solar panels to the ground or to a roof. The lifetime of the inverter in a PV system is shorter than that of the PV modules and is typically assumed to be 15 years [21], [22]. Because of its comparatively short lifetime, it is assumed in this research that the inverter of the decommissioned modules is not reused. The reuse of the mounting system is treated in section 5.3.

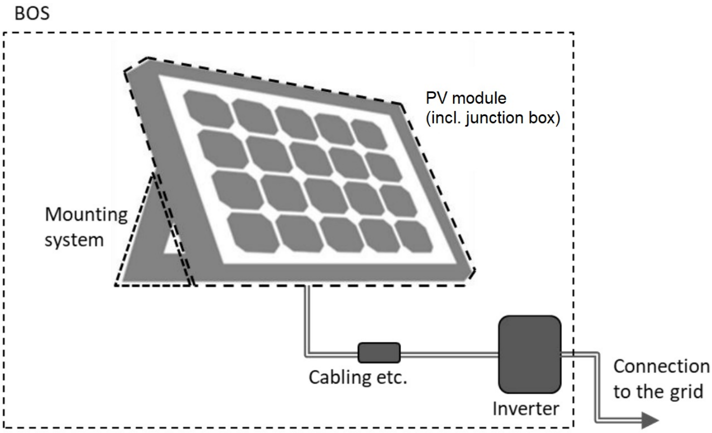


Figure 1.5.: PV system components discussed in this study (simplified). Adapted from [23].

1.3. End-of-Life of PV Modules

Photovoltaic systems for commercial and private use started to become increasingly popular in the Netherlands in the early 2000s [24]. Considering a lifetime of 20 years for modules manufactured around this time [25], a considerable amount of PV modules installed in those years will soon reach their EoL. Aside from reaching the end of their physical lifetime, there are other reasons for PV modules to (prematurely) end up in the waste stream, such as repowering. When PV modules are decommissioned, they are often landfilled or, as is the case in the Netherlands, downcycled [8]. Potentially, PV modules may instead be reused, either within the Netherlands, elsewhere within the EU, or on a different continent entirely.

1.3.1. PV System Repowering

One reason for PV modules to be decommissioned prematurely is the repowering of PV systems. When a PV system is repowered, functional PV modules are replaced by new, more efficient modules. The PV system will then have a significantly higher power output for the following years. The cost of replacing the PV modules is covered by the increased energy yield. Repowering can improve the profitability of a PV power station, but can also be environmentally beneficial, provided that the old modules are recycled properly [26]. The dynamics of the repowering process are driven by innovation (increased efficiency of newer modules) and degradation (efficiency decrease of modules during use). The effect of these dynamics on the potential for reuse are analysed in this report.

1.3.2. Reuse of PV Modules

If PV modules that are being decommissioned have not reached their physical end-of-life yet, one might consider to reuse these PV modules in an effort to reduce the waste volume and to increase the total yield of the PV modules. However, the context in which PV modules can be given a second life is not evident, since the business case for old modules is not immediately clear.

The solar PV industry is characterized by rapid technological developments as well as ongoing cost reductions, and state-of-the-art PV modules are significantly outperforming old modules [16]. PV modules only account for a fraction of the cost of a PV system, as the cost of the inverter, labour cost, etc. also have to be taken into account. The different costs associated with the installation of a commercial PV system are shown in figure 1.6. In a commercial ground-mounted PV system, the PV modules might only amount to as little as 15% of the total cost of the system [10]. For these reasons, even under very conservative assumptions, it is highly unlikely that a second-life PV system would generate electricity at a lower cost than a new system installed at the same location [27].

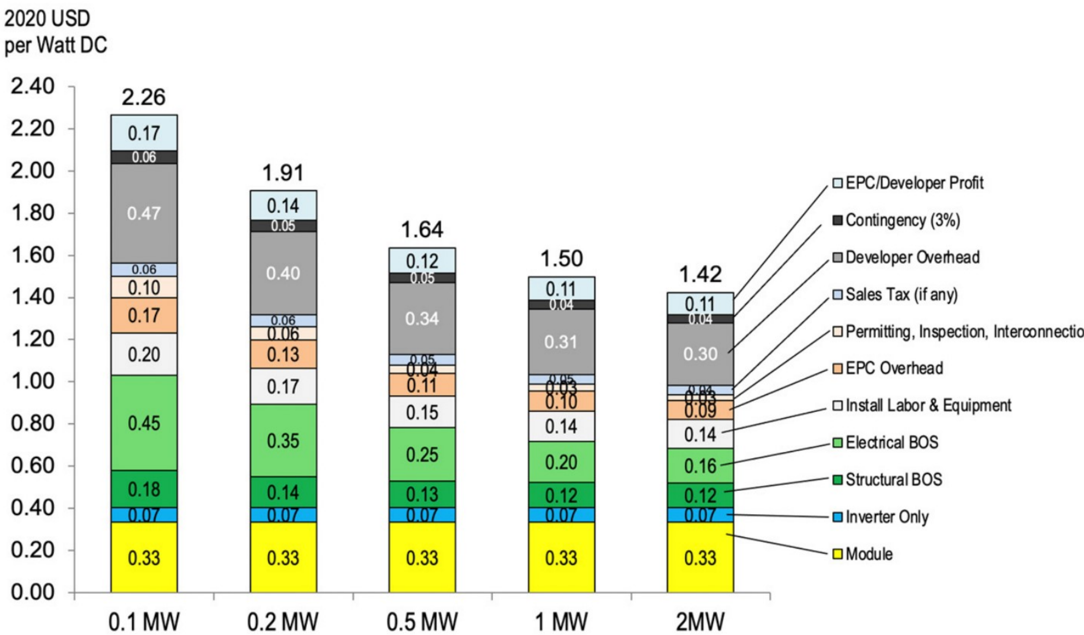


Figure 1.6.: U.S. benchmark: Commercial ground-mounted PV system cost (2020 USD/W_{DC}) [10].

Contrary to the lack of financial incentives, there might be environmental incentives for the reuse of decommissioned PV modules. In a 2021 report, Rajagopalan et al. (IEA PVPS) [21] demonstrated that, under specific circumstances, it is beneficial to the environment to keep the PV modules in use until the end of their physical lifetime as opposed to installing new modules every 10 or 15 years . The report by the IEA PVPS is discussed in more detail in subsection 1.9.

1.3.3. Recycling of PV Modules

The PV module recycling industry has not, as of 2022, matured sufficiently to facilitate profitable, high-grade recycling while recovering the valuable (critical) materials inside the module [8]. There are several possible routes for PV recycling, which can be divided into down-cycling and recycling.

Currently, the down-cycling route is the most common waste management method for PV modules in the Netherlands [8]. This route uses existing recycling infrastructure, e.g. glass recycling plants [28], to mechanically crush or shred the PV modules. After this process, the different materials inside the modules can be separated using an eddy current separator. Unfortunately, most materials are not recycled at a high grade and instead are utilized in lower value applications, such as filler material and sub bases for roads [8].

An example of a company in Europe carrying out the down-cycling of EoL PV modules is *BNE Trading & Recycling* in Belgium, whereas *Caparis N.V.* in the Netherlands and *Reiling Group* in Germany are two examples of companies that are recycling EoL PV modules [6]. In figure 1.7, the resulting materials after mechanical processing at a *Reiling Group* recycling plant can be seen.

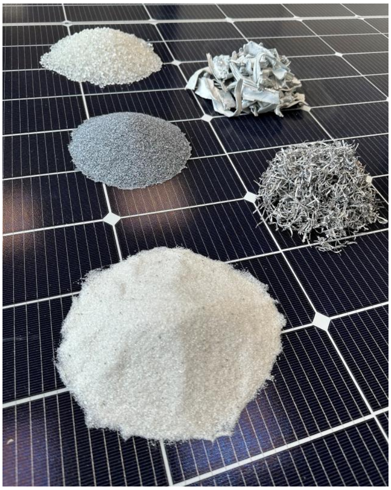


Figure 1.7.: Recovered PV module materials after mechanical processing: glass (fine and coarse grain), silicon, busbars (tinned copper) and aluminium [28].

The high-grade recycling of PV modules represents a critical step towards a sustainable PV energy sector [29]. Despite the fact that several technologies for this type of recycling have already been developed, the industry for high-grade recycling of PV modules has yet to reach maturity [8]. The challenges faced by the industry include ensuring the cost-effectiveness of recycling processes and the establishment of an appropriate collection and logistics infrastructure [29]. The demand for antimony containing glass might also pose a challenge, [8]. Nevertheless, regulations on EoL PV and R&D investment in PV recycling are expected to facilitate high-value, low-cost recycling in the future [30].

1.3.4. Landfilling of PV Modules

Due to a lack of policy mandates and a lack of financially viable recycling options, landfilling is a common method to manage discarded PV modules in many countries outside Europe [21]. It is evident that this waste management strategy is not sustainable because of the loss of (critical) raw materials. Additionally, multiple studies have demonstrated that the recycling of EoL PV modules is an important step to limit the environmental impact of their life cycle [31], [32]. Furthermore, the practice of landfilling does not align with the EU waste recycling targets and the Critical Raw Materials Act proposed by the European Commission [33], [34]. Landfilling is therefore not considered a viable PV waste treatment strategy in this study.

1.4. Recyclability of PV Module Materials

The recycling (as opposed to landfilling) of PV modules is beneficial from an environmental perspective since it allows the manufacturing of new products using secondary materials instead of primary materials. Primary materials are produced using raw materials, such as ores. Secondary materials, on the other hand, are produced by recycling (e.g. remelting) used primary materials. Secondary materials usually have a substantially lower environmental impact than primary materials [35]. The extent to which the different layers of a PV module can be recycled varies. In this section, the recyclability of the most important PV waste materials is described.

1.4.1. Glass Recyclability

Glass is an eminently recyclable material and can be recycled indefinitely without any loss of performance [36]. However, the high-quality solar glass used for PV modules is often down-cycled into fiberglass or glass pellets [6], [28], even though energy savings of up to 30% can be achieved by replacing the virgin material by glass cullet [37].

Seeing as glass accounts for around 70% of the mass of a silicon PV module [38], it is an important material to recycle to reduce the volume of the PV waste stream. The glass fraction of a PV module can be effectively recovered by applying the 'hot-knife' method. In this process, after the aluminium frame of the PV module has been removed, the module is clamped between two rollers that run the module through a steel blade that has been heated to 180-200 °C [39]. This separates the glass layer from the rest of the PV module. Glass recovery rates of 98% have been demonstrated [38]. The hot-knife technology is being used in one of the largest PV recycling facilities in the world (by *Soren* and *Envie 2E Aquitaine*) in France, near Bordeaux [40].

Figure 1.8.: Flowchart of the “hot knife” process used to remove glass sheet from PV modules [39].

The composition of solar glass varies depending on the production method. Solar glass is commonly produced via the rolled glass process, using antimony as an additive [41]. Antimony is added to reduce the absorption of light by iron atoms present in the glass, thereby improving the module efficiency as well as the stability of the solar performance of the glass when exposed to sunlight [38], [42]. Antimony is poisonous and high antimony concentrations are toxic to ecosystems and potentially are toxic to public health through accumulation in the food chain [43]. Due to the antimony content of solar glass, it is important that solar glass is kept separate from other types of glass, in particular from glass used in the food industry. The fraction of solar glass that contains antimony and the weight percentage of antimony in antimony-containing solar glass are unclear and can be considered trade secrets. In a 2016 report, the European Commission assumes a range of 0.01 - 1% antimony per kg of solar glass [38]. After laboratory analysis of a solar glass sample, The OPEN Foundation found an antimony content of 0.22% [6].

In the EU, the majority of flat glass is produced via the float glass process, in which the glass panel is manufactured in a liquid tin bath [41]. When (recovered) antimony-containing glass is introduced in this manufacturing process, the antimony reacts with the molten tin causing a colouration on the surface, rendering the glass unusable [41]. Antimony-containing glass can in principle be recycled to produce new (antimony-containing) solar glass via the rolled process [41]. In the rolled process, molten glass is poured on metal sheets and flattened with a large roller.

Closed-loop recycling of solar glass via the rolled process would present an effective solution to the large volume of antimony-contaminated glass waste coming from the PV industry, as well as its large demand for solar glass. Recycling solar glass entails the added benefit of recycling antimony, which is a critical raw material [33], further improving the potential environmental benefits of PV waste recycling [38].

1.4.2. Metal Recyclability

Aluminium, copper and silver are the predominant metals present in PV modules, and these metals can be recycled effectively [38]. In principle, metals can be recycled infinitely, using processes that consume substantially less energy than the primary production methods of the metals [35]. A very high percentage (e.g. Al 99%, Cu 99%, Ag 94% [38]) of the metals can be recovered. However, the recovery rates of these metals depend on the recycling process that is applied, and different recycling technologies are needed to recover each element. The aluminium frame can be easily removed from the PV module. The majority of the recovered copper in PV recycling comes from the copper in the cables, which is usually recovered through incineration of the polymer covering the copper wire [35]. For the recovery of silver and the remaining copper fraction, which are part of the solar cell, chemical processing (usually an acid leaching process using nitric acid) needs to be implemented in the recycling process [38], [44].

1.4.3. Silicon Recyclability

Silicon can be recovered from old modules by using a combination of mechanical, thermal and chemical processing [45]. The production of the silicon semiconductor inside the PV module represents a large share of the total environmental impact of the module, because high purity, solar grade silicon (SoG-Si) with 6N (>99.9999%) or higher purity is used, and the silicon purification process is highly energy intensive [46]. The environmental impact of PV module production could therefore be reduced if one can efficiently recover SoG-Si from discarded PV modules. However, current silicon recycling practices yield silicon with too many impurities to be considered solar grade, and is considered metallurgical grade silicon (MG-Si) (>98% purity) instead [8]. Nevertheless, MG-Si from discarded modules can be chemically treated and remelted into SoG-Si [47]. In this study, it is assumed that the silicon recovered through PV module recycling will not have a purity higher than metallurgical grade.

Reuse of intact silicon solar cells

There have been successful experiments on the reuse of intact c-Si solar cells on lab-scale [48]. However, considerable challenges for the large-scale reuse of recovered cells have been identified. They are often cracked, even in PV systems that are still producing power, and PV cells are becoming increasingly fragile as a result of decreasing wafer thickness [49]. Additionally, given the rapid developments in the PV industry, it is unlikely that recovered cells coming from old PV modules will be of commercial interest [49]. For these reasons, the reuse of solar cells from decommissioned PV modules is not considered in this study, only the reuse of the whole, intact PV module is considered.

1.4.4. Polymer Recyclability

The primary sources of polymers in PV waste are the backsheet layer, the EVA encapsulant of the solar cells and the cables [38]. The polymers are usually not recyled, neither in rudimentary PV recycling processes [28], nor in state-of-the-art PV recycling processes [38], but instead incinerated. Because the debonding of the EVA layer is critical for recycling PV modules, different methods of removing and/or recycling the EVA encapsulant are continuously researched. Pyrolysis and chemical dissolution are two techniques that are used for the debonding of the EVA but they do not allow recycling of the polymer [50]. Laser irradiation of the encapsulant is a novel technology with satisfactory results on lab scale for the recycling of EVA [50]. In this research, the backsheet layer, the encapsulant and the cables (excluding the copper wires) are either incinerated with energy recovery or landfilled, depending on the scenario.

Backsheet Pyrolysis

The backsheet of a PV module can be manufactured using fluorinated materials such as polyvinyl fluoride or polyvinylidene fluoride, or fluorine-free materials, such as polyethylene terephthalate (PET). For fluorine-free backsheets, pyrolysis can be considered as a treatment option. Some studies have demonstrated an advantage in several impact categories when comparing pyrolysis of fluorine-free backsheets to incineration [38], [51]. However, pyrolysis of fluorinated backsheet materials is not viable either financially or environmentally, as this process produces a high amount of hydrogen fluoride, which poses an environmental hazard [52]. Since the backsheet market is dominated by fluorinated materials [51], pyrolysis is not considered a viable pathway for the treatment of PV module backsheets in this study.

1.5. Critical Raw Materials & The Critical Raw Materials Act

Several of the materials inside PV modules are classified as critical raw materials (CRM) by the European Commission. The main parameters used to determine the criticality of a material for the EU are the economic importance and the supply risk [34]. Based on the 2023 assessment by the European Commission, the materials in figure 1.9 have been identified as CRMs:

2023 Critical Raw Materials (*Strategic Raw Materials in italics)*			
aluminium/bauxite	coking coal	*lithium*	phosphorus
antimony	feldspar	*LREE*	scandium
arsenic	fluorspar	*magnesium*	*silicon metal*
baryte	*gallium*	*manganese*	strontium
beryllium	*germanium*	*natural graphite*	tantalum
bismuth	hafnium	niobium	*titanium metal*
boron/borate	helium	*PGM*	*tungsten*
cobalt	*HREE*	phosphate rock	vanadium
		*copper**	*nickel**

* Copper and nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials.

Figure 1.9.: 2023 European Commission Critical Raw Materials list [34].

Strategical Raw Materials (SRMs) are materials that do not meet the CRM threshold but are nonetheless indispensable throughout the value chain. For example, copper does not meet the threshold to be considered a CRM since its supply is very well diversified. However, its performance in electrical application makes this material difficult to substitute and therefore it is deemed a SRM [34].

In a 2016 report, the European Commission identified various CRMs that are used in the PV sector [38]. Table 1.1, illustrates the amount of materials used during the manufacturing and recycling of one tonne of PV modules. It should be noted that the research was conducted in 2016 and the composition of PV waste is continuously changing. Also, the origin of the substantial fraction of iron is not clear, since silicon PV modules do not typically contain a significant amount of iron. A possible explanation for this of amount iron is the inclusion of the mounting system in the manufacturing system boundary, but this is not clarified in the report. Table 1.1 thus only serves as a rough representation of the material requirement. The study shows that 7 CRMs and 7 SRMs were used during the life cycle of the PV modules.

Table 1.1.: Material requirement for the production and recycling of 1000 kg of PV panels. Adapted from [38] to match the 2023 Critical Materials List [34]. CRMs are displayed in bold. Asterisks denote SRMs.

Material	Mass [kg]	Material	Mass [kg]
Gravel, in ground	1.87E+03	**Phosphorus, total**	2.59E-01
Aluminium	2.21E+02	Molybdenum, total	1.47E-01
Iron	1.01E+02	Tin	5.63E-02
Clay	1.08E+02	Tellurium	2.72E-02
Fluorspar	1.86E+01	Talc	1.96E-02
Copper*, total	6.99E+00	Diatomite, in ground	6.95E-05
Nickel*, total	6.04E+00	Gold, total	3.83E-05
Antimony	5.24E+00	**Tantalum**	3.83E-05
Baryte	4.22E+00	**Feldspar, in ground**	1.52E-05
Chromium	3.17E+00	Indium	1.53E-05
Manganese*	3.18E+00	**Cobalt***	5.65E-06
Sand, unspecified, in ground	2.79E+00	**Lithium***	3.70E-06
Zinc	2.42E+00	Palladium, total	3.61E-06
Clay, bentonite, in ground	1.64E+00	Platinum, total	5.68E-07
Magnesite*, 60% in crude ore	1.35E+00	Rhenium, total	2.01E-08
Gypsum, in ground	1.02E+00	**Gallium***	1.28E-08
Silver, total	5.52E-01		

Since the European Commission has identified these materials as indispensable for the EU economy and the renewable energy sector, it has proposed the Critical Raw Materials Act. The CRM Act is designed to ensure EU access to a secure and sustainable supply of CRMs. One of the cornerstones of the CRM Act is the collection and recycling of CRM-rich waste in order to recycle these materials into secondary CRMs [34]. Following the goal of achieving 15% of the EU's annual consumption of CRM through recycling, it is desirable to reduce the export of CRM-rich waste to non-EU countries. Not only would this lead to CRMs leaving the EU, increasing the EU's need to import CRMs, but, depending on the export destination, might also lead to CRMs being landfilled.

1.6. Life Cycle Assessment & Life Cycle Inventory

Life cycle assessment (LCA) is a comprehensive evaluation of the environmental impact of a product throughout its entire life cycle, from raw material extraction to disposal of the product [53]. It can be used to compare different products and manufacturing technologies, but also different waste management strategies [54]. The Life Cycle Inventory (LCI) is the data collection component of the LCA and consists of the compilation and quantification of inputs and outputs of materials and energy of a product during its life cycle [55].

In the case of this study, an LCA is carried out to compare various scenarios with respect to the EoL of PV Modules. Results from the LCA can be used to inform about potential environmental impacts of each scenario and suggest possible improvements, strategies and policies.

1.6.1. PV Life Cycle Inventory

There are two prominently used LCI sources for existing PV LCAs, being the ecoinvent database, which covers the production of crystalline silicon PV modules in 2005, and the IEA PVPS 2015 dataset [56], which treats the production of the same module type in 2011 [23]. In a 2021 report, Müller et al. [23] demonstrate that using either the ecoinvent (v3.7) or the IEA PVPS 2015 LCIs leads to a significant overestimation of the environmental impacts of PV module manufacturing. Müller et al. [23] have therefore compiled updated LCI data, in order to perform a more accurate assessment of the environmental impacts of PV module manufacturing. The inventory data by Müller et al. [23] are taken as a guideline for the LCIA (Life Cycle Impact Assessment) of module manufacturing in this study.

To further improve the accuracy of the assessment in this study, impacts are calculated using the IDEMAT database [57] (instead of the ecoinvent database) where possible. The IDEMAT database was developed in collaboration with Delft University of Technology following a growing dissatisfaction with the lack of transparency and accuracy of the ecoinvent database [58]. IDEMAT data are based primarily on peer-reviewed scientific papers and LCIs made by Delft University of Technology. It is not possible to base the LCIA completely on IDEMAT data, since only a fraction of the ecoinvent datasets have an IDEMAT equivalent.

1.7. Impact Categories

In this study, the environmental impacts are calculated based on three different impact categories. The impact categories are: global warming potential (GWP) [kg CO_2-eq], eco-costs of resource depletion [€] and total eco-costs [€].

The global warming potential (sometimes referred to as climate change impact or carbon footprint) is a common method of quantifying environmental impacts. The concept of GWP was developed to allow the greenhouse effect of different greenhouse gases to be easily compared by expressing their greenhouse effect in terms of carbon dioxide (CO_2) equivalent [59]. The GWP of a substance depends on the time horizon over which it is calculated, because the rate at which the gas concentration decays over time in the atmosphere is different for different substances

[59]. This means that the GWP of a gas can be different when the time frame is 20 years compared to when the time frame is 100 years [59]. Usually, the time horizon used for GWP calculations is 100 years and it is also the time horizon used in this study. This impact category was selected for this study because it relates directly to EU (and global) climate goals such as the 2015 UN Paris Agreement (greenhouse gas emissions must decline by 43% before 2030) [60] and the 2019 European Green Deal (net-zero emissions of greenhouse gases by 2050) [61].

