Assessment of the ecological lifetime of photovoltaic systems considering aging effects, end-of-life and early replacement

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Zusammenfassung

Der weltweite Ausbau der Photovoltaik (PV) Kapazitäten ist ein wichtiger Bestandteil der Wende hin zu einer klimafreundlicheren Energieversorgung. Dennoch wird der massive Einsatz erneuerbarer Energietechnologien in den kommenden Jahren große Mengen an Energie und Ressourcen verbrauchen. Die Emissionen aus der Produktion von Solarenergiesystemen sind in den letzten Jahren stetig gesunken. Allerdings sind nicht nur die Produktionsemissionen, sondern auch Faktoren wie Lebensdauer und Energieertrag entscheidend für die Umweltwirkungen der nutzbaren elektrischen Energie. Bisherige Ökobilanzstudien konzentrieren sich hauptsächlich auf die Quantifizierung des Primärenergie- und Ressourcenverbrauchs während der Herstellung der PV Module, wohingegen die Nutzungs- und die End-of-Life-Phase, sowie die diesbezüglichen Auswirkungen auf die Gesamtumweltleistung von PV-Strom selten untersucht werden. So wirken sich beispielsweise Alterung und Degradation während der Nutzungsphase, die stark von standortspezifischen Bedingungen wie einer korrosiven Atmosphäre abhängen können, auf die Lebensdauer und den Gesamtertrag der Systeme und damit auf den ökologischen Fußabdruck der elektrischen Energie aus. Da in den kommenden Jahren immer mehr PV-Module ihr Lebensende erreichen werden, gewinnen das Recycling und die Verwertung der Module an Bedeutung für die Quantifizierung der Emissionen von PV-Strom. Um die Emissionen über den gesamten Lebenszyklus einer PV-Anlage zu bewerten, ist es daher wichtig, auch diese Auswirkungen zu quantifizieren, da sie die Gesamtemissionen über den Lebenszyklus stark beeinflussen können.

Diese Arbeit zielt darauf ab, die Ökobilanz von PV Anlagen über ihren gesamten Lebenszyklus zu untersuchen und damit die oben genannten Forschungslücken zu schließen. Der Einfluss von Degradation, Behandlung am Lebensende sowie der tatsächlichen Betriebszeit auf den ökologischen Fußabdruck des erzeugten Stromes und damit die ökologisch optimale Lebensdauer von PV-Systemen wird mittels Life Cycle Assessment (LCA) bewertet. Die Thematik wird dabei in drei separaten Zeitschriftenartikeln untersucht: 1) Die Auswirkungen verschiedener Recyclingansätze (End-of-Life-Management) für PV-Module, wobei das Potenzial für eine verbesserte Umweltleistung durch spezielle Recyclingtechnologien hervorgehoben wird. 2) Der Einfluss regionaler Degradationsmuster auf die Treibhausgasemissionen von PV-Strom, wobei orts- und temperaturabhängige Unterschiede in den Emissionen identifiziert werden. 3) Die Berechnung des frühesten sowie des optimalen Zeitpunkts für einen Austausch von PV-Modulen (Repowering) zur Maximierung der ökologischen Vorteile, wobei die Vorteile des Repowerings in Kombination mit Recycling und erhöhter Anlagenleistung hervorgehoben werden.

Die Ergebnisse zeigen, dass alle der untersuchten Mechanismen über den gesamten Lebenszyklus der Systeme einen erheblichen Einfluss auf die Emissionen von PV-Strom haben können. So können beispielsweise durch gezieltes Recycling die CO_2-Emissionen, trotz eines höheren Aufwands für die Abfallbehandlung, um bis zu 4% gesenkt werden. Auch die Verwendung nichtlinearer Degradationsraten anstelle einer linearen Degradationsrate von 0,7% in der Berechnung führt zu einer Veränderung der CO_2-Emissionen um bis zu -4 % bis +6 %. Außerdem verdoppeln sich in Regionen mit hohem klimatischem Stress, die CO_2-Emissionen pro kWh, wenn klimaspezifische Degradationsmuster in der Berechnung berücksichtig werden. Schließlich konnte

gezeigt werden, dass das Repowering von PV-Modulen unter bestimmten Bedingungen ökologisch vorteilhaft sein kann, insbesondere in Verbindung mit spezialisiertem Recycling.

Die Ergebnisse aller drei Studien tragen dazu bei, die Bewertung der Lebenszyklusemissionen von PV-Anlagen zu verbessern. Auf diese Weise können Strategien für den Ausbau von PV-Anlagen optimiert werden. Künftige Forschungsarbeiten sollten sich auf die Integration der hier vorgestellten Methoden und Ergebnisse konzentrieren, um eine standortspezifische Quantifizierung der Lebenszyklusemissionen von PV-Strom und die Entwicklung verbesserter Strategien für das End-of-Life-Management zur Verbesserung der Nachhaltigkeit zu ermöglichen.

Abstract

Photovoltaic (PV) systems are crucial for a clean energy transition. Still, their massive deployment in the coming years will consume significant amounts of energy and resources. Emissions from the production of solar energy systems have been constantly decreasing in the past years. However, not only production emissions but also factors like lifetime and energy yield are decisive for the life cycle environmental impact of PV electricity. Previous Life Cycle Assessment (LCA) studies focus mainly on the quantification of primary energy and resource use during PV production, whereas their use and end-of-life phase and the regarding impact on the overall environmental performance of PV electricity are rarely investigated. For example, aging and degradation during use phase which can be strongly dependent on site-specific conditions like a corrosive atmosphere, are affecting the systems lifetime and therefore its environmental footprint. Further, the end-of-life treatment of PV modules is gaining relevance for quantifying the emissions of PV electricity due to increasing amounts of PV module waist in the coming years. Hence, to assess the emissions over the whole life cycle of a PV system it is important to also be able to quantify the aforementioned impacts since they can have a strong effect on its overall lifecycle emissions.

This work aims to investigate the environmental impact of PV systems throughout their lifecycle, addressing the research gaps identified above. The influence of performance degradation, end-of-life (EoL) treatment as well as actual operational time on the environmental footprint of PV electricity and therefore the optimal ecological lifetime of PV systems is assessed using LCA methodology. Three sub-questions are explored in separate peer-reviewed journal articles: 1) The impact of different recycling approaches for PV modules, highlighting the potential for improved environmental performance with dedicated recycling technologies. 2) The influence of regionalized degradation patterns on greenhouse gas emissions from PV electricity, revealing location and temperature-dependent variations in emissions. 3) The calculation of the earliest and the optimum point to maximize the ecological benefits of early PV system replacement (repowering), emphasizing the benefits of repowering when combined with recycling and increased peak power.

The results show that all the mechanisms under study can significantly influence the life cycle environmental emissions of a PV system. For example, dedicated recycling can reduce CO_2-emissions by up to 4%, despite the higher efforts for waste treatment. Also, using non-linear degradation rates instead of a linear degradation rate of 0.7% results in a variation of up to -4 % to +6 % in CO_2-emissions per kWh of produced electricity. Moreover, in regions where climatic stressors like temperature, humidity and corrosion are high, the CO_2-emissions per kWh almost double when climate-specific degradation rates are used. Finally, it could be shown that the premature replacement of PV-modules can be environmentally beneficial under certain conditions, especially in combination with dedicated recycling.

By using the results from all three studies, the assessment of PV life cycle emissions is improved and, in doing so, PV deployment strategies can be optimized. Future research should focus on integrating the here presented methodologies and results, enabling site-specific quantification of PV system life cycle emissions and the development of improved end-of-life management strategies to enhance sustainability.

Table of contents

Danksagung..I
Zusammenfassung II
Abstract IV
Table of contents VI
List of Figures VII
List of Tables VIII
Abbreviations IX
1......Introduction 1
1.1. Motivation..1
1.2. Purpose and scope of the work 4
1.3. Outline...6
2......Methods and Definitions 7
2.1. Photovoltaic lifetime definition 7
2.2. Life Cycle Assessment 7
2.3. Photovoltaic Degradation 8
2.4. Photovoltaic Repowering: Definitions and Calculation 10
3......Synthesis 14
3.1. The influence of PV module end-of-life treatment on the environmental footprint of PV electricity 14
3.2. The influence of different degradation patterns on the lifetime energy output and the environmental footprint of PV electricity..........20
3.3. The optimal lifetime of PV systems to minimize the environmental footprint of PV electricity 25
4......Discussion and Conclusion 35
5......Outlook..38
6......References..39
7......List of Publications 46
Appendix..I
Appendix A: Life Cycle Inventories of recycling approaches as in Herceg et al. 2020 (*48*)...............I
Appendix B: Life Cycle Inventories for repowered PV Systems as in Herceg et al. 2022b (*42*) XII
Appendix C: Recycling Rates per treatment and material as in Herceg et al. 2022b (*42*).......XXXVII