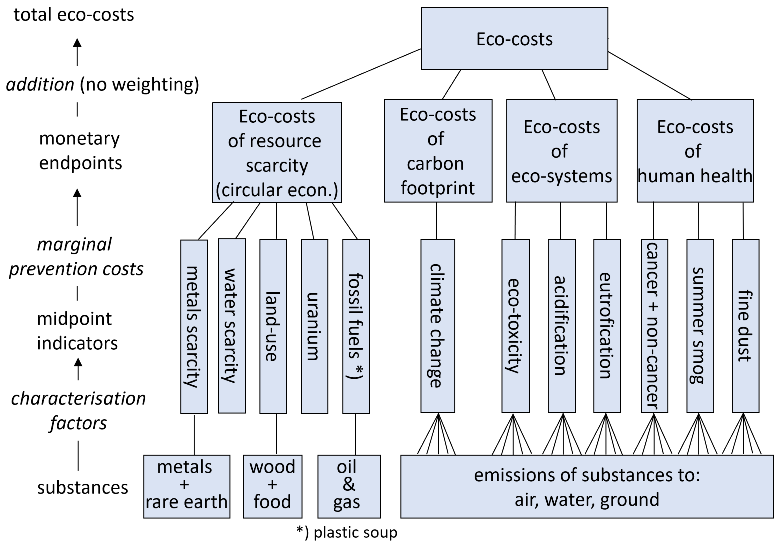


Figure 1.10.: The eco-costs model developed by Vogtländer et al., showing the different components [62].

The eco-cost of resource scarcity is an impact category developed by Vogtländer et al. and is a method to quantify the short-term supply risk of metals [63]. It is an alternative to the classical LCA approach in which the impact category abiotic depletion potential (sometimes referred to as mineral and metal resource use) is used. This impact category is expressed in kilograms of antimony-equivalent (kg Sb-eq). The classical approach aims to express the scarcity of resources for future generations (100-1000 years) in relation to the scarcity of antimony, but Vogtländer et al. argue that the long term availability is simply not known (within a factor of 100-1000) [63]. The eco-cost method instead focuses on the short term (10-30 years) supply risk of metals, in line with the philosophy of the CRM parameters of the EU.

The total eco-costs is an impact category that, likewise, has been developed by Vogtländer et al. [63]. It is the sum of the eco-costs of human health, ecosystems, resource scarcity and carbon footprint. Figure 1.10 shows the subcomponents of the different eco-costs and the total eco-cost. The eco-cost of resource scarcity is the sum of abiotic depletion (scarcity of metals, rare earth elements and energy carriers), land-use, water, and land-fill. This impact category was selected in this study because it quantifies all environmental impacts in a single indicator.

1.8. STICHTING OPEN/THE OPEN FOUNDATION

THE OPEN Foundation is a Dutch producer responsibility organization (PRO). It is responsible for the collection and treatment of waste electronic and electrical equipment (WEEE) in the Netherlands, including decommissioned PV modules. The OPEN Foundation does not own or operate any recycling or sorting facilities but instead contracts external parties to treat the WEEE it collects.

It is of significant interest to the OPEN Foundation to have a fundamental understanding of whether the reuse or the recycling of decommissioned modules holds the greatest environmental benefit. The age and (remaining) efficiency of the decommissioned modules evidently play a role in this. This study will make it easier to determine which panels should be considered for reuse and which panels should go directly to recycling.

1.9. KNOWLEDGE GAP

THERE have been many life cycle assessments of PV module manufacturing. More than a dozen of these studies were collected and reviewed by Müller et al. in a 2021 publication [23]. Life cycle assessments on high-quality recycling of PV modules are scarce, only one study was found in which enough LCI data is specified to be able to reproduce and adapt the LCIA (2016 report by the European Commission [38]).

However, there are no peer-reviewed papers that specifically treat the reuse potential of PV modules (in the Netherlands). This knowledge gap has been identified before, in a 2021 report by the IEA PVPS [21]. The report is discussed below. In the report, it is argued that "there is no market or literature for prematurely decommissioned PV panels whose lifetime can be satisfied through repair or direct reuse" and the results of the study should therefore be considered preliminary.

It is therefore not clear if, or under which circumstances, it is desirable from an environmental perspective to reuse decommissioned PV modules coming from the Dutch market as compared to recycling and replacing them. This study aims to answer this question and could therefore contribute to the academic and political discussion on decommissioned PV modules in terms of environmental impact reduction, waste reduction and policy making.

IEA PVPS - PRELIMINARY ENVIRONMENTAL AND FINANCIAL VIABILITY ANALYSIS OF CIRCULAR ECONOMY SCENARIOS FOR SATISFYING PV SYSTEM SERVICE LIFETIME

The International Energy Agency (IEA) has published a report in 2021 that has similarities to this study and in which two broad strategies for the management of decommissioned PV modules are compared [21]:

- Premature recycling and replacement of decommissioned modules.
- Satisfying the typical service lifetime of 30 years of these modules through circular economy strategies such as repair and reuse.

The report assesses the environmental and financial burdens and benefits of these two scenarios. In the report, it is suggested that it is better for the environment to keep the modules in use until the end of their 30-year lifetime. However, there are important differences in the approach used in the IEA report and the approach used in this study. In the IEA report, the starting point of the environmental assessment is a new PV module. It is then analysed whether it is favourable (environmentally or economically) to replace the module every 10 or 15 years, or use the module until the end of its expected lifetime of 30 years.

Contrary to the IEA report, this study takes decommissioned modules which have degraded over time as the starting point. In other words, using decommissioned modules in a new PV system is compared to using new modules in a new PV system. Furthermore, Müller et al. [23] argue that the IEA overestimates the environmental impact of PV module production by at least 52%.

1.10. Research Questions and Objectives

This research aims to support the OPEN Foundation in identifying the most environmentally beneficial strategy for decommissioned but functioning PV modules collected in the Netherlands.

The main research question of this thesis therefore is:

Under which circumstances does the recycling and replacement of PV modules have a greater environmental benefit than the reuse of PV modules?

To answer this question, the following sub-goals are defined:

Sub-goal 1: Define different scenarios for the decommissioned but functional PV modules.

By describing a set of scenarios that could apply to decommissioned PV modules from the Netherlands, ranging from a base scenario based on current recycling practices to more ambitious developments in PV module waste management as well as different reuse scenarios, a broad overview of the possible strategies can be provided.

Sub-goal 2: Collect the LCI data and define the LCA method.

LCI data of many different processes need to be collected before the LCIA can be conducted to properly describe each scenario. All the materials, fuels and energy sources used within the chosen system boundary need to be determined.

Sub-goal 3: Compare the scenarios in terms of environmental impacts.

After the LCIA has been conducted, the different scenarios need to be compared to assess which of the scenarios is most environmentally beneficial. The comparison should be based on the total environmental benefit, the emissions intensity of the produced electricity and the duration for which the benefits of reuse outweigh those of replacement.

1.11. THESIS OUTLINE

THIS report consists of 8 Chapters. Chapter 1 introduced the research topic and explained the motivation behind the research. In chapter 2, the process of defining different scenarios for decommissioned PV modules is described. After that, in chapter 3, the methods used to quantify the environmental impact of each scenario are explained. Chapter 4 presents the results of the research. In chapter 5, four different sensitivity analyses are applied to gain an improved understanding of the most important parameters. Chapter 6 evaluates the quality and meaning of the results, while in chapter 7 the key conclusions of the research are highlighted and. In chapter 8 a number of recommendations for further research are discussed.

1.12. CHAPTER SUMMARY

This chapter introduced the motivation behind the research and provided background information: PV technology is developing rapidly and new modules are much more efficient than old modules. Additionally, old PV modules have experienced degradation during their use. The yield of new modules is therefore substantially higher. Because of this, many PV systems are repowered before the end of their functional lifetime. It is difficult to find a good business case for the decommissioned modules, which is why many functional PV modules are recycled. At the moment, this is a rudimentary recycling process in which only the aluminium and some copper is recovered. However, since most PV module materials (glass, silver, copper, aluminium) can be recycled effectively, a high-quality recycling process might be implemented in the near future.

Despite the lack of a financial incentive, there might be an environmental incentive to reuse the decommissioned modules as opposed to recycling and replacing them. This leads to the main research question:

Under which circumstances does the recycling and replacement of PV modules have a greater environmental benefit than the reuse of PV modules?

To answer that question, the current and future strategies to manage decommissioned modules need to be identified. After the scenarios are defined, the environmental impact of each scenario can be assessed by conducting an LCA. The LCA will be conducted using a combination of the ecoinvent and IDEMAT databases, and three impact categories are chosen to express the environmental impacts: global warming potential, eco-cost of resource scarcity and total eco-cost.

Three sub-goals are set to perform the analysis:

- Sub-goal 1: Define different scenarios for the decommissioned but functional PV modules.

- Sub-goal 2: Collect the LCI data and define the LCA method.
- Sub-goal 3: Compare the scenarios in terms of environmental impacts and feasibility

The next step in the research is to define the scenarios.

2

Definition of Scenarios

Four different end-of-life scenarios for functional, decommissioned PV module are compared. Two of these scenarios consider the recycling of the decommissioned modules and the other two scenarios consider the reuse of the modules. In the recycling scenarios, new modules are manufactured and installed, and compared to the scenarios in which the modules are reused. The following scenarios are reviewed:

- A: Low-quality recycling and replacement
- B: High-quality recycling and replacement
- C: Reuse within the Netherlands
- D: Reuse within the EU - Greece

The starting point of each scenario is 1000 kg of tested, functional decommissioned PV modules, that have experienced degradation during their use phase. The moment at which the modules are decommissioned cannot be controlled. Since the material composition of PV modules varies between manufacturers and models, and the average material composition of decommissioned PV modules changes over time, it is impossible to present a definitive material composition for all PV module waste. For this study, the mass composition as presented in table 2.1, based on a 2016 study by the European Commission [38], is assumed for the decommissioned PV modules. The specifications of the decommissioned PV modules are based on a report by the IEA PVPS [21] and correspond to modules manufactured in 2011. The annual specific energy yield in the Netherlands is assumed to be 961 kWh/kWp/year [64]. This means that the yield of a 1 kWp system is expected to be 961 kWh per year. In other countries, the annual specific energy yield is different, and a 1 kWp system might be able to produce more kWh per year.

For each scenario, an overview is presented of the environmental burdens and benefits that are associated with its specific conditions. The expected environmental impacts of the recycling processes, transportation and module manufacturing can then be calculated and combined with the expected energy yield of each scenario. With this information, the strategy that entails the greatest environmental benefit can be determined.

Table 2.1.: Assumed mass composition of 1000 kg of PV waste [38].

Component	**Quantity**	**Unit**
Glass, containing antimony (0.01–1%/kg of glass)	700	kg
Aluminium frame	180	kg
EVA encapsulation	51	kg
Silicon solar cell	36.5	kg
PVF Backsheet	15	kg
Cables (containing copper and aluminium)	10	kg
Internal conductor, aluminium	5.3	kg
Internal conductor, copper	1.14	kg
Silver	0.53	kg
Other metals (tin, lead)	0.53	kg
Total	**1000**	**kg**

2.1. A: Low-quality Recycling and Replacement

In scenario A, the current practices for recycling EoL PV modules in the Netherlands are maintained. In this rudimentary recycling process, the decommissioned modules are processed using existing recycling infrastructure, in which the modules are mechanically crushed and shredded. This recycling process yields aluminium and copper scrap, which can be recycled, but the other materials end up in lower value applications [8].

After the decommissioned modules have been recycled, they are replaced by new modules manufactured in China. The modules are transported by lorry, freight train and transoceanic ship to the port of Rotterdam. The transportation distances and modes of transport for the shipment from China to the Netherlands are based on a study by Müller et al. [23]. After the modules have arrived in the Netherlands, they are transported by lorry to an estimated average installation location.

There is a significant advantage to this scenario in terms of practicality. In the low-quality recycling scenario, the large variety of modules, which differ in output, vintage and dimensions, can simply be collected and recycled together. This contrasts the reuse scenarios, in which the modules preferably are of the same make and model, for aesthetic and performance reasons.

2.2. B: High-quality Recycling and Replacement

Scenario B covers the use of dedicated PV recycling facilities for the high-quality recycling of PV modules. The materials inside the PV module are recovered through the “Full Recovery End of Life Photovoltaic – FRELP” process as described by Latunussa et al. (European Commission) [38].

In the FRELP process, the aluminium frame and cables are removed from the module, after which the solar glass is separated from the PV sandwich layer in a high temperature process. The remaining sandwich is sectioned into 2 x 3 cm pieces and transported to an incineration plant, where the polymers in the PV sandwich are incinerated with energy recovery. The ashes are then sent back to the recycling plant. Through acid leaching of the ashes, the silver and copper can be dissolved while the silicon metal remains as a residue. The silver and copper are recovered through electrolysis. The last part of the chemical process is the neutralisation of the acid solution using lime (calcium hydroxide). The liquid waste and the sludge containing unrecovered metals and residual lime are transported to different landfill sites.

The FRELP process facilitates the recovery of more than 90% of the materials (wt.%). The recovered materials in this process are:

Table 2.2.: Material recovery of 1000kg of PV modules via the FRELP process [38].

Component	Quantity	Unit
Glass cullet	686.0	kg
Aluminium scrap	182.6	kg
MG-Si	34.7	kg
Copper scrap	4.4	kg
Silver scrap	0.5	kg
Total	**908.2**	**kg**

The material losses of the FRELP process, i.e. the materials that are not recycled, consist primarily of polymers. The EVA encapsulant, the polymer backsheet and the polymer used in the cables have a combined weight of 72.7 kg, representing 80.6% of the weight that is not recovered in the process. In the FRELP process, the polymers are incinerated with energy recovery [38].

The recovered materials are assumed to be used to manufacture new PV modules, decreasing the environmental impact of the PV module manufacturing process. Although not explicitly mentioned in the FRELP process, the recovered antimony-containing glass is recycled into solar glass via the rolled glass process. The new PV modules are manufactured in the Netherlands, which not only decreases the environmental impact of transportation (compared to manufacturing in China), but also the environmental impact of the manufacturing, since the Dutch energy mix is less emissions intensive than the Chinese energy mix [57].

SolarNL

In June 2023, SolarNL, a national research, innovation, and industrial investment program, was awarded with a 312 million euro subsidy from the Dutch government through the National Economic Growth Fund. The goal of the program is to bring back PV manufacturing to the Netherlands and Europe [65]. The subsidy demonstrates the desire of the Dutch government and the EU to strengthen local supply chains and this scenario might represent a part of the strategy to achieve it. Although the necessary infrastructure for this scenario does not exist yet, it is not unlikely that dedicated PV recycling plants and PV manufacturing infrastructure will appear in the Netherlands in the near future [6].

2.3. C: Reuse within the Netherlands

Scenario C treats the reuse of the PV modules within the Netherlands. The decommissioned modules are to be transported to a new location and used until the end of their 25-year assumed lifetime.

Keeping the older, lower-efficiency PV modules in use until the end of their lifetime has the advantage that the modules have already been manufactured, i.e. there is no environmental burden due to the manufacturing of PV modules. However, it is assumed in this research that this scenario involves forgoing the opportunity to install new, more efficient modules.

2.4. D: Reuse within the EU - Greece

In scenario D, the decommissioned PV modules are transported to a different country in order to increase the environmental benefits of the modules. The modules are to be reused in a country that:

- Is an EU member state and thereby has implemented the WEEE directive [66] through national regulations.
- Has a higher 'annual avoided burden per kWp' than the Netherlands.

The destination country of the decommissioned PV modules should be a country in which the potential environmental benefits of the modules are increased compared to when they are installed in the Netherlands. Two factors that can increase the environmental benefits of a PV module are the annual specific energy yield of a country and the emissions intensity of its electricity mix. Both of these factors need to be taken into account in order to get an understanding of the environmental benefits of PV electricity in a specific country.

Only comparing the emissions intensities of the electricity mixes is not enough, since some countries have a highly polluting energy mix but a low annual specific energy yield, leading to sub-optimal environmental benefits of the PV modules. By multiplying the two factors, the 'annual avoided burden per kWp' of each country can be calculated and the country in which the PV modules would have the greatest environmental benefits can be determined.

The average annual yield of selected EU member states [67] was compared to the global warming potential of their electricity production mixes (IDEMAT [57]). A scatter plot of this comparison can be seen in figure 2.1. The calculation of the IDEMAT Global Electricity impacts applies data from 2019. For 2020 and 2021, data were not stable because of COVID-19. For 2022, data are not stable because of the war in the Ukraine. Some countries (e.g. Poland, Estonia) are not included in the plot, since the annual specific yield of these countries was not available in [67]. The orange line in figure 2.1 indicates a constant avoided burden per kWp, where points to the left/bottom of line have a lower avoided burden per kWp than points to the right/top. Similar plots were made for the eco-costs of resource scarcity and the total eco-costs of the electricity production mixes. These graphs are presented in the appendix (A.1 and A.2 respectively).

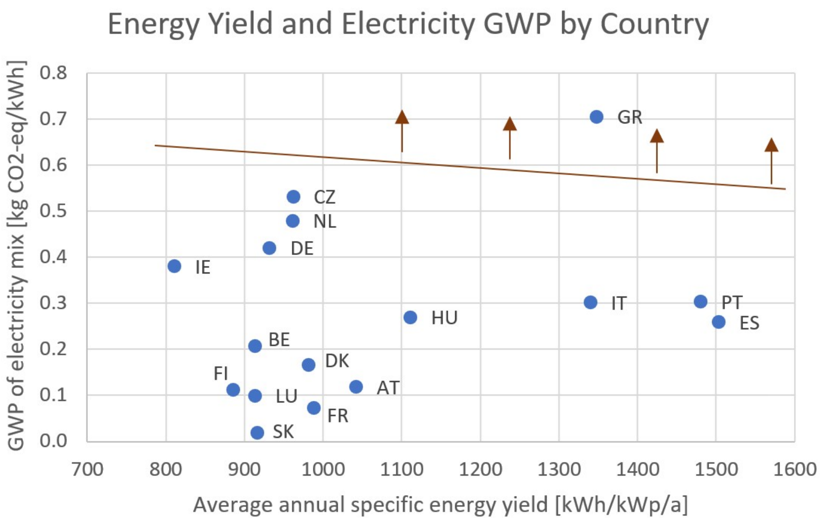


Figure 2.1.: Scatter plot of GWP of 2019 electricity production mix [57] vs. average annual specific yield of selected EU member states [67]. Orange line indicates constant avoided burden per kWp. Points to the left/bottom of line have a lower avoided burden per kWp than points to the right/top.

The avoided burden per kWp can be calculated using equation 2.1:

$$B = G_{mix} \cdot E_a \tag{2.1}$$

In which,

B	Annual avoided burden per kWp [kg CO_2-eq/kWp/a]
G_{mix}	GWP of electricity production mix [kg CO_2-eq/kWh]
E_a	Annual specific energy yield [kWh/kWp/a]

By examining figure 2.2, it can be concluded that countries such as Sweden and France have a very low annual avoided burden per kWp in terms of GWP. In other words, the environmental benefits (GWP) of a PV module are lower when it is installed in these countries than when it is installed in the Netherlands. Exporting the PV modules to a country that is to the left of the Netherlands in figure 2.2 is not beneficial from an emissions reduction perspective.

For this research, Greece is taken as a case study. Greece has an exceptionally high avoided burden per kWp, as can be seen in figure 2.2. The average annual specific energy yield in Greece is assumed to be 1348 kWh/kWp/year [64]. In this scenario, the PV modules are assumed to be used until the end of their 25-year designated lifetime.

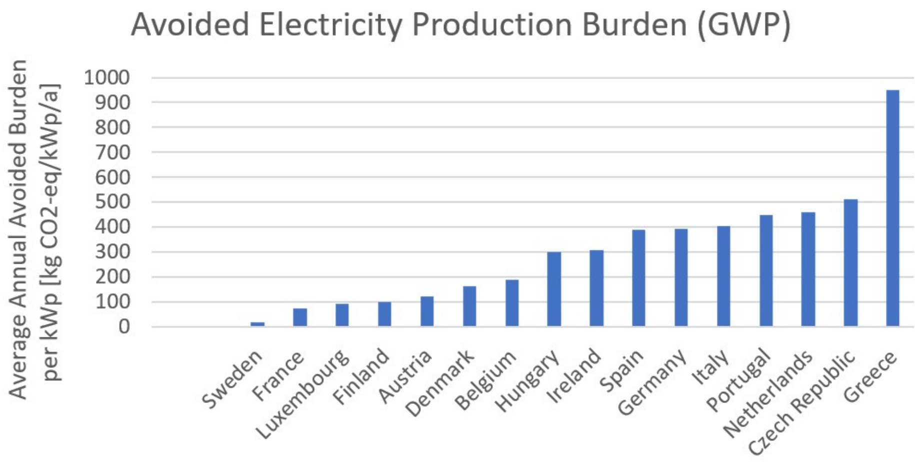


Figure 2.2.: Average annual avoided burden per kWp of selected EU member states. Calculated by combining the average annual yield of selected EU member states [67] and the GWP of their electricity production mixes [57].

2.5. EXPORT OUTSIDE OF THE EU

ONLY export within the EU is considered in order to retain the critical raw materials within the EU, following the CRM Act discussed in section 1.5. The WEEE directive requires the proper treatment of WEEE and has set targets for the collection and recycling of WEEE, including PV modules [66]. Exporting the PV modules to a country that has implemented the WEEE directive should decrease the risk of the disposal of the PV modules at an E-waste dump at the end of their lifetime.

Landfilling and informal recycling of electronic waste are common practices in many countries outside of the EU such as in Africa and Asia. For example, in India, informal recycling accounts for 95% of all E-waste recycling [68]. Informal recycling of E-waste often involves dumping or open burning of the remaining materials and is associated with child labour, health hazards and damages to the environment [69]. Ghana is another example of a country with a tremendous informal recycling sector and it is home to one of the largest E-waste dumps in the world [70]. Individuals working in this landfill are exposed to a number of toxic elements at concerning levels [70].