List of Figures

Figure 1 Share of PV module and BOS components on the environmental impact of a 3 kWp rooftop PV plant (own illustration based on (13)). 2
Figure 2 End-of-Life mass of PV modules depending on expected service lifetime in million tons (own illustration after (18).) 3
Figure 3 Research questions. 4
Figure 4 (A) Power degradation curves using different shape parameters and (B) correlation of the shapes with energy yield. From Kaaya et al. 2020 (*25*). 9
Figure 5 (A) Spatial distribution of the degradation mechanism in relation to KGPV zones. (B) Spatial distribution of the total degradation rates in relation to KGPV zones (*27*). 10
Figure 6 Potential contribution of waste management options to the environmental footprint of electricity production with mono-Si modules (Herceg et al. 2020 (*48*)). 17
Figure 7 (A) LCIA results for the sensitivity analysis of PV recycling for all scenarios. Results for freshwater ecotoxicity are displayed separately in Figure 7 (B). After Herceg et al. 2020 (*48*). 18
Figure 8 (A) Different degradation profiles for different PV systems. (B) Simulated degradation scenarios based on the different degradation profiles. See Herceg et al. 2022 a (*49*). 21
Figure 9 (A) Relative difference of the GHG emissions for all four degradation scenarios in relation to linear degradation. (B) GHG emissions per 1 kWh PV electricity in g CO_2 eq. for all four degradation scenarios and linear degradation. 22
Figure 10 Spatial distribution of GHG emissions (IPCC GWP 100a kg CO_2 eq.) in view of the KGPV climate zones. The average GHG emissions in kg CO_2 eq. per climate zone is indicated below each label for the two cases (Rd: degradation rate). 23
Figure 11 (A) World map of the GHG emissions of 1 kWh PV electricity calculated from climate-based degradation rates (lifetime not fixed) (B) World map of the GHG emissions of 1 kWh PV electricity calculated using a constant degradation rate (lifetime fixed to 30 years). 24
Figure 12 Characterization results per impact category and scenario of the repowered system, when repowered at the optimum repowering time. The results are presented relative to each other: the highest impact value per category is defined to be 100 %. All other impacts in the same category are presented relative to this. Stacked columns in the capacity scenarios: the calculated optimum repowering time is earlier than 17 years, therefore the additional impacts when repowered after 17 years are included. Functional unit: 1 kWh of produced electricity. 30
Figure 13 Impacts of the RT basic scenario in the category “climate change” in kg CO_2 eq. per kWh. The vertical line marks year 17, which is the interval between the two reference years. 31
Figure 14 Relative changes of total impact (CO_2 eq.) over time of the repowering case depending on the repowering time (B: (IR− IB)/IB; see also chapter 2.1) in the category climate change as well as relative changes of electricity production of the repowering case over time (A: (SR-SB)/SB). The variables are calculated according to equations (1), (2), (6) and (7) in chapter 2.4. 32

List of Tables

Table 1 Adapted KGPV scheme (*55*). Each climate zone is defined by two letters, the first one implies the relation of temperature and precipitation (TP-zones) and the second is related to the irradiation level (H-zones). 9
Table 2 Module and modelling parameters (after Herceg et al. 2020 (*48*)). 15
Table 3 EoL treatment approaches under study (Herceg et al. 2020 (*48*)). 16
Table 4 Potentially avoided greenhouse gas emissions per ton of PV waste in the year 2040 and 2050 (Herceg et al. 2020 (*48*)). 19
Table 5 Different degradation profiles and corresponding parameters. 21
Table 6 Baseline scenario of a 3 kWp slanted-roof PV plant installed in the EU. 21
Table 7 PERC PV system specifications. Three systems are modelled for the rooftop scale and the open field- scale: one for 2004, and two for 2020, while the 4.01 kWp system (2020) is extrapolated from the 3 kWp system (2020) and the 4.39 MWp system (2020) is extrapolated from the 1.07 MWp system (2020) (*42*). 27
Table 8 Six different scenarios are investigated. Three scenarios consider a small-scale rooftop silicon PV plant (scenarios 1a-c), while the other three focus on a large-scale open-field silicon PV plant (scenarios 2a-c). RT = rooftop, OF = open-field (*42*). 28
Table 9 Earliest and optimal repowering times in years after the commissioning of the original system, according to scenario and impact category (*42*). 29

Abbreviations

BOS	Balance of system
EC	European Commission
EoL	End-of-life
EPBT	Energy Payback Time
ErP	Energy-related-product
EU	European Union
EuP	Energy-using-product
FU	Functional Unit
GHG	Greenhouse gas
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KG	Köppen-Geiger
KGPV	Köppen-Geiger Photovoltaic
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PERC	Passivated emitter and rear cell
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
US	United States
WEC	Wind Energy Converters
WEEE	Waste Electrical and Electronic Equipment

1. Introduction

In the following, the motivation behind this thesis is presented by providing an overview over the topic and the respective research gaps. Further, the research questions deriving from these gaps are framed.