Considering the EU CRM Act, the WEEE directive, the high likelihood and associated health and environmental hazards of landfilling in non-EU countries, it becomes evident that exporting the decommissioned modules to countries outside of the EU should not be encouraged. Export outside of the EU is therefore not included as a scenario in this research.

2

2.6. Chapter summary

Four different scenarios for the decommissioned modules were defined. There are two scenarios in which the modules are recycled and replaced, and two scenarios in which the decommissioned modules are reused.

Scenario A (Low-quality recycling and replacement) represents the base case, in which the aluminium and copper is recovered from the modules and the old modules are replaced by new modules manufactured in China.

Scenario B (High-quality recycling and replacement) treats a more ambitious recycling scenario, in which 91% of the materials are recovered and the modules are replaced by new modules manufactured in the Netherlands.

Scenario C (Reuse within the Netherlands) covers the reuse of the decommissioned modules within the Netherlands.

Scenario D (Reuse within the EU) treats the 'optimal' reuse case, in which the avoided environmental burdens are maximized by evaluating the carbon intensity of the electricity mix and the annual specific energy yield of EU member states. In this research, Greece is taken as a case study.

By defining these scenarios, sub-goal 1 (*Define different scenarios for the decommissioned but functional PV modules*) is achieved. The next step in the research is to to define the LCA method and to collect the necessary LCI data for each of the processes within the scenarios, so that the environmental impacts can be calculated and the scenarios can be compared.

3

METHODOLOGY

AFTER describing the different scenarios for the reuse and recycling of decommissioned PV modules, a suitable method to calculate the environmental impacts of each scenario needs to be identified. The purpose of the research is to determine under which circumstances the recycling and replacement of PV modules has a greater environmental benefit than the reuse. This chapter describes the different steps of the calculation method.

The first step of the process is to define the system boundaries of the life cycle assessment and the LCA approach. This includes identifying the relevant processes that constitute each of the scenarios. Suitable inventory data need to be collected and an LCI database needs to be selected so that the environmental impacts of those processes can be calculated. Then, a method to calculate the energy yield for each scenario needs to be defined. After quantifying the environmental benefits and burdens of each scenario, the scenarios as a whole can be compared. The results of the study are presented in chapter 4.

3.1. LCA GOAL & SCOPE

THE main objective of this study is to compare the environmental impacts of each scenario defined in chapter 2. The environmental impacts are quantified based on three impact categories: global warming potential [kg CO_2-eq], eco-costs of resource depletion [€] and total eco-costs [€]. Two databases are used for the LCIA: the ecoinvent (v3.7 and v3.8) database and the IDEMAT2023 database.

To determine the environmental impact of a scenario, inventory data from existing studies are combined and adjusted to match the described scenario. The ecoinvent datasets taken from the literature are, where possible, substituted by IDEMAT datasets. Scenarios may consist of over a dozen processes, such as the manufacturing of metallurgical silicon, the wafering process, transportation of the modules, etc. The full inventory data of each process, including the functional unit, weight of materials and energy consumption, are presented in the appendix (section A.5).

Figure 3.1 visualizes the system boundaries of the research:

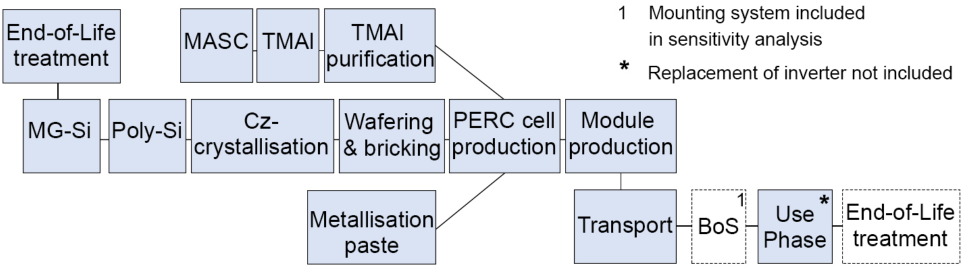


Figure 3.1.: System boundaries of this study. Blue processes are included in the study, processes with a dotted border are not included.

Following the method proposed by Müller et al. [23], the impacts of the production of silicon, methyl aluminium sesquichloride (MASC), trimethylaluminium (TMAl) and metallisation paste are not taken from an LCI database but are calculated separately. Czochralski (Cz) crystallisation is the process of pulling a silicon crystal from molten silicon.

In this research, the processes within the system boundaries are divided into four main components: EoL treatment, manufacturing (all processes between MG-Si production and module production), transport and the use phase.

3.1.1. LCA Approach

In LCAs that involve recycling, according to ISO 14040/44 [53], the practitioner has to choose between two different approaches to fit the goal and scope of the assessment. The two main approaches to recycling LCAs are the cut-off approach and the End-of-Life recycling approach.

Cut-off approach

The cut-off (or recycled content) approach is based on three principles [71]:

- secondary materials (materials that are input to a process have zero attached environmental burden, except for energy use and transport for collection, sorting, etc.
- secondary materials on the output leave the product system without any further environmental burden (positive or negative); this is called cut off.
- the benefit of additional recycling goes entirely to the new product.

Secondary materials are materials that have been used and recycled or come from scrap or residuals from manufacturing processes. In figure 3.2, the cut-off LCA approach is visualized for a generic system. The cut-off LCA approach is used for each component of this research except the recycling process. In the case of PV module recycling, product A represents the PV module, whereas Product B represents products that are manufactured using recycled materials coming from the PV module. These products could include fiberglass, secondary aluminium or a new PV module.

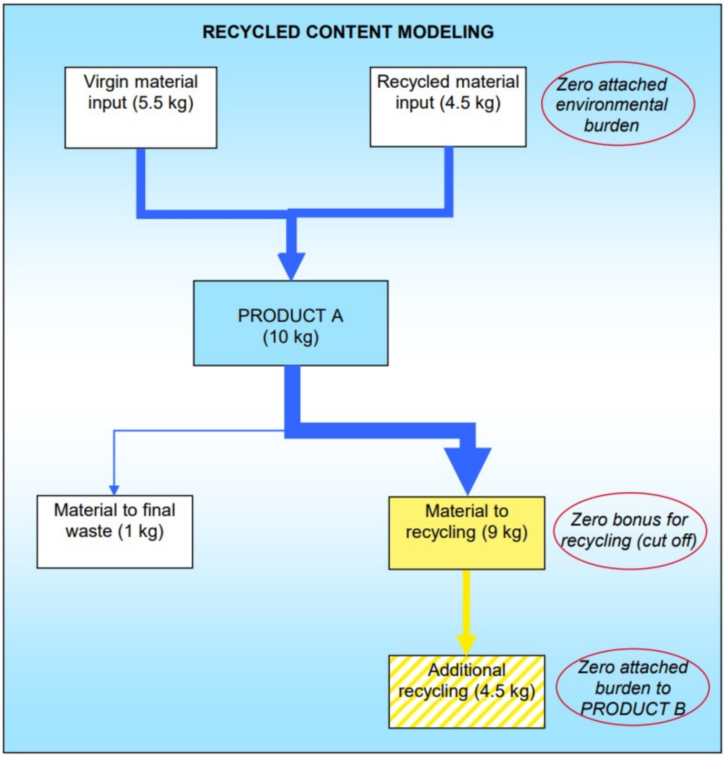


Figure 3.2.: Cut-off (recycled content) LCA modeling approach of a generic system [71].

END-OF-LIFE APPROACH

The EoL (or avoided burden) approach is also based on three principles [71]:

- secondary materials that are input to a process have the same attached environmental burden as virgin materials;
- secondary materials on the output side leave the product system causing extra environmental burden (energy use for melting and transport for collection, sorting) as well as an environmental benefit (avoided burden of virgin material production);
- the benefit of recycling goes entirely to product A, which represents the PV module in the case of PV module recycling.

A visualization of the end-of-life LCA modeling approach can be seen in figure 3.3. The figure shows the EoL approach for a generic system.

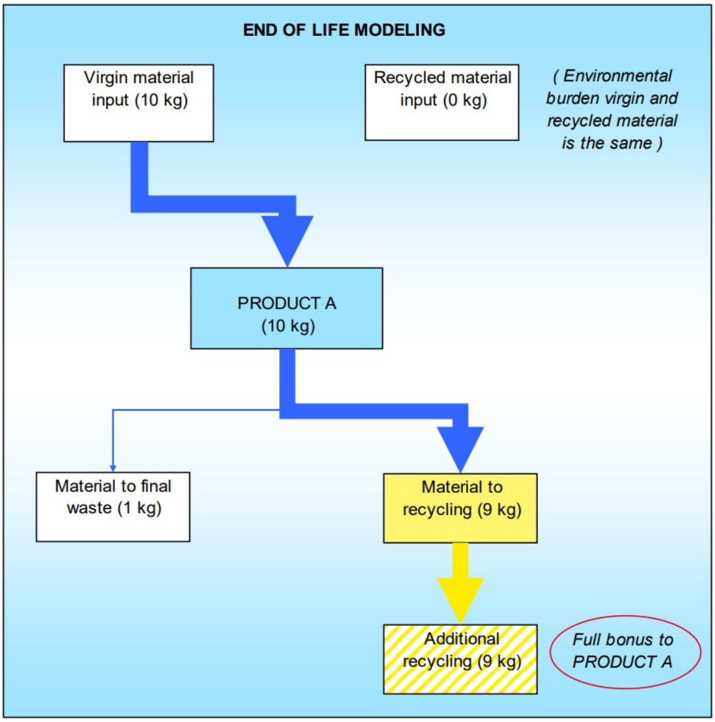


Figure 3.3.: End-of-Life LCA modeling approach of a generic system [71].

LCAs are commonly conducted with a 'cradle-to-grave' of 'cradle-to-cradle' system boundary. This study has an unorthodox system boundary because the starting point of the assessment is a finished product, i.e. the environmental impact of the manufacturing of the decommissioned modules is not of interest. According to ISO 14044, when recycled material of product A (decommissioned modules) is input to product B (new modules) without change in inherent quality, it is essentially closed-loop recycling [71]. Based on this, the EoL LCA approach is used in this study to quantify the environmental burdens and benefits of the recycling processes.

The EoL approach is used because, contrary to the cut-off approach, it allows the avoided burdens associated with the recycling of materials to be calculated. The net benefit of recycling the decommissioned modules is allocated to the new modules. To avoid double counting when combining the LCAs of the recycling processes (EoL approach) with the LCAs of module manufacturing (cut-off approach), the recycling benefits are only allocated to the net surplus amount of recycled material that leaves the PV module. This method is explained in more detail in subsection 3.3.2.

3

3.2. ENVIRONMENTAL IMPACTS

THERE are three main components that constitute the negative environmental impacts: recycling, manufacturing and transport. The methods used to assess the impacts of these three components are described in subsections 3.2.1, 3.2.2 and 3.2.3.

3.2.1. RECYCLING

Based on the scenarios described in chapter 2, two different types of recycling are treated in this research: low-quality recycling and high-quality recycling. For both recycling processes, the material composition as presented in table 2.1 is used, based on research by the European Commission [38]. The EoL LCA approach is used to calculate the environmental impact of the recycling processes.

The LCI data of the high-quality recycling process are based on the FRELP process [38] and can be found in appendix table A.1. The LCI data of the low-quality recycling process are based on [72], but the recovery of glass has been removed from the process, since this is not the current practice for PV modules coming from the Dutch market [8], [6]. The inventory data used for the LQ recycling process can be found in appendix table A.2. The aluminium and copper fractions have been adjusted to match the material composition of the PV waste assumed in this study (see table 2.1).The materials that are not recovered are assumed to be either landfilled or used in lower value applications such as sub bases for roads. In the latter case, the energy use for mechanical treatment (i.e. shredding) of the material is still included but no environmental benefit is attributed to the material.

3.2.2. PV MODULE MANUFACTURING

The manufacturing process has the largest environmental burden of all the stages of the life cycle of a PV module [21], [23]. The LQ and HQ recycling and replacement scenarios entail the production of new modules to replace the decommissioned modules after they have been recycled, so the environmental impacts of their manufacturing need to be determined. The calculations of the environmental impacts of PV module manufacturing are based on inventory data compiled by Müller et al. [23]. The inventory data are the same for both scenarios and can be found in appendix tables A.4 to A.15, however, the impacts of the electrcity use are based on the electricity mix of the country the modules are manufactured in. That means the Chinese electricity mix is used in the LQ recycling scenario and the Dutch electricity mix is used in the HQ recycling scenario.

SANITY CHECK

The LCIA performed by Müller et al. [23] for a PV module produced in Germany was reproduced for the purpose of a sanity check and yielded a GWP of 96.5% of the GWP calculated in [23] (544.1 vs. 564 kg CO_2-eq/kWp). The 3.5% difference in results might be caused by small differences in the method. There are two aspects in which the calculation method used in the sanity check deviates from the method applied by Müller et al. [23]:

- In this research, the environmental impacts are calculated based on the more recent ecoinvent v3.8 database, whereas Müller et al. use the ecoinvent v3.7 database.
- In this research, the environmental impacts of the construction of the factories are not taken into account.

A sanity check for the impact categories eco-costs of resource scarcity and total eco-costs could not be carried out, since Müller et al. [23] do not use these impact categories in their research. However, the impacts in those impact categories are calculated in the same way as the GWP impacts, just using a different column (impact category) of the LCI dataset. Therefore, expressing the impacts in those categories should not influence the reliability of the results.

After completing the sanity check, the correct electricity mixes were selected and, where possible, the ecoinvent datasets were substituted by IDEMAT datasets.

3.2.3. TRANSPORT

The transportation distance and modes of transport vary between each of the scenarios. Depending on the scenario, the decommissioned modules are either reused in the Netherlands, exported to Greece, or sent to a recycling plant. The new modules are either manufactured in China or in the Netherlands. The environmental impacts of transportation are based on the IDEMAT database. In table 3.1, the modes of transport and (estimated) transportation distances of each scenario are listed.

Table 3.1.: Modes of transport and transportation distances in each of the scenarios.

Scenario	A: LQ	B: HQ	C: Reuse NL	D: Export
Decommissioned modules				
Lorry [km]	200	200	200	200
Freight train [km]	-	-	-	2600
Lorry [km]	-	-	-	250
New modules				
Lorry [km]	200 [23]	200	-	-
Freight train [km]	500 [23]	-	-	-
Transoceanic ship [km]	20,000 [23]	-	-	-
Lorry [km]	200	-	-	-

3

3.3. AVOIDED ENVIRONMENTAL BURDENS

THERE are two types of avoided environmental burdens in this study. Subsection 3.3.1 treats the avoided environmental burden associated with the generation of electricity using PV systems. Subsection 3.3.2 covers the avoided environmental burden due to the use of recycled materials instead of primary materials.

3.3.1. ELECTRICITY PRODUCTION

The production of electricity using PV modules entails an avoided burden, since it has a lower environmental impact than electricity produced using fossil fuels [73]. It is assumed that the production of PV electricity replaces the production of electricity using conventional, non-renewable energy sources.

For the avoided environmental burden of PV electricity in scenarios A, B and C, the environmental impact of the Dutch electricity mix as provided in the IDEMAT database is used. In the Export scenario, the environmental impact of the Greek electricity mix (IDEMAT) is used instead. The reference year of these datasets is 2021. The avoided burden per kWh is assumed to be constant over time in this study, although in reality the avoided burden per kWh will likely decrease due to an increasing share of renewable energy sources in the Dutch energy mix.

Table 3.2.: Environmental impacts of the Dutch and Greek electricity production mixes. Taken from the IDEMAT database [58].

Impact Category	**NL**	**GR**	**Unit**
Global warming potential	0.4795	0.7050	kg CO_2-eq/kWh
Eco-cost of resource scarcity	0.0026	0.0004	€/kWh
Total eco-cost	0.0635	0.1083	€/kWh

Table 3.2 shows the environmental impacts of the Dutch and Greek production mixes. These values are used to calculate the avoided burden associated with the generation of PV energy. For each year, the avoided environmental burden due to the production of PV electricity is calculated using equation 3.1:

$$B_E = I_{mix} \cdot E_{year} \tag{3.1}$$

In which,

B_E	Avoided burden [kg CO_2-eq or €]
I_{mix}	Environmental impact of production mix [kg CO_2-eq/kWh or €/kWh]
E_{year}	Electricity yield [kWh]

3.3.2. RECOVERED MATERIALS

The recovery of materials during the recycling of decommissioned PV modules represents an avoided environmental burden for the manufacturing of new modules, since fewer raw materials need to be extracted and processed when using recycled materials. The benefits of the recycling process are calculated using the end-of-life LCA approach. The environmental benefit of material recovery is calculated by subtracting the impacts of the use of secondary materials from the impacts of the use of primary materials. The inventory data of the avoided burdens of LQ and HQ recycling can be found in appendix tables A.2 and A.3 respectively.

Following the method used in [72], in order to avoid double counting (incorrect/double allocation of environmental impacts or benefits to a product), benefits are granted only for the net surplus amount of recycled material that leaves the PV system, in comparison to the current supply mix (trade mix) of that material. To calculate the net surplus amount of recycled material, the trade mixes as given in the IDEMAT2023 database are used [57]. The trade mixes assumed in this research are presented in table 3.3:

Table 3.3.: Trade mix of the metals recovered during the recycling of PV modules [57].

Trade Mix	Primary material	Secondary material
Aluminium	80%	20%
Copper	45%	55%
Silver	45%	55%

In this research, the MG-silicon and solar glass supply mixes are assumed to consist entirely of primary material.

3.4. Energy Yield

This section describes the method used to calculate the energy yield of the PV system in each of the scenarios. To calculate the system yield, the total PV surface area of the system needs to be determined. The surface area calculation is explained in 3.4.1. The method for the yield calculations is demonstrated in 3.4.2.

3.4.1. PV System Surface Area

For the purpose of the energy yield and environmental impact calculations, the combined surface area of the 1000 kg (M_{Total}) of decommissioned PV modules needs to be determined. To calculate the total PV surface area, the simple equation 3.2 is used:

$$A_{total} = A \cdot \frac{M_{total}}{M_{module}} \tag{3.2}$$

Considering that, based on [21], the module surface area A of the decommissioned modules is assumed to be 1.6 m^2 and the weight M_{module} of these modules is assumed to be 13.2 kg/m^2, the total PV surface area A_{total} is 75.8 m^2. The system surface area is kept constant in each scenario. In other words, 75.8 m^2 of

A_{total}	Total PV surface area [m^2]
A	Module surface area [m^2]
M_{total}	Total mass of decommissioned modules [kg]
M_{module}	Mass per decommissioned module [kg]

decommissioned modules are replaced by 75.8 m^2 of new modules with a different weight and performance. This is done to get an understanding of the trade-off between using old and new panels on the same available land area.

3

3.4.2. SYSTEM YIELD

The total energy yield in each scenario needs to be calculated in order to compare the environmental benefits of the different scenarios. The total electricity yield of a module is approximated using the simplified equation 3.3. The equation is based on the equation used in [21].

$$E_{total} = n \cdot \sum_{i=1}^{N} [E_a \cdot P \cdot R_P \cdot (1 - r(i-1))] \tag{3.3}$$

In which,

n	Number of modules
i	Year
N	Remaining module lifetime
E_a	Average annual specific energy yield [kWh/kWp/a]
P	Remaining peak power of the module [kWp]
r	Annual degradation rate [%/a]
R_P	Performance ratio [-]

In the calculations of the total energy yield of each module, the degradation rate is assumed to be constant over the lifetime of the module and the efficiency of the module declines linearly over time. Each of the parameters in equation 3.3 is adjusted in the yield calculations of the different scenarios to fit the respective scenario.

Considering that the decommissioned modules are assumed to have been installed in 2011 and are assumed to have a lifetime of 25 years, the modules have a remaining lifetime of 12 years at the time of installation in 2024. The values of the annual specific energy yield are based on a 2020 report by Frischknecht et al. [67]: the assumed annual specific energy yield is 961 kWh/kWp/a in the Netherlands and 1348 kWh/kWp/a in Greece.

The peak power of the decommissioned modules at the time of installation is calculated using equation 3.4.

$$P = P_0 \cdot (1 - r \cdot i) \tag{3.4}$$

In which P_0 denotes the peak power of the modules when the modules were manufactured in 2011, which was 235.2 Wp [21]. Using equation 3.4, the remaining peak power of the decommissioned modules in 2024 was calculated to be 213.8 Wp.

Table 3.4.: Parameters of the energy yield calculation in each of the scenarios.

Parameter	**A: LQ**	**A: HQ**	**C: Reuse**	**D: Export**	**Unit**
N	30 [21]	30 [21]	12	12	a
E_a	961 [67]	961 [67]	961 [67]	1348 [67]	kWh/kWp/a
P	0.366 [23]	0.366 [23]	0.2138	0.2138	kWp
r	0.5 [17]	0.5 [17]	0.7 [21]	0.7 [21]	%/a
R_P	0.85 [23]	0.85 [23]	0.82 [21]	0.82 [21]	-

Table 3.4 shows the parameters that were used to calculate the energy yield of the system in each scenario, including the source of each parameter.

3.4.3. EMISSIONS INTENSITY OF ELECTRICITY

By taking the combined environmental impacts of a scenario and dividing by its total electricity yield, the emissions intensity of the electricity produced in that scenario can be calculated. To provide a fair comparison between the reuse and recycling scenarios, the impacts of the BoS have to be included in the calculation (otherwise the emissions intensity in the reuse scenarios would be almost zero). Since an LCA of the BoS is outside of the scope of this study, the values for the GWP of the BoS are taken from literature. Unfortunately, the IDEMAT impact categories 'eco-cost of resource scarcity' and 'total eco-cost' are not commonly used in literature and the BoS impacts in these categories could not be found. Therefore, the impacts per kWh could not be calculated in these categories.

Based on a 2021 report by the IEA PVPS [21], the following impacts were assumed for the BoS components:

- Inverter: 42.9 kg CO_2-eq per panel
- BoS (excl. inverter and mounting system): 13.2 kg CO_2-eq per panel

It is assumed that the maximum service lifetime of the inverter is 15 years [21]. Therefore, the inverter needs to replaced once during the 30 year lifetime of the new modules. The LCI of the mounting system is based on [74]. The emissions intensity is calculated using equation 3.5

$$I_{emission} = \frac{G_{year0} + q \cdot g_{inv} \cdot n + \cdot g_{bos} \cdot n + g_{mount} \cdot n}{E_{total}} \quad (3.5)$$

In which,

$I_{emission}$	Emissions Intensity [kg CO_2-eq/kWh]
G_{year0}	GWP in year 0 of scenario [kg CO_2-eq]
g_{inv}	GWP of inverter (per panel) [kg CO_2-eq]
g_{bos}	GWP of BoS (excl. mounting system) per panel [kg CO_2-eq]
g_{mount}	GWP of mounting system (per panel) [kg CO_2-eq]
q	Number of inverters
n	Number of panels
E_{total}	Total Lifetime system yield [kWh]

3.5. CUMULATIVE IMPACT

To compare the scenarios to each other, the cumulative impact is calculated numerically (per year) in Microsoft Excel. For each year, the remaining module power is calculated using equation 3.4 and multiplied by the specific yield and the performance ratio to determine the yield in that year. Equation 3.6 shows this calculation. It is essentially the same as equation 3.3, just for one year.

$$E_{year} = n \cdot E_a \cdot P \cdot R_P \tag{3.6}$$

In which,

n	Number of modules
E_a	Average annual specific energy yield [kWh/kWp/a]
P	Remaining peak power of the module [kWp]
R_P	Performance ratio [-]

The environmental benefit in that year is then calculated using equation 3.1. In year 0, there are environmental impacts due to the manufacturing and transport of the modules. The modules have not yet started to generate electricity. Each year after that, the environmental benefit associated with PV energy production is calculated and subtracted from the cumulative impacts of the year before it. When plotted, this results in a graph starting above 0 and over time becoming negative (net environmental benefit) as the initial impacts are compensated by the avoided burdens.

3.6. CHAPTER SUMMARY

In order to calculate the environmental impacts of each scenario, the LCA system boundaries were defined, after which the different processes within the system boundaries were identified. Suitable LCIs were then collected to be able to calculate the environmental impacts of each scenario.

In the recycling scenarios, the system boundaries consist of four main stages: end-of-life treatment, manufacturing, transport and the use phase. The system boundaries of the reuse scenarios only consist of two stages: transport and the use phase. A combination of the ecoinvent and IDEMAT LCI databases is used to calculate the environmental impacts of each scenario, using IDEMAT where possible.

The methods to calculate the system yield and associated benefits are explained, as well as the methods to determine the emissions intensity of the electricity and the cumulative impact of the system in each scenario.

By defining the system boundaries and the LCA approach, choosing the LCI databases and collecting the inventory data for each of the processes within the system boundaries, sub-goal 2 (*Collect the LCI data and define the LCA method*) was achieved.

The next step in the research is to calculate the impacts of each process and after that compare the scenarios as a whole in terms of global warming potential, eco-cost of resource scarcity and total eco-cost.

4

Results

Using the method described in chapter 3, an environmental analysis of the different scenarios is carried out. The impacts within the scenarios are divided into four main components: end-of-life treatment, manufacturing, transport and use phase. The results of the research are presented in the following order: first, the impacts of the end-of-life treatment and the manufacturing process are assessed in sections 4.1 and 4.2. Section 4.3 shows the environmental impact of the transport of the decommissioned modules and the new modules. In section 4.4, the energy yield of the system in each scenario is calculated. Finally, in section 4.5, the scenarios are compared to each other in terms of GWP, eco-cost of resource scarcity and total eco-cost.

4.1. Impacts of End-of-Life Treatment

The environmental burdens and benefits of the low-quality and high-quality recycling processes are compared in terms of GWP, eco-costs of resource scarcity and total eco-costs. Both the low-quality and high-quality recycling processes have a net environmental benefit. The impacts of the recycling processes are treated in subsection 4.1.1 and their benefits are treated in subsection 4.1.2.

4.1.1. Environmental impacts of the recycling processes

In table 4.1, the impacts of the low-quality and high-quality recycling processes are compared in all three impact categories. In all impact categories, HQ recycling has a higher environmental burden than LQ recycling because of the more elaborate process involving chemical treatment of the waste.

The increased burden of HQ recycling is compensated by the increased material recovery, which is treated in subsection 4.1.2. The recycling impacts per component (electricity use, fuel use etc.) are visualized in appendix A.6.

Table 4.1.: Environmental impacts of low- and high-quality recycling of 1000 kg PV waste in terms of GWP, eco-cost of resource scarcity and total eco-costs.

Impact Category	A: LQ Recycling	B: HQ Recycling
Global Warming Potential [kg CO_2-eq]	219	335
Eco-cost of Resource Scarcity [€]	9	12
Total Eco-cost [€]	53	77

4

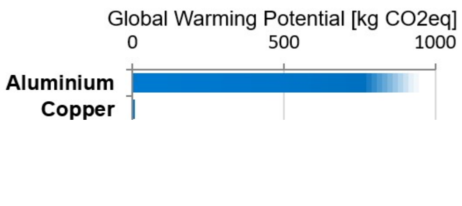
4.1.2. AVOIDED PRODUCTION BURDENS

In figure 4.1, the benefits of recycling due to the avoided production of primary materials and energy are visualized. The avoided burdens are dominated by the avoided production of primary aluminium.

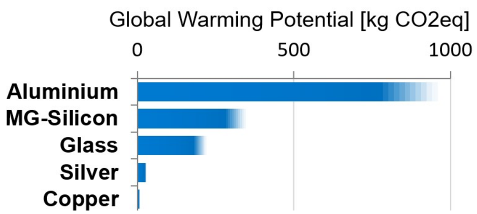
In the low-quality recycling process, aluminium and copper are recovered. The impacts of the low-quality recycling process per component are visualized in figures 4.1a, 4.1c and 4.1e in terms of GWP, eco-costs of resource scarcity and total eco-costs respectively.

In the high-quality recycling process, glass, aluminium, MG-silicon, silver, copper, thermal energy and electricity are recovered. The impacts of the high-quality recycling process per component are visualized in figures 4.1b, 4.1d and 4.1f in terms of GWP, eco-costs of resource scarcity and total eco-costs respectively.

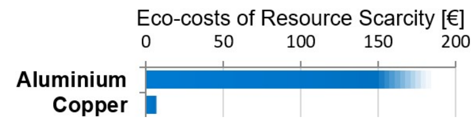
In both LQ and HQ recycling, the majority of the environmental benefits are attributable to the avoided production of primary aluminium. In comparison, the recovery of copper has a low environmental benefit, since the aluminium fraction is much larger and the percentage of primary material in the trade mix is much higher for aluminium (80%) than for copper (45%). The recovery of silver in the high-quality recycling process is associated with a great benefit in terms of resource scarcity.



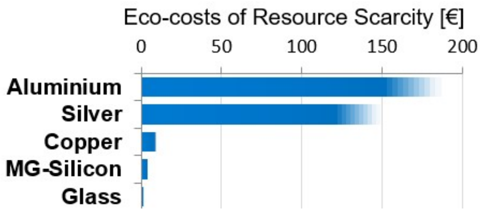
(a) Avoided material burdens of LQ recycling. Total benefit: 863 kg CO_2-eq.



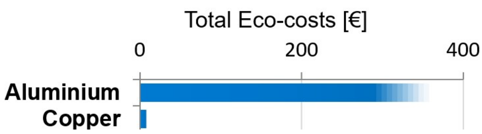
(b) Avoided material burdens of HQ recycling. Total benefit: 1418 kg CO_2-eq.



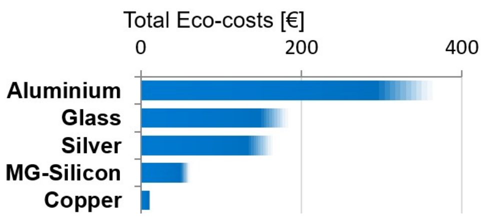
(c) Avoided material burdens of LQ recycling. Total benefit: €179.



(d) Avoided material burdens of HQ recycling. Total benefit: €353.



(e) Avoided material burdens of LQ recycling. Total benefit: €332.



(f) Avoided material burdens of HQ recycling. Total benefit: €711.

Figure 4.1.: Environmental benefits (avoided production of primary materials) of low- and high quality recycling of 1000 kg of PV modules in terms of GWP, eco-cost of resource scarcity and total eco-costs.

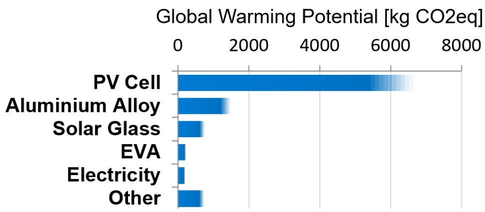
Subtracting the impacts of the recycling processes, the net benefits of the EoL treatment per ton of PV module waste are 644 kg CO_2-eq, €170 and €279 (GWP, eco-cost of resource scarcity, total-eco cost) in the LQ scenario and 1083 kg CO_2-eq, €351 and €634 (GWP, eco-cost of resource scarcity, total-eco cost) in the HQ scenario.

Considering that the cumulative PV capacity in the Netherlands added up to 1.2 million tons by the end of 2021 [6] and assuming that PV capacity consists entirely of c-Si modules with the same material composition assumed in this study, an additional 526.8 million kg CO_2-eq can be saved by not only recycling the aluminium and copper from those modules (LQ recycling), but also recovering the solar glass, silver and MG-silicon (HQ recycling).

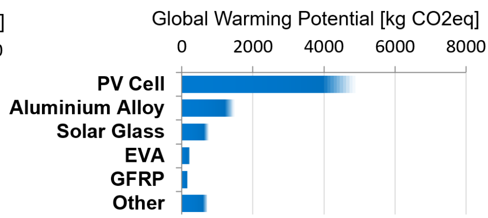
4.2. IMPACTS OF MODULE MANUFACTURING

THE manufacturing of the modules represents the largest environmental burden in the recycling scenarios. In figure 4.2, the impacts of the last step of the manufacturing process are shown. This step consists of 26 inputs, of which only the five most impactful inputs are shown in each figure for the sake of brevity. The remaining inputs are combined and named 'Other'. Some inputs, such as the use of silver, do not appear explicitly in these figures, since they are included in the 'PV cell' input. The full list of environmental impacts associated with the last manufacturing step are presented in appendix A.2.

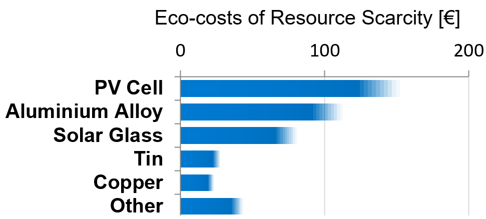
The 1000 kg of decommissioned PV modules, which represent the starting point of the environmental analysis, correspond to a total area of 75.8m^2. The PV system area is kept constant throughout the comparison of scenarios, therefore the impacts of manufacturing 75.8 m^2 of PV modules are shown.



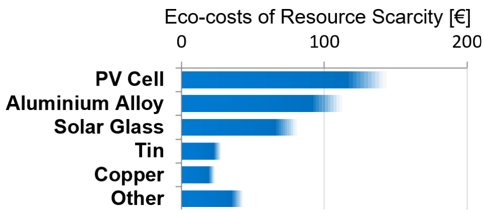
(a) Impacts of module manufacturing in CN. Total impact: 9140 kg CO_2-eq.



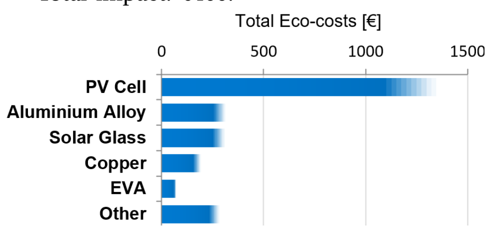
(b) Impacts of module manufacturing in NL. Total impact: 7490 kg CO_2-eq.



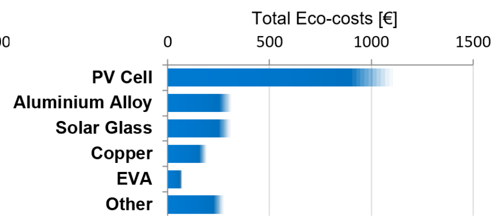
(c) Impacts of module manufacturing in CN. Total impact: €400.



(d) Impacts of module manufacturing in NL. Total impact: €392.



(e) Impacts of module manufacturing in CN. Total impact: €2287.



(f) Impacts of module manufacturing in NL. Total impact: €2062.

Figure 4.2.: Environmental impacts of manufacturing 75.8m^2 of PV modules (replacing 1000 kg of decommissioned modules) in China (CN) and the Netherlands (NL) in terms of GWP, eco-cost of resource scarcity and total eco-costs.

The calculations show that local manufacturing entails an 18.1% reduction of the impacts in the GWP category, a 2.0% reduction of the impacts in the eco-cost of resource scarcity category and a 9.8% reduction of the impacts in the total eco-cost impact category compared to manufacturing in China.

4.3. IMPACTS OF TRANSPORT

THE transport of the modules represents only a small fraction of the environmental impacts over the life cycle of a PV module. The LQ recycling scenario has the highest transport impacts, since the new modules are shipped from China. In the Export scenario, the decommissioned modules are transported across Europe, causing a relatively high environmental impact compared to the HQ and Reuse scenarios in which the modules did not leave the Netherlands.

Table 4.2.: Environmental impacts of transport of the PV modules in each scenarios in terms of GWP, eco-cost of resource scarcity and total eco-costs.

Impact Category	A: LQ	B: HQ	C: Reuse	D: Export
Global Warming Potential [kg CO2-eq]	170	36	18	67
Eco-cost of Resource Scarcity [€]	22	5	2	6
Total Eco-cost [€]	50	10	5	16

4.4. IMPACTS OF USE PHASE: ENERGY YIELD

THE last component within the system boundary is the use phase of the modules. The use phase of the PV system has an environmental benefit due to the production of electricity from sunlight. There is a significant difference in energy yield between the newly manufactured modules and the older modules when installed at the same location.

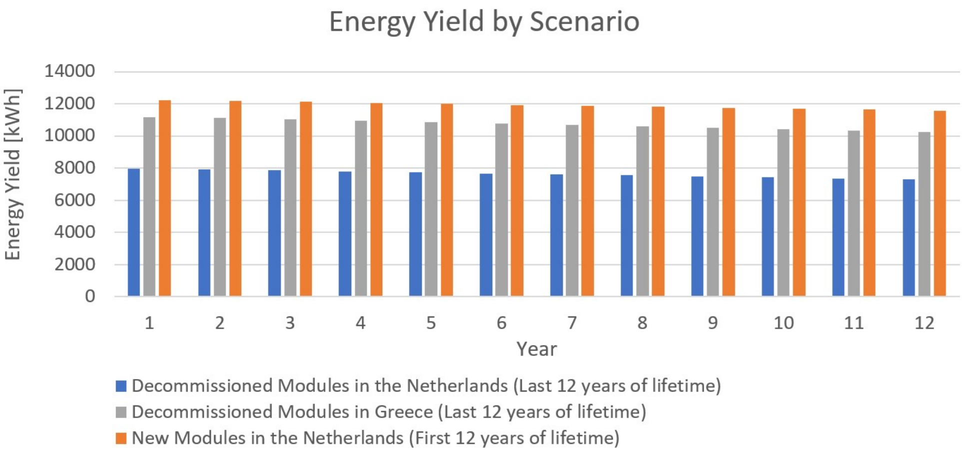


Figure 4.3.: Performance of the decommissioned modules when reused in the Netherlands (blue) vs. when reused in Greece (grey) vs. the performance of the new modules (orange), until the decommissioned modules have reached the end of their lifetime. The system area is 75.8 m^2, corresponding to 1000 kg of decommissioned modules.

In figure 4.3, the annual output of the PV system is plotted for the four scenarios. The output of the system is identical for both of the recycling scenarios (new modules), since the performance of the modules produced in the Netherlands is assumed to be identical to the performance of the modules produced in China. The energy yield is calculated using equation 3.3.

Because of the 10 year age difference between the modules, and the 13 years of degradation of the decommissioned modules, there is a significant difference in performance between the decommissioned and the new modules installed at the same location. At the end of the first year, the new modules have produced 12243 kWh whereas the decommissioned modules installed in NL have produced 7977 kWh. The yield of the new modules is 53.5% higher in the first year. Naturally, the yield of the decommissioned modules installed in Greece is much higher than those installed in NL.

4.5. SCENARIO COMPARISON

AFTER calculating the impacts of the EoL treatment, manufacturing, transport and the energy yield of each scenario, the impacts were summed and the scenarios as a whole can be compared. The impacts and benefits of the four scenarios are visualized for each of the three impact categories.

First, a bar chart is presented, showing the calculated environmental impacts and benefits in year 0. At this point, the newly manufactured modules have not yet started to produce energy and the decommissioned modules (reuse scenarios) have not yet started their second life. In the recycling scenarios, the impacts include a recycling process, module manufacturing and transport. The impacts in the reuse scenarios are only caused by transportation of the modules. In the recycling scenarios there is also an environmental benefit in year 0, due to the avoided production burdens of the materials recovered during the recycling processes.

Then, the cumulative environmental impacts of the PV system are shown. The time frame of the calculation is 30 years, which is the assumed lifetime of the new modules. Since the decommissioned modules have a lifetime of 25 years and have already operated for 13 years, they are assumed to stop producing electricity after 12 years, at which point their environmental benefits stop increasing.

In all impact categories, the impacts of the recycling scenarios are higher in year 0 than the impacts of the reuse scenarios, because no environmental burden is attributed to the decommissioned modules. Since the new modules have a higher energy yield than the decommissioned modules, there is generally a point in time where the cumulative environmental benefits of the recycling scenarios outweigh those of the reuse scenarios. This point in time might be called the 'Replacement Payback Time' (RPT). The duration of the RPT is presented for each scenario.

Subsection 4.5.1 shows this environmental comparison in terms of the global warming potential. Subsections 4.5.2 and 4.5.3 show the comparison for the eco-cost of resource scarcity and total eco-cost impact categories respectively.

4.5.1. SCENARIO COMPARISON: GLOBAL WARMING POTENTIAL

In this subsection, the GWP of the four scenarios in year 0 and over time are visualized. Figure 4.4 shows a bar chart of the impacts at the starting point of the scenarios. The environmental impacts of the recycling scenarios are much higher in year 0 than the impacts of the reuse scenarios because of the manufacturing of the new modules. The avoided material burdens compensate for 9.4% of the manufacturing impacts in the LQ scenario and 18.9% in the HQ scenario. The total relative impact reduction between the LQ and HQ scenarios is 25.7%

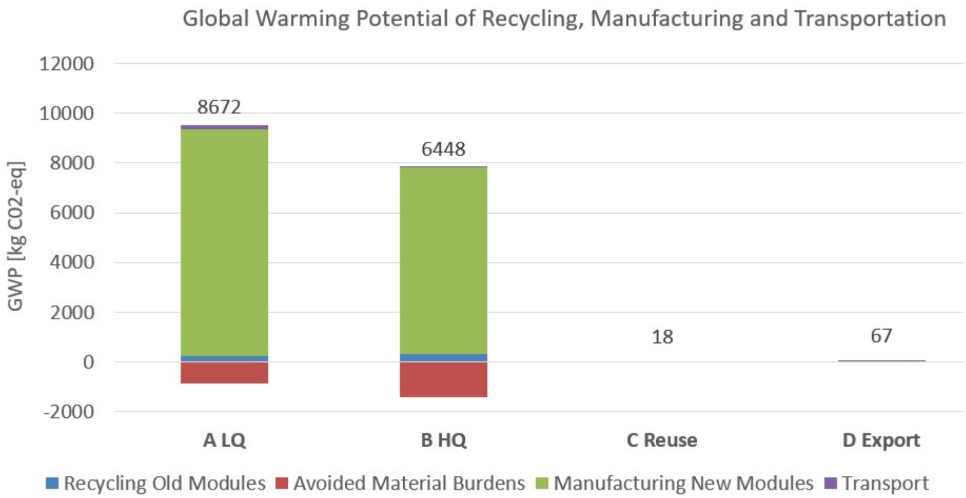


Figure 4.4.: GWP per component of each scenario in year 0.

Figure 4.5 visualizes that the benefits of Reuse in NL only outweigh those of the recycling and replacement scenarios in the first 4 years. In other words, compared to recycling and replacement, the reuse of decommissioned modules in the Netherlands is not beneficial to the environment from a GWP perspective if one intends to keep the PV system in use for 5 years or longer. Export to Greece provides the greatest environmental benefits during the remaining lifetime of the decommissioned modules.

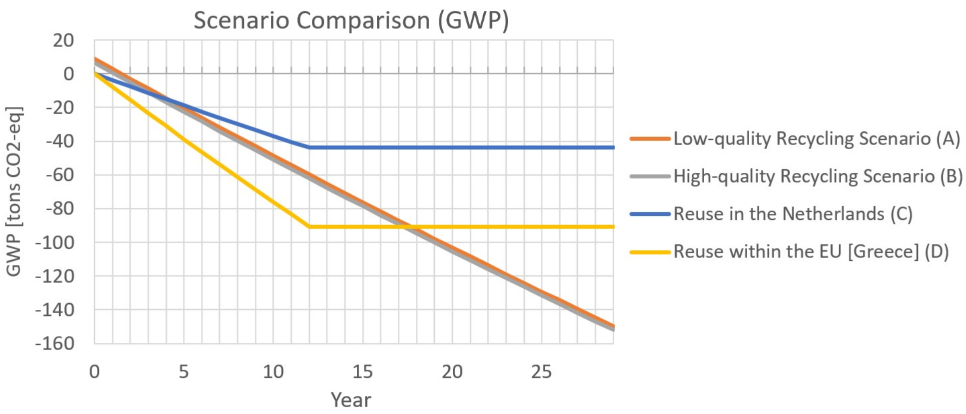


Figure 4.5.: Comparison of the four scenarios in terms of GWP until the new modules have reached EoL. Replacement Payback Time of LQ recycling and replacement: 5 years compared to reuse in NL, not applicable compared to reuse in GR. RPT of HQ recycling and replacement: 4 years compared to reuse in NL, not applicable compared to reuse in GR.

Emissions Intensity of Electricity

The calculated year 0 impacts (EoL treatment, manufacturing, transport) are combined with the environmental impacts of the balance of system taken from [21] and divided by the calculated electricity yield to determine the emissions intensity of the produced electricity in each scenario. Since the impacts of the BoS and inverter in [21] are based on the impact per panel, their impacts are higher in the reuse scenarios (47.3 panels of 1.6 m^2) than in the replacement scenarios (41.0 panels of 1.85 m^2). In the replacement scenarios an additional inverter is needed to replace the original inverter after 15 years of use. A graph showing the cumulative GWP impacts in this analysis is included in Appendix A.13.

Table 4.3.: Emissions intensity of the produced electricity in each scenario, including the parameters used in the calculations. The yield is calculated for the remaining lifetime of the PV modules: 12 years for the decommissioned modules, 30 years for the new modules.