1.1. Motivation

Photovoltaic (PV) systems are an essential constituent of the much-needed clean energy transition. Between 2010 and 2020, the annual global growth rate of cumulative PV installations was 34 % (*1*). Through technological improvements, the CO_2 emissions related to PV electricity have decreased rapidly and are still decreasing due to measures like higher module efficiencies and design optimizations. Still, the massive deployment of PV installations that can be expected will consume a significant amount of energy and resources. Cumulative installed PV capacity has been about 700 GWp globally in 2020 (*2*) and is expected to rise to up to 63 TWp in 2050 (*3*).

Former concerns that PV module manufacturing would consume more energy than can be generated during the PV system's useful life have long been disproved (*4, 5*). Nevertheless, for the life cycle assessment (LCA) of solar energy systems, lifetime and energy yield are of central importance to assess their life cycle environmental impacts (*6*). Therefore, it is important not only to further decrease production emissions, but also to quantify factors influencing the overall life cycle emissions like performance degradation, end-of-life (EoL) treatment or actual technological run-time. Although life cycle assessments of photovoltaic modules demonstrate a positive CO_2 balance, the results vary in the amount of CO_2 emissions calculated (*7*). This variation results from different assumptions about temporal and geographical system boundaries, different calculation methods and allocation procedures as well as varying assumptions about energy yield, lifetime and end-of-life treatment.

In silicon PV module production, the environmental hot spots can mainly be pinned down to the energy-intensive silicon wafer manufacturing and the material intensive aluminum frame as well as the silver paste used for metallization (*8, 9*). Technological improvements have been achieved over the last decades, like the development of thinner wafers or the reduction of silver use in metallization pastes (*3*). Recently, a couple of studies have been published that quantify the massive reduction of the carbon footprint that has come along with these technological improvements, which has decreased from 125 - 164 g CO_2 eq./kWh in 1992 (*10*) to 13 – 57 g CO_2 eq./kWh (*9, 11, 12*) today. Balance-of-system (BOS) components can thereby account for up to 65 % of the PV plants life cycle emissions (see Figure 1). While most of these studies consider the reduced energy and resource consumption as well as higher energy conversion efficiencies, they often fail to account for end-of-life treatment or a dedicated analysis of lifetime energy output losses through degradation.

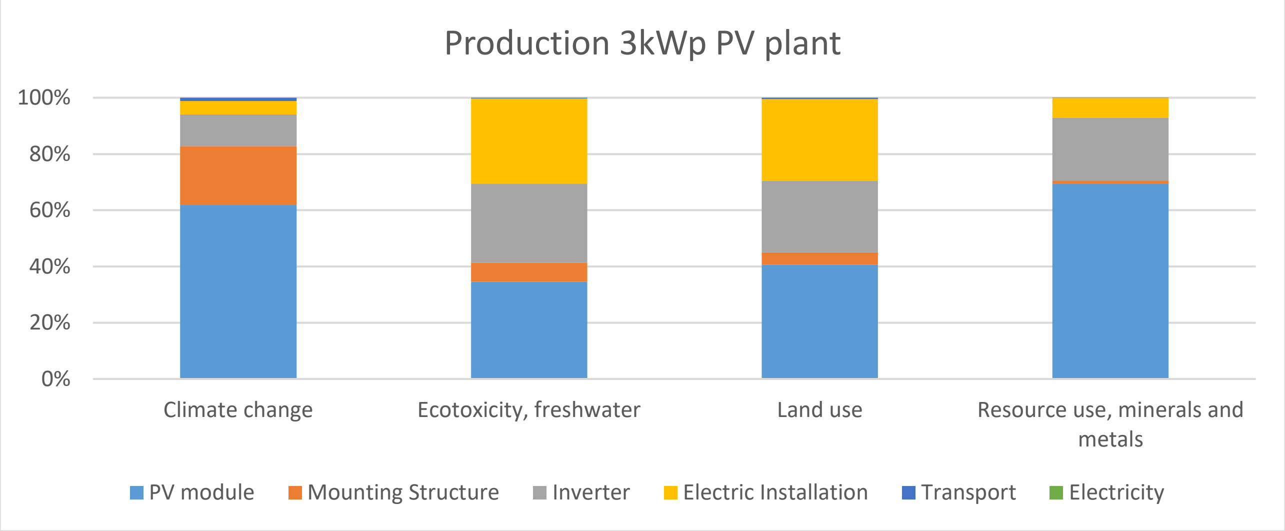

Figure 1 Share of PV module and BOS components on the environmental impact of a 3 kWp rooftop PV plant (own illustration based on (13)).

Today, end-of-life treatment for PV modules is regulated in the European Union (EU) under the Waste Electrical and Electronic Equipment (WEEE) Directive (*14*) which requires a recycling rate of 80 % in mass for PV modules. Regulations for PV waste treatment also exist in some parts of the United States (US), however, PV modules still end up being landfilled without any resource recovery in most regions worldwide (*15*). Yet, due to the small amount of present PV waste flows, a more dedicated recycling is not profitable in the EU nor the US up to now (*16*). While currently only small flows of PV waste have had to be handled, the International Renewable Energy Agency IRENA predicts 78 million tons of PV panel waste globally by 2050 (*17, 18*) (see Figure 2) making EoL treatment and circular economy strategies more and more important, since decommissioned PV modules can act as a valuable source for new module production.

PV systems reach their EoL at different points in time. Typically, a lifetime of 25 or 30 years is assumed in literature, based on typical PV module warranties. Also, the point in time where the modules energy conversion efficiency has decreased to less than 80 % of its original power can be defined as the modules EoL (*19*). Naturally, solar energy systems are strongly exposed to weathering and ambient conditions like irradiation, thermal loads or a corrosive atmosphere (*20, 21*). Those parameters vary in different geographical regions and affect performance and lifetime of the system through degradation mechanisms (*22, 23*). Most PV LCA studies only consider the higher energy yield that the module provides in regions with higher insolation, but neglect that fact that more extreme environmental conditions also negatively affect degradation and lifetime. Usually, a linear degradation of 0.7 % per year is assumed for all climate zones, which corresponds to a loss in yield of 21 % at the end of a 30-year lifetime (*19, 21, 22*). However, several studies show that the aging pattern of PV modules usually follows a non-linear degradation curve (*24–26*) and is dependent on installation location (*23, 27*). Consequently, the environmental footprint of PV electricity can vary in different climate zones, not only due to higher lifetime energy yields from higher irradiation, but also because of reduced lifetime energy yields from early EoL and degradation.

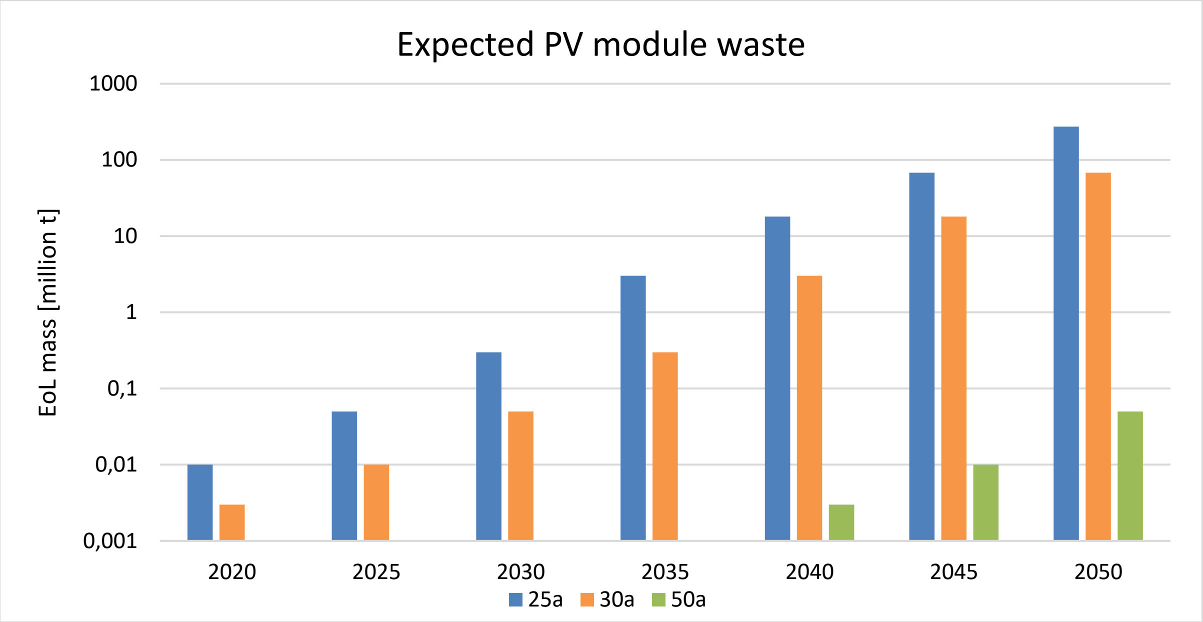

Figure 2 End-of-Life mass of PV modules depending on expected service lifetime in million tons (own illustration after (18).)