Parameter	A: LQ	B: HQ	C: Reuse	D: Export	Unit
Year 0 impacts	8672	6448	18	67	kg CO2-eq
BoS excl. inverter and mounting system	541	541	624	624	kg CO2-eq
Inverter (+replacement)	3514	3514	2029	2029	kg CO2-eq
Mounting system	3302	3302	3302	3302	kg CO2-eq
Yield	341	341	92	129	MWh
Emissions Intensity	47.1	40.5	65.2	46.8	g CO2-eq/kWh

Based on these assumptions, the HQ recycling scenario has the lowest emissions intensity of all scenarios with 40.5 g CO_2-eq/kWh. The emissions intensity of the LQ recycling and the Export scenario are both approximately 16% higher. Reuse in NL has a substantially higher emissions intensity of 65.2 g CO_2-eq/kWh, nearly 61% higher than the HQ recycling scenario.

The emissions intensity in the reuse scenario is relatively high because this scenario has the lowest annual yield and the remaining lifetime is only 12 years, while the BoS impacts are still substantial. Although the BoS impacts in the export scenario are the same, the yield is significantly higher because of the higher annual irradiance in Greece. The values of the LQ and HQ scenarios are similar to those reported by the IEA. The IEA calculated the green house gas emissions of a PV system with an efficiency of 20% and an annual production of 975 kWh/kWp to be 42.9 g CO_2-eq/kWh [73]. In this research, the efficiency is 19.79% and the annual production is 961 kWh/kWp.

4.5.2. Scenario Comparison: Eco-costs of Resource Scarcity

This subsection compares the impacts of the scenarios from a resource scarcity perspective, both at the starting point and cumulatively. Figure 4.6 shows the impacts at the outset of these scenarios in a bar chart. In year 0, the environmental impacts of the recycling scenarios are considerably higher than those of the reuse scenarios. This can be attributed to the manufacturing of the new modules in the recycling scenarios. However, because of the high percentage of material recovery from the decommissioned modules in the HQ recycling scenario, the avoided material burdens compensate for of the manufacturing impacts in the HQ scenario. Therefore, in year 0, the impacts in the resource scarcity category are nearly three times as high in the LQ recycling scenario as in the HQ recycling scenario. The total relative impact reduction between the LQ and HQ scenarios is 64.7%

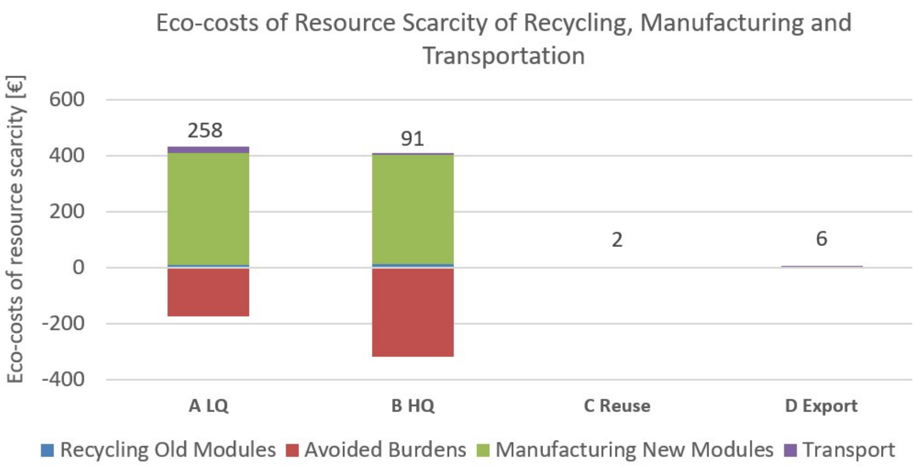


Figure 4.6.: Eco-costs of resource scarcity per component of each scenario in year 0.

From a resource scarcity perspective, reuse in the Netherlands has the highest environmental benefits for the first 9 years of the calculation. If the lifetime of a PV project is more than 9 years, the HQ recycling scenario is the preferred strategy in this impact category. The environmental benefits of the export scenario in this impact category are low, because the Greek electricity mix has a considerably lower eco-cost of resource scarcity than the Dutch electricity mix.

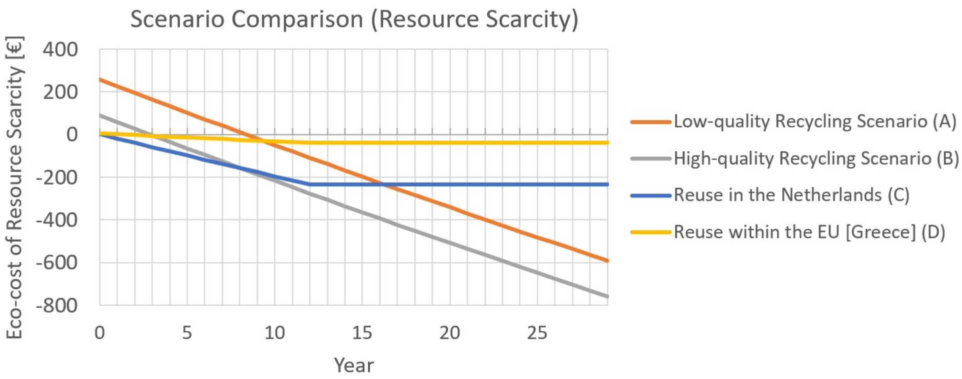


Figure 4.7.: Comparison of the four scenarios in terms of eco-costs of resource scarcity until the new modules have reached the end of their lifetime. Replacement Payback Time of LQ recycling and replacement: not applicable compared to reuse in NL, 8 years compared to reuse in GR. RPT of HQ recycling and replacement: 9 years compared to reuse in NL, 4 years compared to reuse in GR.

4.5.3. Scenario Comparison: Total Eco-costs

In this subsection, the scenarios are compared on the basis of total eco-costs. As in the other impact categories, the environmental impact of the recycling scenarios in year 0 is substantially greater than the impact of the reuse scenarios. The avoided material burdens compensate for 14.5% of the manufacturing impacts in the LQ scenario and 34.4% in the HQ scenario. The total relative impact reduction between the LQ and HQ scenarios is 30.0%

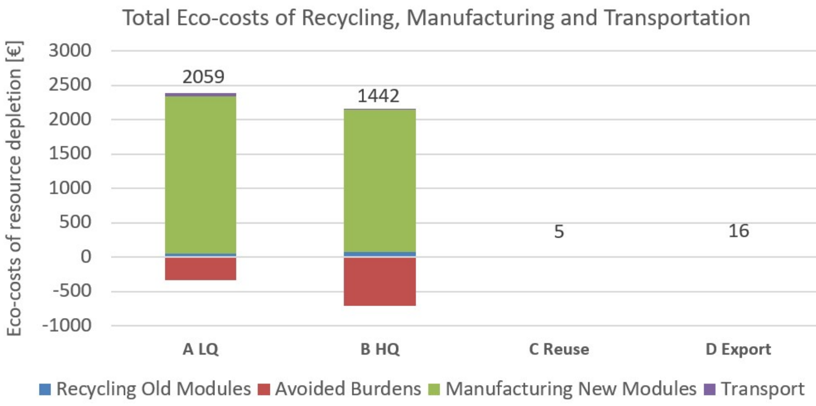


Figure 4.8.: Environmental impacts (Total eco-costs) per component of each scenario in year 0.

When considering all eco-costs (resource scarcity, carbon footprint, ecosystems and human health), the scenario in which the decommissioned modules are exported to Greece provided, by far, the greatest environmental benefits during the remaining lifetime of the PV system.

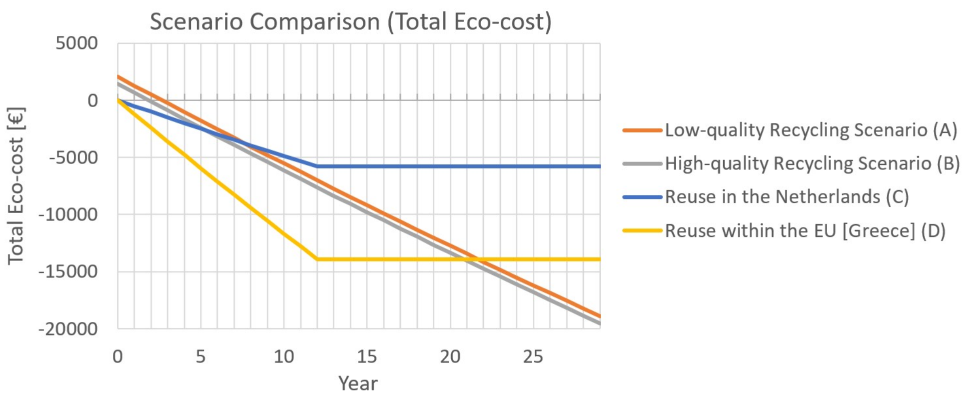


Figure 4.9.: Comparison of the four scenarios in terms of total eco-costs until the new modules have reached the end of their lifetime. Replacement Payback Time of LQ recycling and replacement: 8 years compared to reuse in NL, not applicable compared to reuse in GR. RPT of HQ recycling and replacement: 6 years compared to reuse in NL, not applicable compared to reuse in GR.

4.6. CHAPTER SUMMARY

The methods described in chapter 3 for the assessment of the environmental impacts of each scenario were applied and the results were presented in this chapter. The analysis showed that aluminium, silicon, silver and glass are the most important materials to recover from an environmental perspective.

In the recycling scenarios, 75.8 m^2 of PV modules were manufactured to replace the same system area of decommissioned modules. The impacts of module manufacturing in China (LQ scenario) were calculated to be 9140 kg CO_2-eq, €400 and €2287 in the impact categories GWP, eco-cost of resource scarcity and total eco-cost respectively. When manufactured in the Netherlands (HQ scenario), the impacts amounted to 7490 kg CO_2-eq, €392 and €2062 in the impact categories GWP, eco-cost of resource scarcity and total eco-cost respectively.

By subtracting the impacts of the recycling processes from the avoided burden of primary material production, the net benefits of recycling amounted to 644 kg CO_2-eq, €170 and €279 (GWP, eco-cost of resource scarcity, total-eco cost) in the LQ scenario and 1083 kg CO_2-eq, €351 and €634 (GWP, eco-cost of resource scarcity, total-eco cost) in the HQ scenario.

The total relative impact reduction between the LQ and HQ scenarios amounts to 25.7% of the GWP. In the eco-cost of resource scarcity and the total eco-cost impact categories, the relative reductions between the HQ and LQ scenarios are 64.7% and 30.0% respectively.

The transportation impacts did not play a significant role in any of the scenarios.

The impacts of the different processes within the scenarios were summed, after which the scenarios as a whole could be compared to each other. In doing so, sub-goal 3 (*Compare the scenarios in terms of environmental impacts and feasibility*) was achieved.

When comparing decommissioned modules from 2011 to new modules from 2021, reuse in a sunny country entailed the greatest environmental benefits during the remaining lifetime of the decommissioned modules in the GWP and total eco-cost impact categories.

From a global warming perspective, recycling and replacement was more beneficial to the environment than reuse in the Netherlands if the PV system was to be used for longer than 4 years (HQ recycling and replacement) or 5 years (LQ recycling and replacement). In terms of total eco-cost, the Replacement Payback Times were 6 years for LQ recycling and replacement and 8 years for HQ recycling and replacement. From a resource scarcity perspective, reuse in the Netherlands was only the preferred strategy if the PV system was to be used for shorter than 9 years. Otherwise, HQ recycling and replacement had the greatest environmental benefits.

In almost all impact categories, the benefits of LQ and HQ recycling and replacement were higher than the benefits of reuse after 10 years. The only exception is the eco-cost of resource scarcity in the LQ recycling and replacement scenario. It can therefore be concluded that there is no strong environmental incentive to reuse the decommissioned modules, unless a short-term application can be identified.

5

Sensitivity Analysis

Chapter 4 treated the results of the environmental analysis under specific conditions such as the assumed module efficiency and the system boundary. In this chapter, the robustness of the results is analysed by adjusting some of the parameters of the calculations and assessing their effect on the outcome of the comparison. In section 5.1, the assumed efficiency of the decommissioned modules is increased. Subsequently, section 5.2 contains an analysis of the effect of a decreasing carbon intensity of the electricity mix. Finally, in section 5.3, it is assumed that the mounting system of the decommissioned modules is reused. For each of the 'sensitivity analyses', figures are included for the global warming potential impact category. Appendix A.4 contains the figures showing the effects on the other impact categories.

5.1. Smaller Difference in Efficiency

The average efficiency of PV modules has been rapidly increasing over the last decades. The efficiency of a typical mono c-Si PV module increased from 14% to 19.7% between 2010 and 2020 alone [9], [15]. In the future, the rate at which the efficiency of new PV modules improves might decrease. The difference in efficiency between a 10 year old module and a new module would then be smaller than it is in this research.

The effect of a smaller difference in efficiency is analyzed in this section. To that end, it is assumed that the efficiency of the decommissioned modules was 17.245% instead of 14.7% at the start of their lifetime. An efficiency of 17.245% represents the midpoint of the efficiencies of the old modules (14.7%) and the new modules (19.79%) in this research. In this hypothetical scenario, all other parameters (module age, degradation rate, etc.) are left unchanged. A graph showing the environmental benefits (GWP) over time in this scenario is shown in figure 4.5.

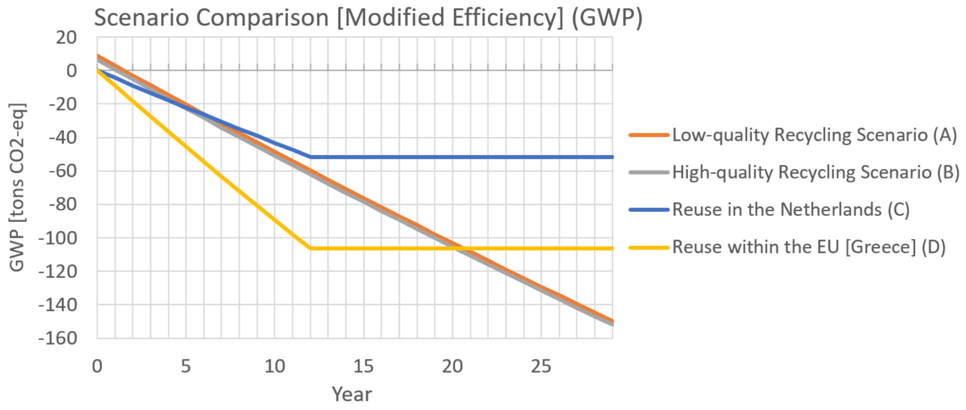


Figure 5.1.: Sensitivity analysis: the assumed nameplate efficiency of the decommissioned modules is 17.245% instead of 14.7%. Comparison of the four scenarios in terms of global warming potential until the new modules have reached the end of their lifetime.

It is evident that a smaller difference in efficiency improves the conditions of the reuse scenarios. In this case, when considering the GWP, the Replacement Payback Time with LQ recycling is increased from 5 years to 7 years compared to reuse in NL. The RPT with HQ recycling is increased from 4 years to 5 years compared to reuse in NL. Since the export scenario has the highest environmental benefits, the RPT is not applicable to that scenario.

The environmental benefits were also plotted in terms of eco-cost of resource scarcity and total eco-cost. These figures can be found in appendix A.4.1.

5.2. NET ZERO IN 2050

IN this research, the electricity mix and its GWP is assumed to be constant over time. In reality, the electricity mix is continually subject to change and is generally declining as sustainable energy technologies attain a larger market share. Considering the goal set in the Paris Agreement to limit the global temperature rise to 1.5 °C [60], the European Union aims to be climate-neutral by 2050 [75]. The effect of moving towards net-zero emissions electricity on the outcome of this research is assessed by decreasing the carbon intensity of the electricity mix. For the analysis, it is assumed that the GWP of the electricity production mix decreases linearly to zero between 2023 and 2050. Consequentially, the avoided burden attributed to the production of PV energy will decrease. Figure 5.2 shows the environmental impacts over time in this scenario.

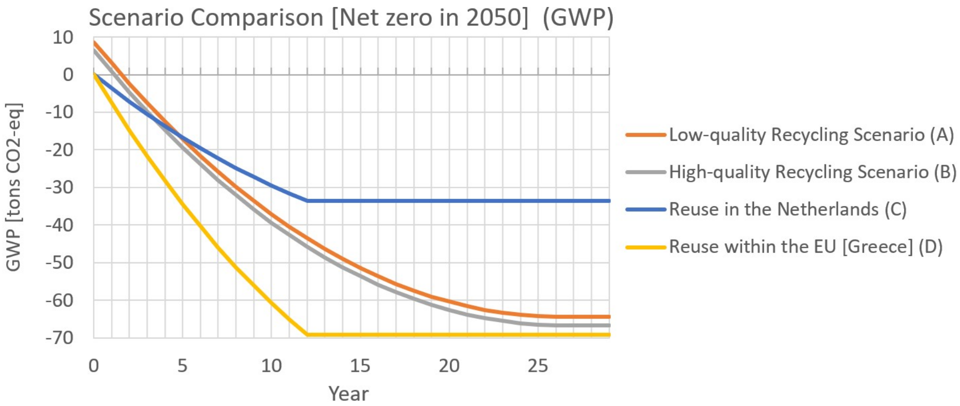


Figure 5.2.: Sensitivity analysis: the carbon intensity is assumed to decrease linearly to 0 kg CO_2-eq in 2050. Comparison of the four scenarios in terms of global warming potential until the new modules have reached the end of their lifetime.

The RPT of the HQ recycling and LQ recycling scenarios are not influenced by the decreasing carbon intensity of the electricity mixes. Compared to Reuse in NL, the RPT of LQ recycling and replacement remains 5 years and the RPT of HQ recycling and replacement remains 4 years. Reuse in a sunny country remains the preferred option in this scenario.

5.3. REUSE OF THE MOUNTING SYSTEM

THE balance of system of a PV system represents a considerable share of its total environmental footprint. Considering that the inverters used in PV systems have an expected lifetime of 15 years [21], it is unlikely that the inverters coming from a 12-year old PV system will be considered for reuse.

However, the expected lifetime of the mounting system is much longer, which allows the mounting system to have a second life after having been used for 12 years. An additional environmental benefit can be realized when the mounting system of the decommissioned PV modules can be reused on the new installation location. The effect of the reuse of the mounting system in the environmental analysis is evaluated in this subsection.

The LCI of the mounting system is based on [74]. The impacts per m^2 of the open ground mounting system are calculated to be 43.6 kg CO_2-eq, €4,13 and €11,43 in the impact categories GWP, eco-cost of resource scarcity and total eco-cost respectively.

Figure 5.3 shows the environmental impacts (GWP) in year 0 for the scenario in which the new modules need to be fitted with a new ground mounting system and the decommissioned modules do not. Figure 5.4 visualizes how the increased environmental impact affects the comparison of the scenarios over time. Assuming that the mounting system can be reused in the reuse scenarios increases the RPT with LQ recycling from 5 years to 6 years and the RPT with HQ recycling from 4 years to 5 years.

The result of reusing the mounting system for the eco-cost of resource scarcity and total eco-cost impact categories can be found in appendix A.4.2.

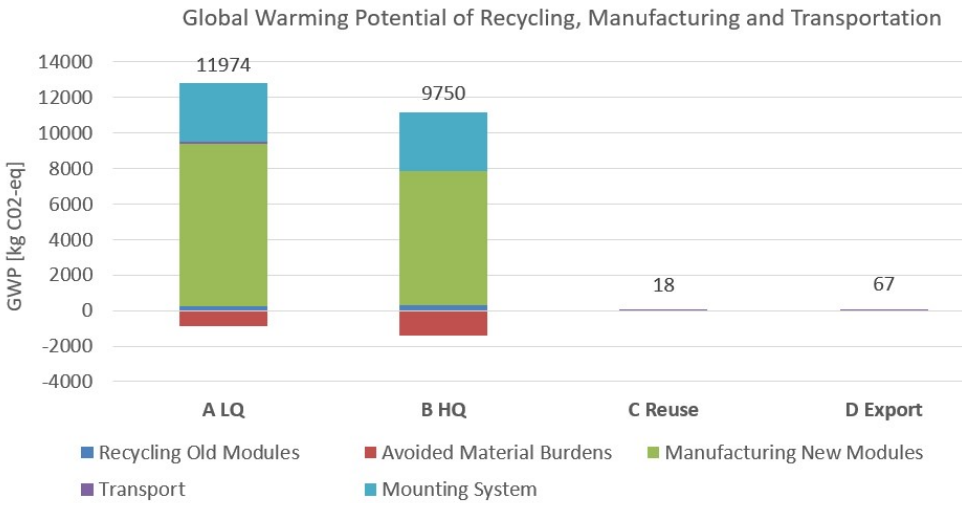


Figure 5.3.: Sensitivity analysis: the mounting system of the decommissioned modules is reused. Environmental impacts (GWP) per component of each scenario in year 0, including the manufacturing of the mounting system.

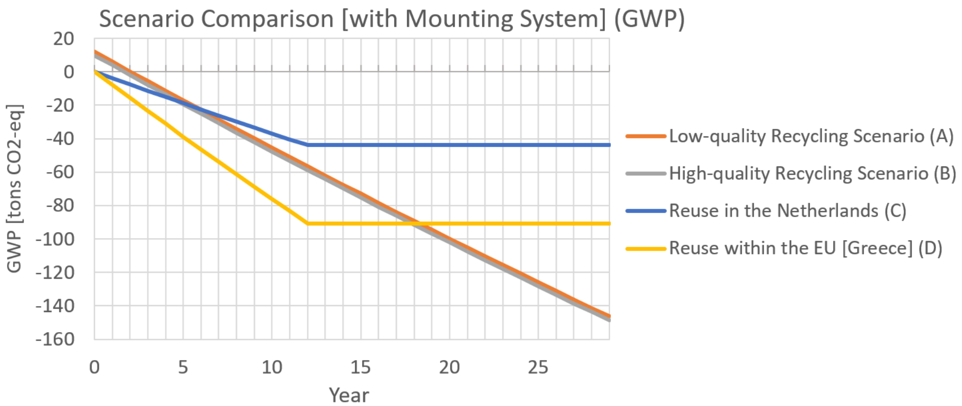


Figure 5.4.: Sensitivity analysis: the mounting system of the decommissioned modules is reused. Comparison of the four scenarios in terms of global warming potential until the new modules have reached the end of their lifetime.