An extended product lifetime is usually associated with environmental benefits and is one of the principles of the EU's Circular Economy Action Plan (*28*). For most consumer products, this association is valid since the prolonged use of a product usually avoids resource consumption for the manufacturing of a new product for at least a certain amount of time. However, for energy related products (ErPs), this correlation is harder to assess. Energy using products (EuPs) like washing machines and vacuum cleaners have been under study to identify the point at which replacing an old product with a new, more energy-efficient version is more environmentally friendly and economically viable than prolonging its lifetime by repair and maintenance (*29, 30*). Products of this type underlie constant development and improvement of their energy consumption, in part due to political regulations such as the EU's Ecodesign or Energylabel directive (*31*). Therefore, regarding the energy consumption, replacing an old, energy-intensive product with a newer version can be profitable economically and environmentally. Most of those aspects are applicable not only to the life cycle of EuPs, but also to energy producing products like PV modules. Especially in the PV sector, products have undergone major change since their first commercial application beginning in 1990. Not only material composition and manufacturing techniques have changed tremendously, but also their efficiency to convert solar radiation into electricity has increased from around 12 % in 1997 to up to 21 % in 2021 (*3*). As a result, energy payback times (EPBT) have shifted from around 7 years in 1995 (*32*) to around 2 years in 2020 (*11*).

From an environmental or economic perspective, the optimum PV lifetime could be defined as the point in time where emissions or costs of the system are at their lowest. The first renewable power plants have usually been installed in locations with the most favorable solar or wind conditions, thus leading to a situation where premium locations cannot be fully exploited today due to old installations which are already outdated by means of efficiency. Early replacement of those modules with new, more efficient modules could not only increase the land use efficiency, but also lower the carbon footprint of the electricity produced. For wind turbines, it is common practice today to replace old systems with newer, more efficient ones before their technical EoL (*33, 34*). This so-called repowering is gaining increasing interest for PV plants (*35–38*).

While state-of-the-art PV modules have been optimized regarding material and resource use, older modules contain a significantly higher amount of valuable materials like silver, aluminum or high-purity silicon. Silver use for example has decreased from 0.3 g per cell in 2010 (*39*) to 0.16 g per cell in 2019 (*3*). Still, the expected growth of the PV sector will further increase the demand for those materials (*40, 41*). In combination with dedicated recycling strategies, repowered PV modules could be a valuable source for raw materials for today's PV industry (*42*). However, PV deployment strategies should be optimized not only economically but also environmentally. Therefore, it is important to better understand the environmental implications of the above-mentioned mechanisms that influence the life cycle environmental footprint of PV electricity, like (regionalized) degradation, environmental impacts and benefits from recycling and the effects of premature module replacement.

1.2. Purpose and scope of the work

As described above, previous research has focused mainly on the production emissions of PV modules in the past, whereas the use and the end-of-life phase have been rarely investigated. To assess the emissions over the whole life cycle of a PV system it is important to also quantify other effects that influence its overall lifecycle emissions.