5.4. Module Age: Determining the Cut-off Age for Reuse

In this research, the decommissioned modules are assumed to have been manufactured in 2011. These modules have a relatively short Replacement Payback Time. It is interesting to consider more recent module ages and determine how much the RPT is increased when the decommissioned modules are younger. In doing so, a cut-off age to consider modules for reuse can be identified, making it easier to determine which panels should be considered for reuse and which panels should go directly to recycling, based on the designated lifetime of the new PV system. For example, considering that the RPT of LQ recycling in the GWP category is 5 years compared to Reuse in NL, decommissioned modules from 2011 should not be used in a PV system that is intended to operate for 5 years or longer (and new modules should be installed instead). An analysis was conducted to determine the RPT of more recent module ages. The calculation is subject to a number of assumptions:

- The efficiency of c-Si PV modules increases linearly from 14.7% [21] to 19.79% [23] between 2011 and 2021, corresponding to an annual (linear) efficiency increase of 0.509%.
- The annual degradation rate of c-Si PV modules decreases linearly from 0.7% [21] to 0.5% [23] between 2011 and 2021.
- The performance ratio of c-Si PV modules increases linearly from 0.82 [21] to 0.85 [23] between 2011 and 2021.
- The material composition (and therefore the benefits of the recycling process) remains equal to the composition assumed in the FRELP process.

The calculated RPTs in this analysis are based on the same equations (3.1 and 3.6) used to calculate the cumulative impact of the scenarios, but the parameters (efficiency, degradation rate, performance ratio) are adjusted for every manufacturing year. Using Microsoft Excel, the year in which the cumulative environmental benefits of a recycling scenario outweigh those of the reuse scenario is determined.

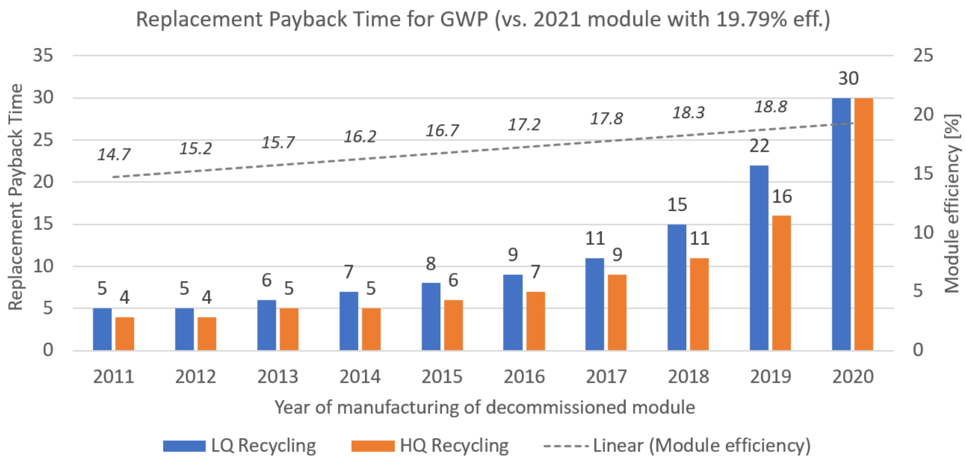


Figure 5.5.: Sensitivity analysis: module age. Figure shows the Replacement Payback Times of HQ and LQ recycling and replacement compared to Reuse in NL for different module ages. The comparison is based on the GWP impact category. The assumed nameplate efficiency for each manufacturing year is included in the graph. 30 years is the maximum possible value of the analysis and a result of 30 years means the concept of RPT does not apply.

Figure 5.5 shows the RPTs for each manufacturing year between 2011 and 2020. It can be concluded from the graph that if a PV project has a designated lifetime of 10 years, reusing decommissioned modules from 2016 or older (corresponding to a 5 year age difference) does not provide an environmental benefit from a global warming perspective compared to recycling those modules and installing new modules instead. Within that time frame, the higher energy yield of the new modules will have compensated for the manufacturing impacts and will have lead to a higher overall cumulative environmental benefit.

The same analysis was performed with respect to the eco-cost of resource scarcity and the total eco-cost. The results are presented in Appendix A.4.4.

5.5. CHAPTER SUMMARY

Chapter 5 assessed the influence of several parameters and conditions on the outcome of the comparison between recycling and reuse.

The first parameter analysed was the efficiency of the decommissioned modules. To this end, their assumed efficiency was increased from 14.7% to 17.245%. In the GWP impact category, this prolonged the RPT of the LQ scenario from 5 years to 7 years and the RPT of the HQ scenario from 4 years to 5 years. Export to a sunny country remained the preferred option in this impact category.

After that, an analysis involving the GWP of the electricity mix was carried out. This involved linearly decreasing the GWP of the electricity mix to zero between 2023 and 2050, in line with the goals set by the European Union to be climate-neutral by 2050. This did not influence the results reported in chapter 4.

Then, the system boundary was adjusted to include the mounting system of the PV modules. It was assumed that the mounting system of the decommissioned modules could be reused, while the new modules would need a new mounting system to be manufactured. This increased the year 0 impacts of the recycling scenarios and extended their RPT. In the GWP impact category, the RPT of the LQ scenario increased from 5 years to 6 years and the RPT of the HQ scenario from 4 years to 5 years.

The final sensitivity analysis examined the influence of the age of the decommissioned modules on the RPT. To that end, it was assumed that the efficiency and performance ratio of PV modules increased linearly between 2011 and 2021 and the annual degradation rate decreased linearly in that time frame. If a PV system is intended to have a lifetime of 10 years or longer, the following conclusions can be drawn: in the case of LQ recycling and replacement, reuse is only the preferred strategy from a global warming perspective if the decommissioned modules are less than 5 years old. For HQ recycling and replacement this is the case if the decommissioned modules are less than 4 years old.

6
Discussion

The results of this research show that the reuse of decommissioned modules in the Netherlands entails an environmental benefit at the outset. However, the benefits of recycling and replacement surpass those of reuse within a few years. Therefore, it is unlikely that the reuse of 10-year old decommissioned PV modules can provide an environmental benefit from a GWP or total eco-cost perspective in a practical time frame, e.g. if it is assumed that PV energy projects should have a financial lifetime of 10 years or longer.

Comparison to Literature

The poor potential for reuse (i.e. short Replacement Payback Times) in this study appears to contrast the findings of the IEA PVPS in a 2021 report [21]. This report argued that, when considering (environmental impact/the environment), it was favourable to keep a panel in use for its 30-year lifetime as opposed to replacing it with new, more efficient panels.

However, contrary to the IEA PVPS report, this study focuses on whether it is environmentally beneficial to reuse decommissioned modules in a new PV system. In other words, a new Balance of System is needed, regardless of whether old or new modules are used. Previous studies on PV system repowering (such as [21]) often compare between two extremes: replacing the entire system and keeping the entire system in use (disregarding some repair activities). In that approach, new modules not only need to compensate for their own manufacturing impacts, but also for the manufacturing impacts of the BoS. It can be argued that this is the primary reason for the disparity between the results of this study and previous research, with repowering studies generally demonstrating higher optimal repowering time compared to the Replacement Payback Times calculated here.

There are additional differences in assumptions and parameters between this study and [21]. Müller et al. [23] have demonstrated that the IEA PVPS overestimates the environmental impacts of PV module manufacturing considerably, due to the use of outdated LCI datasets. This distorts the comparison in favour of reuse.

Furthermore, the IEA PVPS assumed an annual output power improvement of

1.4% per year for silicon PV technology, which is much lower than the technological improvements that have been realized in the real world. After 10 years, this annual improvement amounts to a relative increase in power output of 15%. In reality, the efficiency of typical c-Si modules has increased from 14% in 2010 [9] to 19.7% in 2020 [15], amounting to a 41% increase in efficiency in 10 years. Evidently, underestimating the efficiency of the modules which are to replace the old modules further distorts the comparison in favour of reuse.

In a recent Master thesis by Sietse De Vilder (Delft University of Technology) on strategies for prematurely decommissioned PV modules in the municipality of Amsterdam [76], it is argued that reuse is environmentally preferable despite the rapid technological advancements in the PV sector. The conclusion seems to contradict the results of this thesis, as recycling and replacement is shown to entail the greatest environmental benefits under most circumstances. However, there is a number of important differences in assumptions: the definition of reuse in De Vilder's thesis involves replacing the decommissioned modules *and* reusing the decommissioned on another location. Evidently, this results in greater environmental benefits than just replacement.

Additionally, the electricity mix in De Vilder's thesis is based on the European grid, which has a much lower emissions intensity than the Dutch grid (41.5% lower in the GWP category in IDEMAT). Underestimating the avoided electricity burden causes reuse to be favourable: it takes longer for new modules to compensate for their manufacturing impacts. When the Dutch electricity mix was used in a sensitivity analysis, De Vilder also found that replacement after 12 years is better than using for 25 years.

Limitations of the research

The use phase of the PV modules has been simplified in this study: the environmental impacts of the installation process and the maintenance of the PV system are not taken into account. These processes are assumed to be the same in the replacement and reuse scenarios, therefore the omission of these impacts should not have any effect on the outcome of the study. Also, it is assumed that all the PV modules of the system stay operational for the entire duration of the calculation.

In this research, ecoinvent LCI datasets were substituted by IDEMAT datasets where possible in order to use the most accurate and transparent datasets available, based on peer-reviewed literature. Aside from the commonly used impact category 'Global Warming Potential', the environmental impacts were expressed in the IDEMAT impact categories 'Eco-cost of Resource Scarcity' and 'Total eco-cost'. The reasoning behind this decision was justified in 1.7. A negative consequence of this choice is that the environmental impacts are not expressed in the most common units found in literature, making it difficult to compare the results of this research with other studies. The sanity test for the impacts of module manufacturing, for example, could only be carried out in the GWP impact category. The analyses involving the BoS of the system could also only be conducted from a GWP perspective, since the impacts of the BoS components were taken from literature.

By 2023 standards, the assumed efficiency of 19.79% might be considered outdated, as the total weighted average efficiency of new c-Si modules was already 20.9% in Q4 of 2022 [12]. The assumed efficiency is based on the best available LCA on module manufacturing. Although it is unclear how the manufacturing impacts of the 2022 modules have changed compared to those calculated in this study (2021), it is likely that the increased efficiency of state-of-art modules further deteriorates the potential for reuse of decommissioned modules.

One of the scenarios involves the export of the decommissioned modules to Greece. In most analyses, this provides the highest environmental benefit in the GWP and total eco-cost categories. However, it might not be realistic to assume that all decommissioned PV modules can be exported to Greece. Naturally, it can be argued that the benefits of new modules installed Greece are even higher than those of the decommissioned modules. Additionally, it is not clear whether a strong business case can be made for reuse of the modules in Greece. Finally, although it is evident that PV modules have a higher yield in sunny countries, the Netherlands will still need PV capacity for its energy transition.

7
CONCLUSION

This study aimed to give insight into the potential for the reuse of decommissioned PV modules by comparing the environmental impacts of PV module reuse versus those of recycling and replacement of the modules. The analysis was conducted based on the main research question:

Under which circumstances does the recycling and replacement of PV modules have a greater environmental benefit than the reuse of PV modules?.

To answer this question, the reuse of decommissioned modules was compared to the use of new modules. The decommissioned modules had an efficiency of 14.7% when they where manufactured in 2011, the new modules had an efficiency of 19.79%. An LCA involving the end-of-life treatment, manufacturing, transport and the use phase of PV modules was conducted to assess the environmental impacts across four scenarios:

Scenario A: Low-quality (LQ) recycling and replacement
Scenario B: High-quality (HQ) recycling and replacement
Scenario C: Reuse within the Netherlands
Scenario D: Reuse within the EU [Greece]

The environmental impacts were expressed in the global warming potential (GWP) [kg CO_2-eq], eco-cost of resource scarcity [€] and total eco-cost [€] impact categories.

From the analysis performed in this study, it can be concluded that:

1. Due to the increasing efficiency of silicon PV technology and the degradation of the decommissioned modules, **there is a significant difference in performance between the new modules and the decommissioned modules. The yield of the new modules is 53.5% higher in the first year.**
2. **Compared to the reuse of the decommissioned modules in NL, (low-quality) recycling and replacement has a greater environmental benefit for PV projects with a duration of 5 years or longer.** In the HQ recycling and replacement scenario, the Replacement Payback Time (RPT) in the GWP category is shorter: 4 years. In terms of the eco-cost of resource scarcity, the

RPT of HQ recycling is 8 years. With respect to the total eco-cost, the RPT of LQ and HQ recycling are 8 years and 6 years respectively.

3. Despite the increased performance of new modules, **recycling and replacing the decommissioned modules in the Netherlands does not provide a greater benefit in the GWP and total eco-cost impact categories than reusing them in an EU member state with a higher annual specific yield and an electricity mix with a higher emissions intensity.** The transport emissions are negligible compared to the additional emissions that can be avoided by exporting to a country with higher avoided burden per kWh.

4. If a PV project is intended to have a lifetime of 10 years or longer, **recycling and replacement is more beneficial from a global warming perspective than reuse if the decommissioned modules are (more than) 5 years old** in the case of LQ recycling. In the case of HQ recycling, the same holds if the decommissioned modules are (more than) 4 years old.

5. **The environmental impact of replacement can be reduced significantly by i) applying a HQ instead of a LQ recycling process and ii) manufacturing the PV modules in the Netherlands instead of in China. The reduction amounts to 25.7% of the GWP.** In the eco-cost of resource scarcity and the total eco-cost impact categories, the relative reductions between the HQ and LQ scenarios are 64.7% and 30.0% respectively. Module manufacturing in the Netherlands entails an impact reduction because the process is highly energy intensive and the Dutch grid has a lower emissions intensity than the Chinese grid. The benefits of HQ recycling are higher because, aside from aluminium and copper, solar glass, silicon and silver are recovered.

In addition, the PV system in **the HQ recycling and replacement scenario has the lowest emissions intensity with 40.5 g CO_2-eq/kWh**. The emissions intensities in the LQ recycling and the Reuse within the EU scenarios are both approximately 16% higher. Reuse in NL has a substantially higher emissions intensity of 65.2 g CO_2-eq/kWh, nearly 61% higher than the HQ recycling scenario.

The low emissions intensity of the recycling and replacement scenarios and the short RPTs can be attributed primarily to the increasing efficiency of silicon PV technology and the degradation of the decommissioned modules. The higher energy yield of the new modules leads to increased environmental benefits as more PV electricity displaces the production of electricity using conventional, non-renewable energy sources. This 'avoided burden' is the main driver in the comparison of the scenarios.

8 RECOMMENDATIONS

Over the course of the research, a number of interesting topics for future research have been identified. The recommendations are given below:

1. The export of the decommissioned modules showed great potential environmental benefits in the GWP and total eco-cost impact categories. It would be interesting to research which options and strategies there are from a policy perspective to export the decommissioned modules to European countries (possibly involving the collection of the modules after the end of their lifetime to recycle them in the Netherlands), and what the financial implications would be. The business case for module reuse might become considerably more attractive in countries in which labour and land area have a lower cost than in the Netherlands. The export of inexpensive decommissioned modules to countries with a developing economy might aid in their energy transition. In this proposed research it would be essential to include not only module reuse in the export country but also the installation of new, higher efficiency modules in that country in both an environmental and financial analysis.

2. It would be interesting to develop a more 'continuous' model of the method applied in this research. In this research, the comparison ends when the decommissioned modules reach the end of their lifetime. However, a more elaborate model could be created in which the decommissioned modules are replaced with another set of decommissioned modules (or new modules). The system boundary can also be extended to include the EoL treatment at the end of the scenarios. Furthermore, in this study, the calculations of the BoS impacts were simplified. If the reuse of BoS components is possible, a more rigorous analysis with regards to their environmental impacts would provide more insight into the influence on the replacement payback time.

3. From a circularity perspective, glass-glass PV modules show great potential. The absence of a polymer backsheet that cannot be recovered means that the percentage of recyclable materials inside the glass-glass modules is even higher than in glass-backsheet modules. Furthermore, it can be argued that recycling decommissioned glass-backsheet modules to manufacture glass-glass modules

without an aluminium frame significantly reduces the overall environmental impact of replacement: the recovery of aluminium from the decommissioned modules entails a large avoided burden of the production of primary aluminium.

4. Although the market share of c-Si modules is around 95% at this moment [12], a considerable amount of thin-film PV modules are being produced. In 2021, the global production of CdTe and CIGS modules amounted to more than 8 GWp and 2 GWp respectively [12], corresponding to tens of millions of modules. It will be necessary to perform a similar analysis to this study on the reuse potential of thin-film PV technologies such as CdTe and CIGS modules. Since these modules consist of different materials, have different manufacturing impacts and need to be recycled using different processes [77], the results of this study do not apply directly to those technologies. However, the methods employed in this research (e.g. comparing the avoided burdens to the impacts over the life cycle), can be applied to find the RPTs of those technologies.

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A
APPENDIX

A.1. COUNTRY SPECIFIC AVOIDED BURDENS

In section 2.4, the process of selecting a country to export the decommissioned modules to was explained. It was done on the basis of maximizing the avoided environmental burdens in terms of GWP, by comparing the carbon intensity of the electricity mix of each country. Alternatively, the avoided burdens can be maximized in terms of eco-cost of resource scarcity or in terms of total eco-cost. The figures which can be used to find the optimal country for these two impact categories are shown in figures A.1 and A.2 respectively.

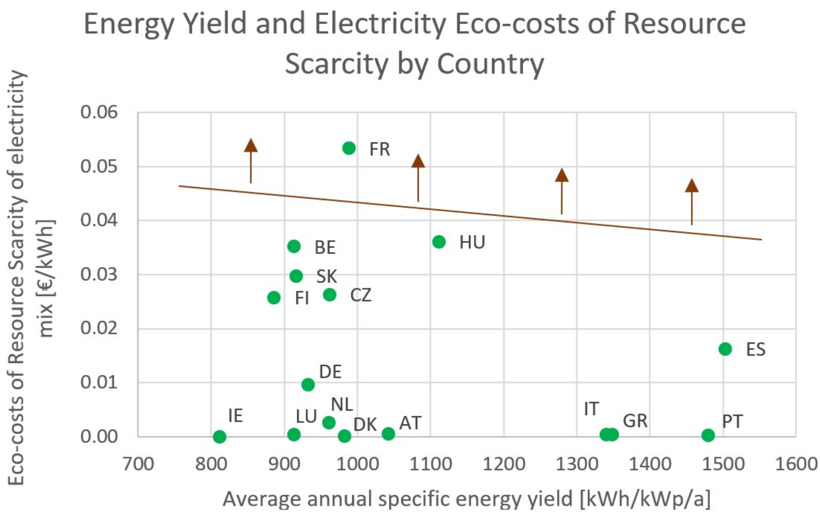

Figure A.1.: Scatter plot of eco-costs of resource scarcity of 2019 electricity production mix [57] vs. average annual specific yield of selected EU member states [67]. Orange line indicates constant avoided eco-costs per kWp. Points to the left/bottom of line have a lower avoided eco-cost per kWp than points to the right/top.

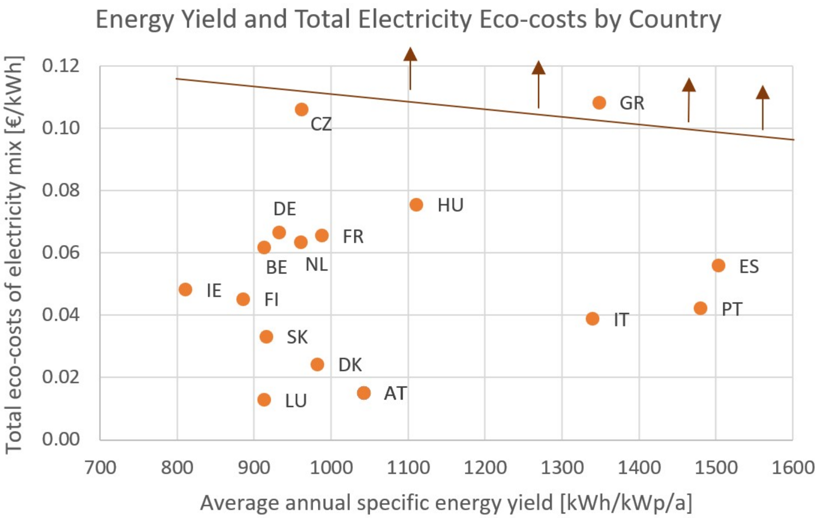

Figure A.2.: Scatter plot of total eco-costs of 2019 electricity production mix [57] vs. average annual specific yield of selected EU member states [67]. Orange line indicates constant avoided eco-costs per kWp. Points to the left/bottom of line have a lower avoided eco-cost per kWp than points to the right/top.

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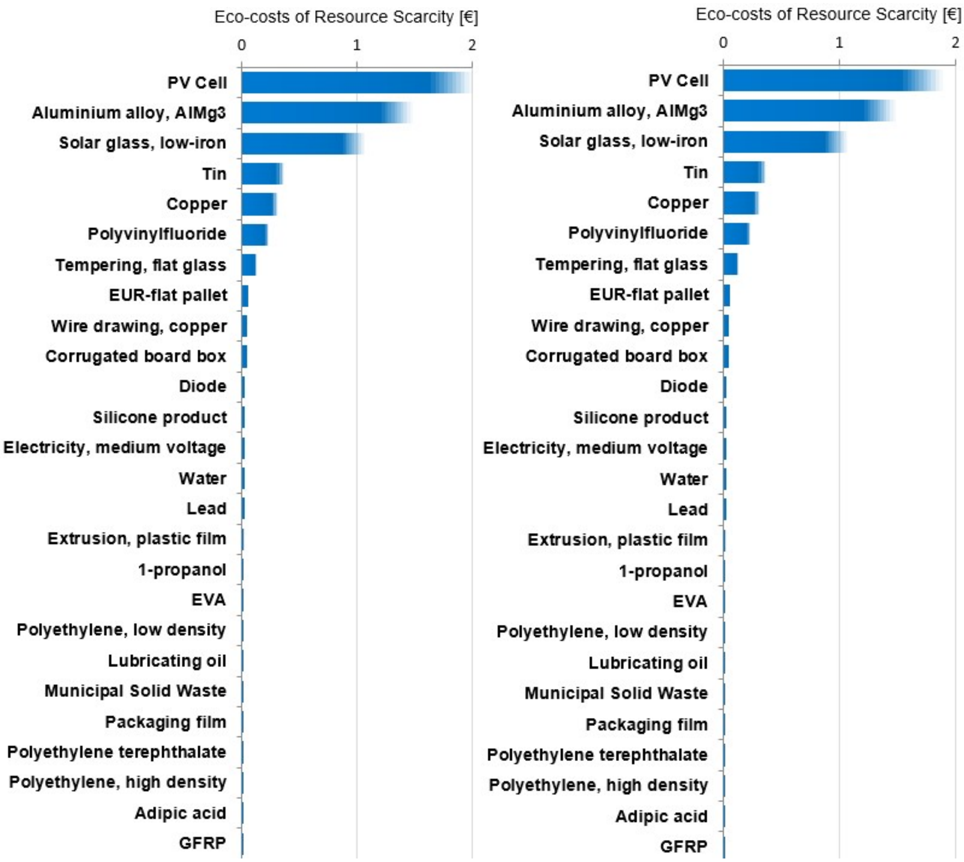
A.2. ENVIRONMENTAL IMPACT OF MODULE MANUFACTURING

Section 3.2.2 showed a compact version of the impacts of module manufacturing. In this section, the full list of environmental impacts associated with the last manufacturing step is presented for modules manufactured in China and in the Netherlands, in the impact categories global warming potential, eco-cost of resource scarcity and total eco-cost. Contrary to section 3.2.2, the impacts are displayed per m^2 instead of showing the total impacts of the scenario.

(a) Impacts of module manufacturing in CN. Total impact: 120.7 kg CO_2-eq/m^2.

(b) Impacts of module manufacturing in NL. Total impact: 98.9 kg CO_2-eq/m^2.

Figure A.3.: GWP of PV module manufacturing in China (CN) and the Netherlands (NL) per m^2.



(a) Impacts of module manufacturing in CN. Total impact: 5,29 €/m^2.

(b) Impacts of module manufacturing in NL. Total impact: 5,18 €/m^2

Figure A.4.: Eco-cost of resource scarcity of PV module manufacturing in China (CN) and the Netherlands (NL) per m^2.

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(a) Impacts of module manufacturing in CN. Total impact: 30,24 €/m^2.

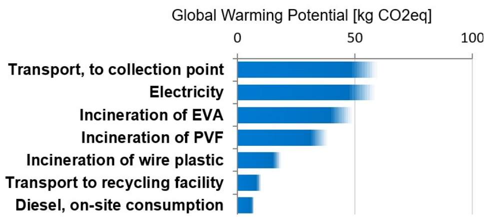
(b) Impacts of module manufacturing in NL. Total impact: 27,27 €/m^2

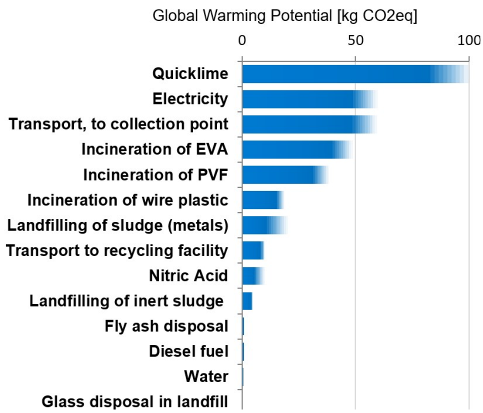
Figure A.5.: Total eco-cost of PV module manufacturing in China (CN) and the Netherlands (NL) per m^2.

A.3. RECYCLING IMPACTS

In section 4.1.1, only the total values of the recycling impacts were reported. In this section, the impacts of the low-quality and high-quality recycling processes are visualized per component.

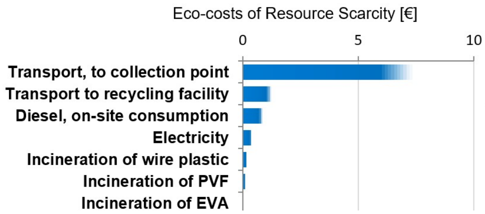
The chemical treatment of the waste, especially the use of quicklime, has a significant impact in the GWP and total eco-cost impact categories. The chemical treatment is included in the FRELP process to recover silver and copper from the PV waste. As a result, the recycling impacts are higher in the HQ recycling scenario in all three impact categories.

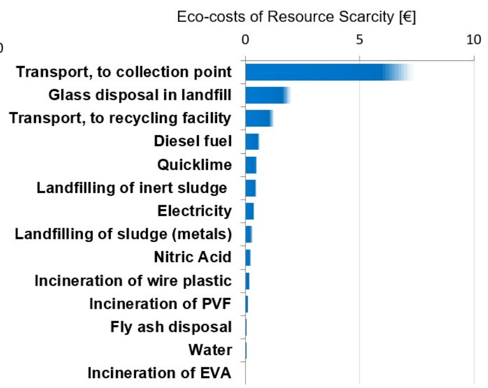




(a) Low-quality recycling impacts. Total impact: 180 kg CO_2-eq.

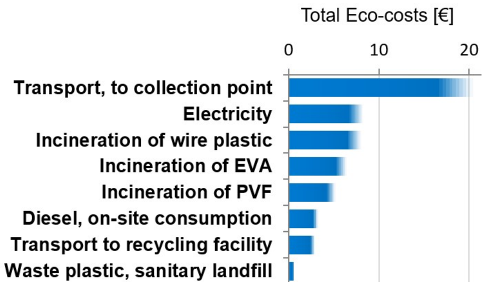
(b) High-quality recycling impacts. Total impact: 335 kg CO_2-eq.



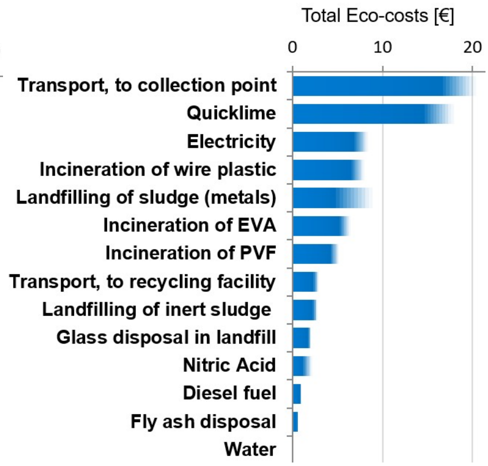


(c) Low-quality recycling impacts. Total impact: €9.

(d) High-quality recycling impacts. Total impact: €12.



(e) Low-quality recycling impacts. Total impact: €48.



(f) High-quality recycling impacts. Total impact: €77.

Figure A.6.: Environmental impacts of low- and high quality recycling in terms of GWP, eco-cost of resource scarcity and total eco-costs.

A.4. Sensitivity Analysis

Chapter 4 covered several sensitivity analyses to evaluate the robustness of the results. For the sake of brevity, only the results in the GWP impact category were shown. For all of the analyses except the net-zero scenario, the analyses were also performed in the eco-cost of resource scarcity and total eco-cost impact categories. The results are presented in this section.

A.4.1. Smaller Difference in Efficiency

The rate at which the efficiency of silicon PV technology improves annually might slow down in the future. The effect of a smaller difference in efficiency between modules with a 10-year age difference on the eco-cost of resource scarcity and the total eco-cost is analyzed in this section. It is assumed that the efficiency of the decommissioned modules was 17.245% instead of 14.7% at the start of their lifetime, representing the midpoint of the efficiencies of the old modules (14.7%) and the new modules (19.79%) in this research. In this hypothetical scenario, all other parameters (module age, degradation rate, etc.) are left unchanged. Evidently, a smaller difference in efficiency improves the potential for reuse.

The environmental benefits are plotted in terms of eco-cost of resource scarcity (figure A.7) and total eco-cost (figure A.8).

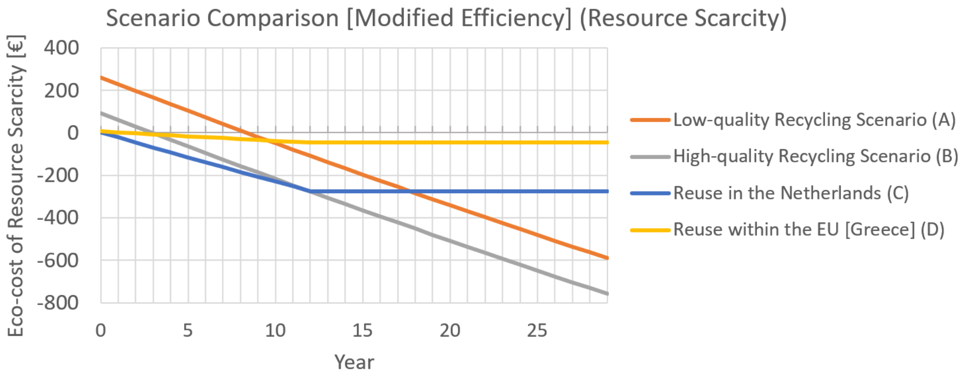


Figure A.7.: Sensitivity analysis: the assumed nameplate efficiency of the decommissioned modules is 17.245% instead of 14.7%. Comparison of the four scenarios in terms of eco-cost of resource scarcity until the new modules have reached the end of their lifetime. Replacement Payback Time of LQ recycling and replacement: not applicable compared to reuse in NL, 10 years compared to reuse in GR. RPT of HQ recycling and replacement: 12 years compared to reuse in NL, 3 years compared to reuse in GR.

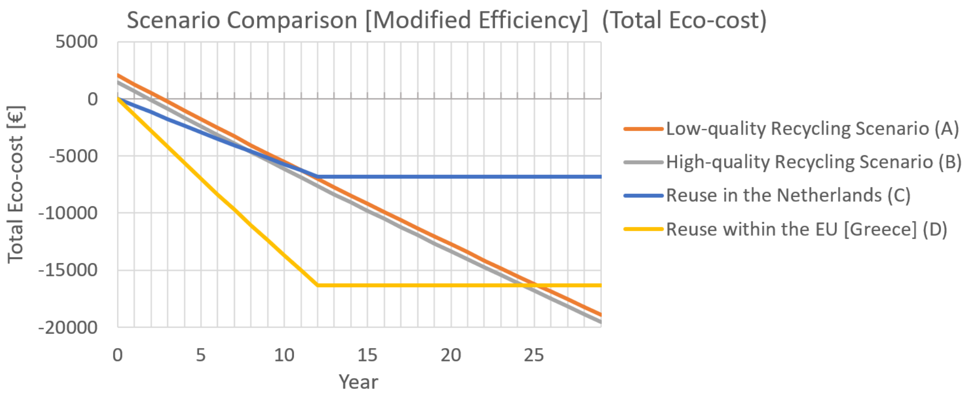


Figure A.8.: Sensitivity analysis: the assumed nameplate efficiency of the decommissioned modules is 17.245% instead of 14.7%. Comparison of the four scenarios in terms of total-eco cost until the new modules have reached the end of their lifetime. Replacement Payback Time of LQ recycling and replacement: 12 years compared to reuse in NL, not applicable compared to reuse in GR. RPT of HQ recycling and replacement: 8 years compared to reuse in NL, not applicable compared to reuse in GR.

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A.4.2. REUSE OF MOUNTING SYSTEM

The mounting system was not included in the scope of this research. It was assumed that a new mounting system was needed in each scenario. However, if it is assumed that the mounting system of the decommissioned modules can reused, then the difference in manufacturing impacts between the replacement and the reuse scenarios is larger. The influence of the additional impacts on the results of the research was analysed in section 5.3 for the GWP impact category. In this section, the influence on the eco-cost of resource scarcity (figures A.9 and A.10) and the total eco-cost (figures A.11 and A.12) impact categories is assessed.

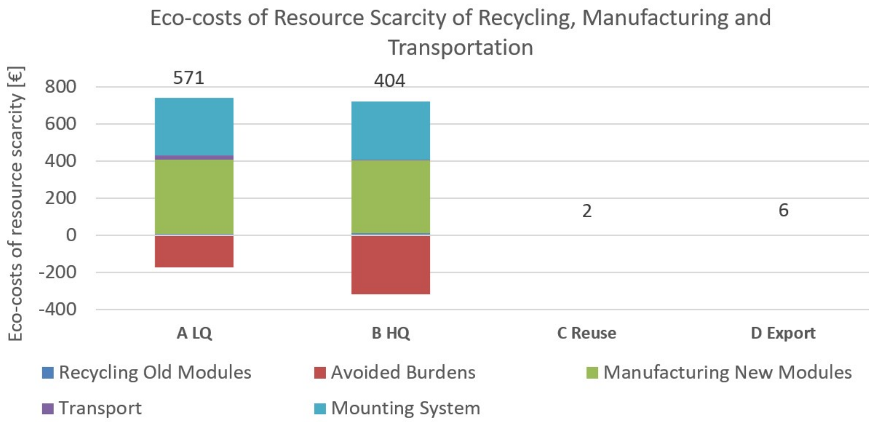

Figure A.9.: Sensitivity analysis: the mounting system of the decommissioned modules is reused. Eco-cost of resource scarcity per component of each scenario in year 0, including the manufacturing of the mounting system.

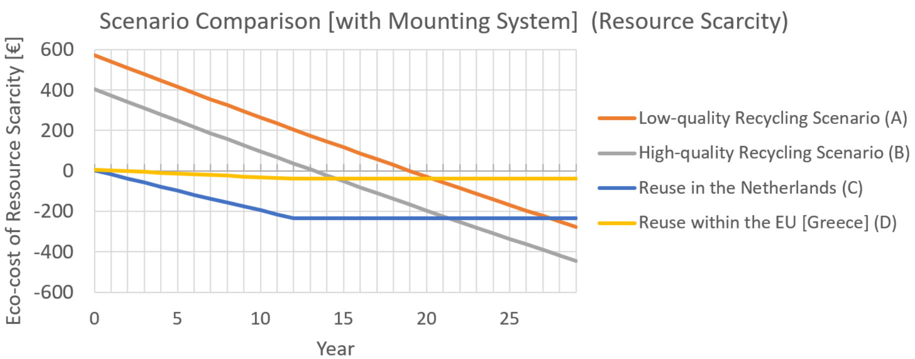

Figure A.10.: Sensitivity analysis: the mounting system of the decommissioned modules is reused. Comparison of the scenarios in terms of eco-cost of resource scarcity until the new modules have reached the end of their lifetime. RPT is not applicable in this case, reuse is always preferred.

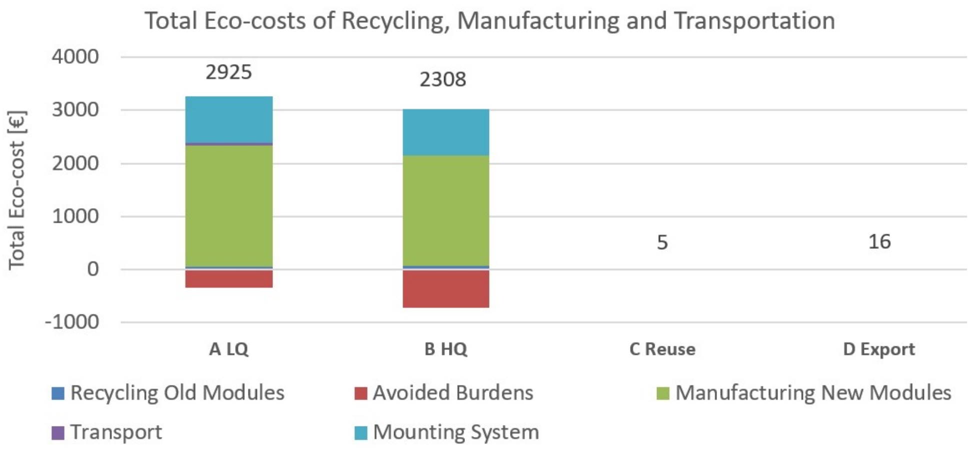

Figure A.11.: Sensitivity analysis: the mounting system of the decommissioned modules is reused. Total eco-cost per component of each scenario in year 0, including the manufacturing of the mounting system.

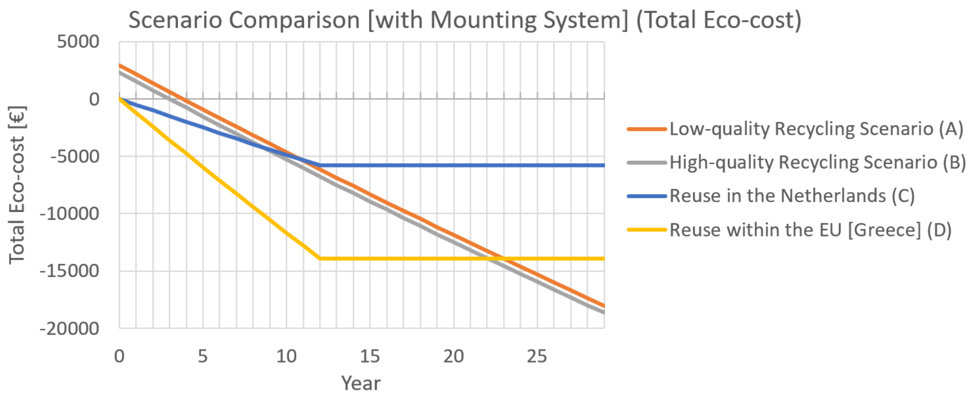

Figure A.12.: Sensitivity analysis: the mounting system of the decommissioned modules is reused. Comparison of the four scenarios in terms of total eco-cost until the new modules have reached the end of their lifetime. Replacement Payback Time of LQ recycling and replacement: 11 years compared to reuse in NL, not applicable compared to reuse in GR. RPT of HQ recycling and replacement: 9 years compared to reuse in NL, not applicable compared to reuse in GR.

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A.4.3. INCLUDING BOS (ESTIMATE)

For the purpose of calculating the emissions intensity of the produced electricity in section 4.5.1, the GWP impacts of the BoS were taken from literature. In this section, it is analysed whether including the BoS impacts has a significant influence on the results of the research.

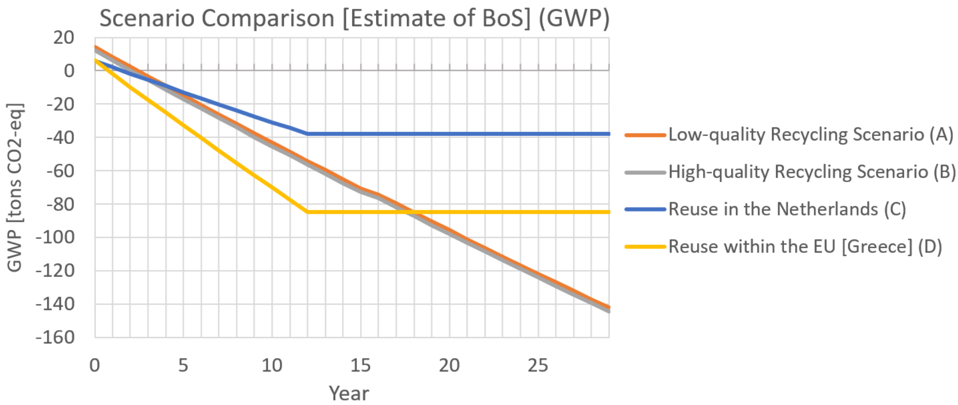

Figure A.13.: Sensitivity analysis: the GWP impact of the mounting system and of the other BoS components (taken from literature) are included. The inverter is replaced after 15 years. Comparison of the four scenarios in terms of GWP until the new modules have reached the end of their lifetime. Replacement Payback Time of LQ recycling and replacement: 5 years compared to reuse in NL, not applicable compared to reuse in GR. RPT of HQ recycling and replacement: 3 years compared to reuse in NL (1 year reduction), not applicable compared to reuse in GR.

Since the BoS impacts are assumed to be similar in all scenarios, the RPTs did not change significantly. There was a 1 year reduction of the RPT of HQ recycling compared to reuse in NL.

A.4.4. MODULE AGE: DETERMINING THE CUT-OFF AGE FOR REUSE

Section 5.4 treated an analysis in which the RPT of more recently manufactured modules (compared to 2011) was calculated. The analysis showed the results from a GWP perspective. In this section, the results from a eco-cost of resource scarcity and total eco-cost perspective are shown. The same assumptions made in 5.4 apply.

The calculated RPTs in this analysis are based on the same equations (3.1 and 3.6) used to calculate the cumulative impact of the scenarios, but the parameters (efficiency, degradation rate, performance ratio) are adjusted for every manufacturing year. Using Microsoft Excel, the year in which the cumulative environmental benefits of a recycling scenario outweigh those of the reuse scenario is determined.

The RPTs that lie beyond the remaining lifetime of the decommissioned modules are purely hypothetical. The maximum possible value of an RPT is 30 years in this analysis. An RPT of 30 years means that the decommissioned module has greater environmental benefits over its entire remaining lifetime than the new module would have. Therefore, the RPT concept does not apply.

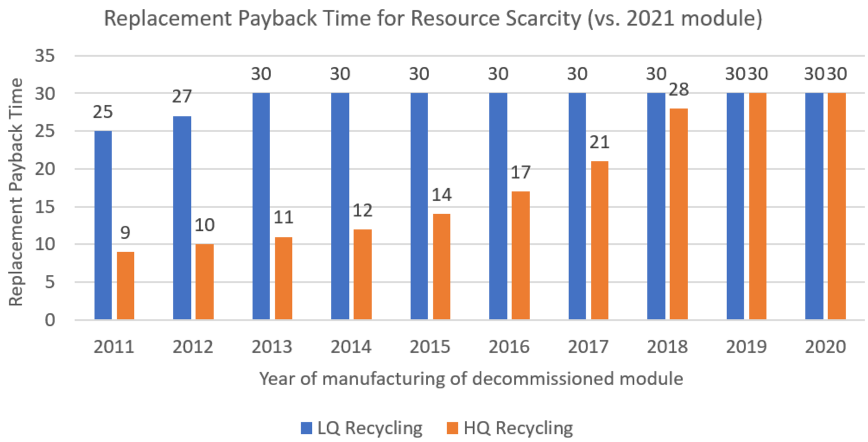

Figure A.14.: Sensitivity analysis: module age. Figure shows the Replacement Payback Times of HQ and LQ recycling and replacement compared to Reuse in NL for different module ages. The comparison is based on the eco-cost of resource scarcity impact category. 30 years is the assumed lifetime of the new modules and therefore the maximum value.