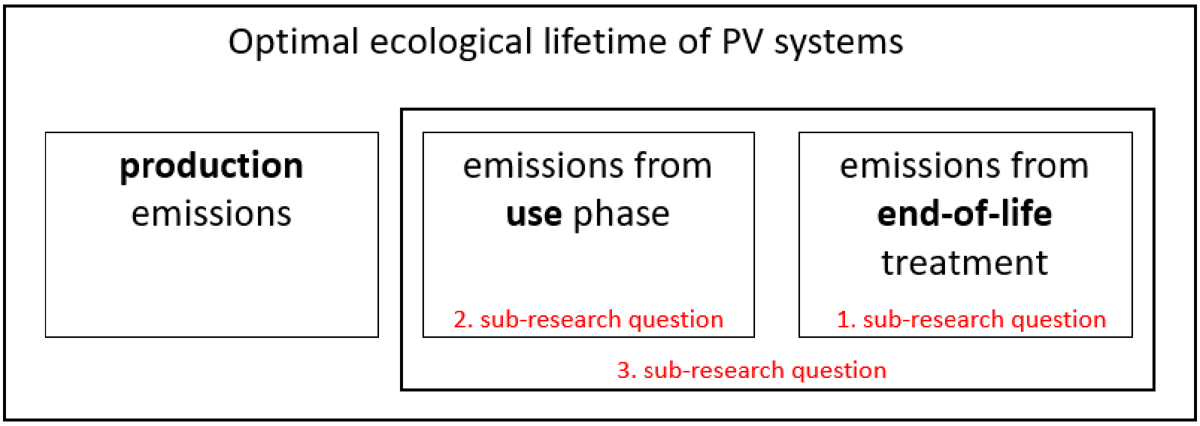

Figure 3 Research questions.

Based on a thorough literature search, the above-mentioned research gaps have been identified and the following research question has been defined:

> **What is the optimal ecological lifetime of PV systems and how do different effects throughout their life cycle influence the environmental footprint of PV electricity?**

To further approach this questions, three sub-questions have been addressed in the form of three peer-reviewed journal articles:

1. **Sub-research question:**

   How does the end-of-life treatment of PV modules affect the environmental footprint of PV electricity?

This question has been addressed in

Herceg S., Pinto-Bautista S., Weiss K-A. Influence of Waste Management on the Environmental Footprint of Electricity Produced by Photovoltaic Systems. *Energies*. 2020.

Here, a detailed LCA study is performed to assess the environmental footprint of six different recycling approaches for silicon PV modules. The results show that recycling has the potential to further improve the environmental performance of PV electricity but at the same time reveals that further efforts should be made in developing dedicated recycling technologies.

2. **Sub-research question:**

   How do different, regionalized degradation patterns affect the lifetime energy output and consequently the environmental footprint of PV electricity?

This question has been addressed in

Herceg S., Kaaya I., Ascencio-Vásquez J., Fischer M., Weiß K-A., Schebek L. The Influence of Different Degradation Characteristics on the Greenhouse Gas Emissions of Silicon Photovoltaics: A Threefold Analysis. *Sustainability*. 2022.

In this article, different degradation patterns are applied for the calculation of the greenhouse gas (GHG) emissions of silicon PV electricity. Location and temperature dependent variations on GHG emissions are demonstrated and compared to emission calculations using linear degradation.

3. **Sub-research question:**

   What is the optimal lifetime of PV systems to minimize the environmental footprint of PV electricity?

This question has been addressed in

Herceg S., Fischer M., Weiß K-A., Schebek L. Life cycle assessment of PV Module repowering. *Energy Strategy Reviews*. 2022.

Here, the earliest as well as the optimum point in time, at which a premature replacement of PV systems can be ecologically beneficial have been calculated. The results show that repowering can be environmentally beneficial, when dedicated recycling and a repowering above the initial peak power are applied.

1.3. Outline

In **Chapter 1** the motivation behind this thesis is presented by providing an overview over the topic and the regarding research gaps. Further, the research questions deriving from these gaps are framed. In **Chapter 2**, the underlying methods and definitions which are shared by the three individual studies are presented. **Chapter 3** is a synthesis of the three individual publications, where the studies are summarized, and results are presented. In **Chapter 4**, the findings and limitations from all studies are discussed and connections are drawn. **Chapter 5** gives an outlook on possible future research based on the findings from this thesis.

2. Methods and Definitions

The research question of this study has been approached through three different peer-reviewed journal articles. The underlying methodology and definitions will be described in the following subchapters.

2.1. Photovoltaic lifetime definition

For most electronic devices, the “termination of the ability of an item to perform a required function” can be defined as its end of useful life (*43*). For PV systems, this definition might not always be applicable. For example, physical damage like glass breakage or a cracked backsheet might not lead to an ultimate loss of function but can determine the modules end-of-life anyway by posing a safety hazard or by reducing the power output to a point where an economic operation is no longer viable (*44*). Another factor that can determine the modules lifetime from an economical perspective is incentives usually guaranteed by national governments over a defined period. For the case of Germany, there is a feed-in-tariff for renewably produced electricity for a period of 20 years. Common guidelines for PV LCA of the European Commission (EC) and the International Energy Agency`s (IEA) Photovoltaic Power Systems Programme (PVPS) recommend a lifetime of 30 years for established PV-technologies, based on the assumption, that after 30 years, the initial energy conversion efficiency has degraded down to 80 % of the initial efficiency (*19, 21*) if a linear constant degradation of 0.7 % per year is assumed. This is in accordance with the lifetime warranty given by most module manufacturers. Many experts claim that PV systems can produce energy for 30 years or even longer and that therefore their lifetime is longer than 30 years, but studies confirming this lifespan are not available due to the relatively young age of the technology. So far, no definition of an ecological lifetime is available. In this dissertation and its related journal articles, the baseline assumptions follow the definition of the PVPS and EC, that assume an efficiency degradation of down to ≤ 80 % after a 30-year lifetime (*19, 21*).