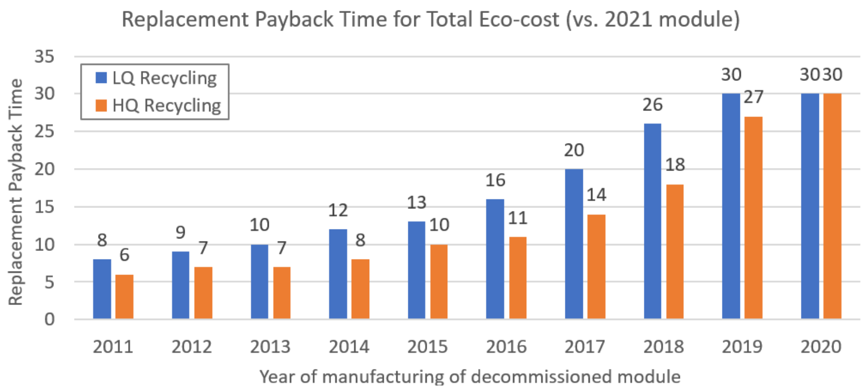

Figure A.15.: Sensitivity analysis: module age. Figure shows the Replacement Payback Times of HQ and LQ recycling and replacement compared to Reuse in NL for different module ages. The comparison is based on the total eco-cost impact category. 30 years is the assumed lifetime of the new modules and therefore the maximum value.

A

A.5. INVENTORY DATA

This section includes all the inventory data used in this research. First, the inventory data of the recycling processes is shown. Then, the inventory data of manufacturing is presented. After that, the inventory data of transport can be found. Finally, the inventory data of the mounting system used in the sensitivity analysis is shown. The source on which the inventory data is based is included in the caption of the table. The tables also include the LCI database that is used for each input of the process.

Table A.1.: Inventory data for HQ recycling of PV modules. Based on [38].

Input	Coefficient	Unit	Activity Link	Source
Diesel fuel	1.14E+00	kg	diesel low-sulphur including combustion CO2	Idemat2023
Electricity	4.09E+02	MJ	electricity netherlands	Idemat2023
Fly ash disposal	2.00E+00	kg	treatment of average incineration residue, residual material landfill [CH]	Ecoinvent v3.7
Glass disposal in landfill	1.40E+01	kg	landfill (inert waste, not biodegradable)	Idemat2023
Incineration of EVA	5.10E+01	kg	EVA (Ethylene vinyl acetate) waste incineration with electricity	Idemat2023
Incineration of PVF	1.50E+01	kg	treatment of waste polyvinylfluoride, municipal incineration [CH]	Ecoinvent v3.7
Incineration of wire plastic	6.70E+00	kg	treatment of waste wire plastic, municipal incineration [CH]	Ecoinvent v3.7
Landfilling of inert sludge	3.06E+02	kg	treatment of limestone residue, inert material landfill [CH]	Ecoinvent v3.7
Landfilling of sludge (metals)	5.03E+01	kg	treatment of blast furnace sludge, residual material landfill [CH]	Ecoinvent v3.7
Nitric Acid	7.08E+00	kg	market for nitric acid, without water, in 50% solution state [RER w/o RU]	Ecoinvent v3.8
Quicklime	3.65E+01	kg	quicklime	Idemat2023
Water	3.10E+02	kg	drinking water europe	Idemat2023
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
HQ Recycling of c-Si PV modules	**1.00E+03**	**kg**		

Table A.2.: Inventory data for LQ recycling of PV modules and avoided material burdens of LQ recycling. Based on [72].

Input	Coefficient	Unit	Activity Link	Source
Diesel, on-site consumption	6.48E+01	MJ	diesel, burned in building machine [GLO]	Idemat2023
Electricity	4.00E+02	MJ	Electricity Netherlands	Idemat2023
Incineration of EVA	5.10E+01	kg	EVA (Ethylene vinyl acetate) waste incineration with electricity	Idemat2023
Incineration of PVF	1.50E+01	kg	treatment of waste polyvinylfluoride, municipal incineration [CH]	Ecoinvent v3.7
Incineration of wire plastic	6.70E+00	kg	treatment of waste wire plastic, municipal incineration [CH]	Ecoinvent v3.7
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
LQ recycling of c-Si PV modules	**1.00E+03**	**kg**		

Input	Coefficient	Unit	Activity Link	Source
aluminium	1.44E+02	kg	aluminium (primary)	Idemat2023
aluminium, secondary	-1.44E+02	kg	aluminium (secondary)	Idemat2023
copper	1.49E+00	kg	copper (primary)	Idemat2023
copper, secondary	-1.49E+00	kg	copper (secondary)	Idemat2023
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
Avoided material burdens due to LQ recycling of PV modules	**1.00E+03**	**kg**		

Table A.3.: Inventory data for avoided material burdens of HQ recycling of PV modules. Based on [38].

Input	Coefficient	Unit	Activity Link	Source
aluminium	1.46E+02	kg	aluminium (primary)	Idemat2023
aluminium scrap	-1.46E+02	kg	aluminium (secondary)	Idemat2023
copper	1.97E+00	kg	copper (primary)	Idemat2023
copper scrap	-1.97E+00	kg	copper (secondary)	Idemat2023
glass	6.86E+02	kg	glass cladding and windows	Idemat2023
glass cullet	-6.86E+02	kg	glass bottles, recycled	Idemat2023
MG-Silicon	3.47E+01	kg	MG-Silicon	This study
silver	2.25E-01	kg	silver (primary)	Idemat2023
silver scrap	-2.25E-01	kg	silver (secondary)	Idemat2023

Output	Coefficient	Unit	Activity Link	Source
Avoided material burdens due to HQ recycling of PV modules	**1.00E+03**	**kg**		

Table A.4.: Inventory data for MG-Silicon production. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
charcoal	1.70E-01	kg	market for charcoal [GLO]	Ecoinvent v3.8
coke	2.31E+01	MJ	market for coke [GLO]	Ecoinvent v3.8
electricity, medium voltage	3.96E+01	MJ	electricity china/ electricity netherlands	Idemat2023
graphite	1.00E-01	kg	market for graphite [GLO]	Ecoinvent v3.8
oxygen, liquid	2.00E-02	kg	market for oxygen, liquid [RER]	Ecoinvent v3.8
petroleum coke	5.00E-01	kg	market for petroleum coke [GLO]	Ecoinvent v3.8
silica sand	2.70E+00	kg	market for silica sand [GLO]	Ecoinvent v3.8
wood chips, wet, measured as dry mass	5.50E-01	kg	market for wood chips, wet, measured as dry mass	Ecoinvent v3.8
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
silicon, metallurgical grade [CN or NL]	**1.00E+00**	**kg**		
slag from metallurgical grade silicon production	2.50E-02	kg	market for slag from metallurgical grade silicon production [GLO]	Ecoinvent v3.7

Table A.5.: Inventory data for poly-silicon. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
electricity, medium voltage	2.59E+02	MJ	electricity china/ electricity netherlands	Idemat2023
heat, district or industrial, natural gas	7.00E+01	MJ	industrial heat, general	Idemat2023
hydrochloric acid, without water, in 30% solution state	1.60E+00	kg	market for hydrochloric acid, without water, in 30% solution state [RoW]	Ecoinvent v3.8
hydrogen, liquid	5.01E-02	kg	market for hydrogen, liquid [RER]	Ecoinvent v3.8
silicon, metallurgical grade	1.13E+00	kg	silicon, metallurgical grade [CN or NL]	This study
sodium hydroxide, without water, in 50% solution state	3.48E-01	kg	market for sodium hydroxide, without water, in 50% solution state [GLO]	Ecoinvent v3.8
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
silicon, poly-silicon [CN or NL]	**1.00E+00**	**kg**		

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Table A.6.: Inventory data for Czochralski (Cz) Silicon. Based on [23]

Input	Coefficient	Unit	Activity Link	Source
argon, liquid	4.60E-02	kg	market for argon, liquid [RoW]	Ecoinvent v3.8
ceramic tile	6.20E-02	kg	market for ceramic tile [GLO]	Ecoinvent v3.8
electricity, medium voltage	1.38E+02	MJ	electricity china/ electricity netherlands	Idemat2023
hydrochloric acid, without water, in 30% solution state	4.38E-04	kg	market for hydrochloric acid, without water, in 30% solution state [RoW]	Ecoinvent v3.8
hydrogen fluoride	3.51E-03	kg	market for hydrogen fluoride [RoW]	Ecoinvent v3.8
lime, hydrated, packed	2.20E-02	kg	market for lime, hydrated, packed [RoW]	Ecoinvent v3.8
nitric acid, without water, in 50% solution state	7.78E-03	kg	market for nitric acid, without water, in 50% solution state [RoW]	Ecoinvent v3.8
silicon, poly-silicon	6.39E-01	kg	silicon, poly-silicon [CN or NL]	This study
sodium hydroxide, without water, in 50% solution state	4.78E-03	kg	market for sodium hydroxide, without water, in 50% solution state [GLO]	Ecoinvent v3.8
water, completely softened	6.84E-02	kg	market for water, completely softened [RoW]	Ecoinvent v3.8
Water, cooling, unspecified natural origin [natural resource/in water]	2.33E+03	kg	market for tap water [GLO]	Ecoinvent v3.8
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
silicon, single crystal, Czochralski [CN or NL]	**1.00E+00**	**kg**		
waste, from silicon wafer production, inorganic	1.00E-01	kg	market for waste, from silicon wafer production, inorganic [GLO]	Ecoinvent v3.7

Table A.7.: Inventory data for single-crystalline Si wafering & bricking. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
acrylic binder, without water, in 34% solution state	4.98E-03	kg	market for acrylic binder, without water, in 34% solution state [RoW]	Ecoinvent v3.8
alkylbenzene sulfonate, linear, petrochemical	3.40E-02	kg	market for alkylbenzene sulfonate, linear, petrochemical [GLO]	Ecoinvent v3.8
brass	7.45E-03	kg	market for brass [RoW]	Ecoinvent v3.8
citric acid	1.87E-01	kg	market for citric acid [GLO]	Ecoinvent v3.8
electricity, medium voltage	8.46E+00	MJ	electricity china/electricity netherlands	Idemat2023
glass wool mat	1.06E-02	kg	market for glass wool mat [GLO]	Ecoinvent v3.8
heat, district or industrial, natural gas	1.80E+00	MJ	industrial heat, general	Idemat2023
hydrogen peroxide, without water, in 50% solution state	2.53E-02	kg	market for hydrogen peroxide, without water, in 50% solution state [RoW]	Ecoinvent v3.8
potassium hydroxide	3.81E-03	kg	market for potassium hydroxide [GLO]	Ecoinvent v3.8
silicon, single crystal, Czochralski process, photovoltaics	1.03E+00	kg	silicon, single crystal, Czochralski [CN or NL]	This study
sodium hydroxide, without water, in 50% solution state	1.50E-02	kg	market for sodium hydroxide, without water, in 50% solution state [GLO]	Ecoinvent v3.8
steel, low-alloyed, hot rolled	8.96E-04	kg	market for steel, low-alloyed, hot rolled [GLO]	Ecoinvent v3.8
water, completely softened	2.17E+01	kg	market for water, completely softened [RoW]	Ecoinvent v3.8
wire drawing, steel	8.96E-04	kg	market for wire drawing, steel [GLO]	Ecoinvent v3.8
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
single-Si wafer, photovoltaic [CN or NL]	**1.00E+00**	**m2**		
waste, from silicon wafer production	2.00E-02	kg	market for waste, from silicon wafer production [GLO]	Ecoinvent v3.7

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Table A.8.: Inventory data for methyl aluminium sesquichloride. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
aluminium chloride	1.62E+00	kg	market for aluminium chloride [GLO]	Ecoinvent v3.8
aluminium, wrought alloy	2.62E+01	kg	market for aluminium, wrought alloy [GLO]	Ecoinvent v3.8
electricity, medium voltage	9.29E-01	MJ	electricity china/ electricity netherlands	Idemat2023
methylchloride	7.37E+01	kg	market for methylchloride [RoW]	Ecoinvent v3.8
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
methyl aluminium sesquichloride	**1.00E+02**	**kg**		

Table A.9.: Inventory data for trimethylaluminium, 98.5%. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
electricity, medium voltage	1.87E+01	MJ	electricity china/ electricity netherlands	Idemat2023
methyl aluminium sesquichloride	8.26E+01	kg	methyl aluminum sesquichloride production [CN or NL]	This study
nitrogen, liquid	8.25E-01	kg	market for nitrogen, liquid [RoW]	Ecoinvent v3.8
paraffin	1.53E-01	kg	market for paraffin [GLO]	Ecoinvent v3.8
sodium	2.70E+01	kg	market for sodium [GLO]	Ecoinvent v3.8
Output	Coefficient	Unit	Activity Link	Source
methyl aluminium sesquichloride	**3.00E+01**	**kg**		
hazardous waste, for incineration	8.93E+01	kg	market for hazardous waste, for incineration [RoW]	Ecoinvent v3.7

Table A.10.: Inventory data for TMAl purification. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
electricity, medium voltage	2.02E+00	MJ	electricity china/ electricity netherlands	Idemat2023
helium	4.00E-01	kg	market for helium [GLO]	Ecoinvent v3.8
sodium	2.00E+01	kg	market for sodium [GLO]	Ecoinvent v3.8
trimethylaluminium, 98.5%	1.00E+02	kg	trimethylaluminium, 98.5% [CN or NL]	This study
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
trimethylaluminium, solar grade [CN or NL]	**6.00E+01**	**kg**		
hazardous waste, for incineration	6.00E+01	kg	market for hazardous waste, for incineration [RoW]	Ecoinvent v3.7

Table A.11.: Inventory data for metallisation paste. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
chemical, organic	5.00E-01	kg	market for chemical, organic [GLO]	Ecoinvent v3.8
electricity, medium voltage	9.00E-01	MJ	electricity china/ electricity netherlands	Idemat2023
heat, district or industrial, natural gas	7.45E-01	MJ	industrial heat, general	Idemat2023
silver	5.00E-01	kg	silver trade mix (45% prim 55% sec)	Idemat2023
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
metallisation paste, back side [CN or NL]	**1.00E+00**	**kg**		

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Table A.12.: Part 1 of Inventory data for PERC cell production. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
ammonia, liquid	1.65E-02	kg	market for ammonia, liquid [RoW]	Ecoinvent v3.8
calcium chloride	2.07E-01	kg	market for calcium chloride [RoW]	Ecoinvent v3.8
electricity, medium voltage	2.17E+01	MJ	electricity china/ electricity netherlands	Idemat2023
heat, district or industrial, natural gas	3.55E+00	MJ	industrial heat, general	Idemat2023
hydrochloric acid, without water, in 30% solution state	6.81E-02	kg	market for hydrochloric acid, without water, in 30% solution state [RER]	Ecoinvent v3.8
hydrogen fluoride	7.47E-02	kg	market for hydrogen fluoride [RoW]	Ecoinvent v3.8
hydrogen peroxide, without water, in 50% solution state	9.40E-02	kg	market for hydrogen peroxide, without water, in 50% solution state [RoW]	Ecoinvent v3.8
metallization paste, back side	1.02E-03	kg	metallization paste, back side [CN or NL]	This study
metallization paste, back side, aluminium	9.01E-03	kg	market for metallization paste, back side, aluminium [RER]	Ecoinvent v3.8
metallization paste, front side	3.48E-03	kg	metallization paste, back side [CN or NL]	This study
nitric acid, without water, in 50% solution state	8.22E-02	kg	market for nitric acid, without water, in 50% solution state [RoW]	Ecoinvent v3.8
nitrogen, liquid	2.62E+00	kg	market for nitrogen, liquid [RER]	Ecoinvent v3.8
nitrous oxide	7.66E-03	kg	market for nitrous oxide [GLO]	Ecoinvent v3.8
oxygen, liquid	3.34E-01	kg	market for oxygen, liquid [RER]	Ecoinvent v3.8
phosphoryl chloride	1.82E-04	kg	market for phosphoryl chloride [RER]	Ecoinvent v3.8
potassium hydroxide	1.51E-01	kg	market for potassium hydroxide [GLO]	Ecoinvent v3.8
propane	4.14E-02	kg	market for propane [GLO]	Ecoinvent v3.8
silicon tetrahydride	2.83E-03	kg	market for silicon tetrahydride [GLO]	Ecoinvent v3.8
single-Si wafer, photovoltaic	1.02E+00	m2	market for single-Si wafer, photovoltaic [CN or NL]	This study
solvent, organic	1.23E-02	kg	market for solvent, organic [GLO]	Ecoinvent v3.8
sulfuric acid	2.06E-02	kg	market for sulfuric acid [RoW]	Ecoinvent v3.8

Table A.13.: Part 2 of Inventory data for PERC cell production. Based on [23].

trimethylaluminium, solar grade	2.88E-04	kg	trimethylaluminium, solar grade [CN or NL]	This study
water, completely softened	2.32E+01	kg	market for water, completely softened [RoW]	Ecoinvent v3.8
Water, cooling, unspecified natural origin [natural resource/in water]	2.31E-01	m3	market for tap water [RoW]	Ecoinvent v3.8
water, deionised	3.94E+01	kg	market for water, deionised [RoW]	Ecoinvent v3.8
Output	Coefficient	Unit	Activity Link	Source
photovoltaic cell, single-Si wafer [CN, DE or EU]	**1.00E+00**	**m2**		
waste, from silicon wafer production, inorganic	6.41E-03	kg	market for waste, from silicon wafer production, inorganic [GLO]	Ecoinvent v3.7

Table A.14.: Part 1 of Inventory data for glass-backsheet module production. Based on [23].

Input	Coefficient	Unit	Activity Link	Source
1-propanol	1.72E-02	kg	market for 1-propanol [GLO]	Ecoinvent v3.8
adipic acid	3.69E-04	kg	market for adipic acid [GLO]	Ecoinvent v3.8
aluminium alloy, AlMg3	1.51E+00	kg	AlMg3 (5754a)	Idemat2023
copper	1.48E-01	kg	copper wire, plate, pipe, trade mix (45% prim 55% sec)	Idemat2023
Corrugated board box	7.63E-01	kg	Market for corrugated board box [RoW]	Ecoinvent v3.8
diode, auxilliaries and energy use	2.81E-03	kg	market for diode, auxilliaries and energy use [GLO]	Ecoinvent v3.8
electricity, medium voltage	1.20E+01	MJ	electricity china\ electricity netherlands	Idemat2023
ethylvinylacetate, foil	7.93E-01	kg	market for ethylvinylacetate, foil [GLO]	Ecoinvent v3.8
EUR-flat pallet	0.05	P	Production of EUR-flat pallet [RoW]	Ecoinvent v3.8
Extrusion, plastic film	3.36E-01	kg	Market for extrusion, plastic film [RoW]	Ecoinvent v3.8
glass fibre reinforced plastic, polyamide, injection moulded	1.88E-01	kg	market for glass fibre reinforced plastic, polyamide,injection moulded [GLO]	Ecoinvent v3.8
lead	1.08E-02	kg	market for lead [GLO]	Ecoinvent v3.8
lubricating oil	1.61E-03	kg	market for lubricating oil [RoW]	Ecoinvent v3.8
Packaging film, low density polyethylene	4.01E-02	kg	Market for packaging film, low density polyethylene [GLO]	Ecoinvent v3.8

Table A.15.: Part 2 of Inventory data for glass-backsheet module production. Based on [23].

photovoltaic cell, single-Si wafer	8.98E-01	m2	Photovoltaic cell, single-Si wafer, [CN or NL]	This study
polyethylene terephthalate, granulate, amorphous	2.81E-01	kg	market for polyethylene terephthalate, granulate, amorphous [GLO]	Ecoinvent v3.8
polyethylene, high density, granulate	2.42E-02	kg	market for polyethylene, high density, granulate [RoW]	Ecoinvent v3.8
Polyethylene, low density, granulate	5.48E-02	kg	Market for polyethylene, low density, granulate [GLO]	Ecoinvent v3.8
polyvinylfluoride, film	4.51E-02	kg	market for polyvinylfluoride, film [GLO]	Ecoinvent v3.8
silicone product	1.44E-01	kg	market for silicone product [RoW]	Ecoinvent v3.8
solar glass, low-iron	8.00E+00	kg	market for solar glass, low-iron [GLO]	Ecoinvent v3.8
tempering, flat glass	8.00E+00	kg	market for tempering, flat glass [GLO]	Ecoinvent v3.8
tin	1.04E-02	kg	market for tin [GLO]	Ecoinvent v3.8
Water, cooling, unspecified natural origin [natural resource/in water]	7.16E-02	m3	market for tap water [GLO]	Ecoinvent v3.8
wire drawing, copper	1.48E-01	kg	market for wire drawing, copper [GLO]	Ecoinvent v3.8
Output	Coefficient	Unit	Activity Link	Source
photovoltaic panel, single-Si wafer, glass-backsheet, [CN, DE or EU]	**1.00E+00**	**m2**		
municipal solid waste	9.69E-02	kg	market group for municipal solid waste [RER]	Ecoinvent v3.7

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Table A.16.: Inventory data for 1000kg PV module transport. Import from CN to NL based on [23].

Input	Coefficient	Unit	Activity Link	Source
transport by lorry in Europe	2.00E+02	tkm	truck+trailer 24 tons net	Idemat2023
Output	Coefficient	Unit	Activity Link	Source
PV panel transport within NL	**1**	**p**		

Input	Coefficient	Unit	Activity Link	Source
transport by lorry in Europe	2.00E+02	tkm	truck+trailer 24 tons net	Idemat2023
transport by freight train in Europe	2.60E+03	tkm	train, freight, electric	Idemat2023
transport by lorry in Europe	2.50E+02	tkm	truck+trailer 24 tons net	Idemat2023
Output	Coefficient	Unit	Activity Link	Source
PV panel export from NL to GR	**1**	**p**		

Input	Coefficient	Unit	Activity Link	Source
transport by lorry in China	2.00E+02	tkm	truck+trailer 24 tons net	Idemat2023
transport by freight train in China	5.00E+02	tkm	train, freight diesel	Idemat2023
transport by transoceanic ship	2.22E+04	tkm	container ship	Idemat2023
transport by lorry in Europe	2.00E+02	tkm	truck+trailer 24 tons net	Idemat2023
Output	Coefficient	Unit	Activity Link	Source
PV panel import from CN to NL	**1**	**p**		

Table A.17.: Inventory data for ground mounting system for PV modules. Based on [74].

Input	Coefficient	Unit	Activity Link	Source
Aluminium	3.98E+00	kg	aluminium trade mix (80% prim 20% sec)	Idemat2023
Section bar rolling, steel	6.15E+00	kg	rolling steel	Idemat2023
Steel, zinc coated	6.15E+00	kg	steel beams, pipes, sheet (trade mix 44% recycled)	Idemat2023
Aluminium extrusion	3.98E+00	kg	extrusion, incl production site	Idemat2023
Stainless steel	2.50E-01	kg	X5CrNi18 (304) 70% inox scrap (EU, USA)	Idemat2023
Output	**Coefficient**	**Unit**	**Activity Link**	**Source**
Ground mounting system for PV module	**1.00E+00**	**m2**		