2.2. Life Cycle Assessment

Life Cycle Assessment is used to assess the environmental impacts that occur during the production, use and disposal of a product or through a service. All material and energy input and output flows that occur over the entire life cycle of a product are inventoried and analyzed for their environmental impact. The structure and content of an LCA are regulated internationally in the ISO 14040 and ISO 14044 standards (*45, 46*). Since ISO 14040 and ISO 14044 leave room for interpretation, LCA guidelines specific to PV systems have been published by the EC and the IEA PVPS (*19, 21*). In addition to the ISO standards, those recommendations have been followed in the articles related to this dissertation. According to ISO 14040 and 14044, an LCA comprises the following four phases:

1. Goal and scope definition,
2. Life cycle inventory analysis (LCI),
3. Life cycle impact assessment (LCIA) and

4. Interpretation of results.

The scope of the study describes the product system to be investigated and the methods used and defines the system boundaries as well as the functional unit (FU). The functional unit quantifies the utility of the product system, all impacts are presented relative to it (*47*). For PV systems a functional unit of 1 kWh of electricity delivered to the grid is recommended by PVPS and EC for comparison of PV technologies, module technologies, and electricity-generating technologies.

During the life cycle inventory analysis, all material and energy flows that connect the processes of the product system with each other and with their environment are compiled and quantified. If a process produces more than one (useful) output, it is necessary to apply physical or mass allocation. The allocation procedure should be consistent throughout the study. No clear recommendation towards a specific allocation approach is given by PVPS or EC.

To relate the life cycle inventory to the products actual environmental impacts, the life cycle impact assessment phase assigns the life cycle inventory results to different impact categories. The environmental impact mechanism is expressed by impact indicators. Several impact assessment methods are available. For the specific case of PV electricity, the assessment shall be performed in accordance with the European Product Environmental Footprint EF method. Therefore, EF 2.0 has been used in (*48*), whereas EF 3.0 has been used for (*49*) and (*42*). For each publication, the most relevant impact categories have been chosen.

For interpretation, results are discussed, and conclusions are drawn. The most significant parameters from the life cycle inventory and impact assessment are identified. The life cycle inventory data, impact categories or life cycle stages that make a particular contribution to the results of the study are structured and placed in relation to the previous phases. PVPS and EC do not give specific instructions for interpretation.

All analyses have been performed with the software SimaPro and the ecoinvent database.

2.3. Photovoltaic Degradation

PV degradation is defined as the irreversible decrease in energy conversion efficiency (*22, 50*). During its operational lifetime, a PV module is exposed to various environmental stress factors like thermal and mechanical loads, moisture and solar irradiation. All these stressors lead to the constant decline of the modules initial capacity to convert sunlight into power. Several studies try to assess the underlying degradation mechanisms and the resulting degradation rates (*22, 51*). Quantifying degradation is of ecological as well as of economic interest. Köntges et al. 2014 (*44*) identify an increased reliability and service life as “one key factor of reducing the costs of photovoltaic systems”. To account for degradation in LCA studies on PV systems, a constant degradation rate of 0.7 % per year is recommended by (*19*) and (*21*). However, research has shown that the ageing pattern of PV modules typically follows a non-linear degradation curve which can be strongly influenced by different climatic conditions (*25, 26, 52*). By using PV module field measurements, Kaaya et al. (*25*) showed that performance degradation does not always follow a linear path. Moreover, the study demonstrates that even at the same failure threshold, the degradation profile taken to reach this threshold influences the lifetime yield of a given PV module (Figure 4 A). To model the non-linear power degradation observed in the field, an adaptable shape parameter μ has been introduced by (*53*),

Equation 1

$$\frac{P(t)}{P_0} = 1 - \exp\left(-\left(\frac{\Gamma}{k \cdot t}\right)^{\mu}\right)$$

where P(t) and P_0 are the power at evaluation time and initial power respectively, k is the degradation rate [year^{-1}], and Γ represents material specific parameters.

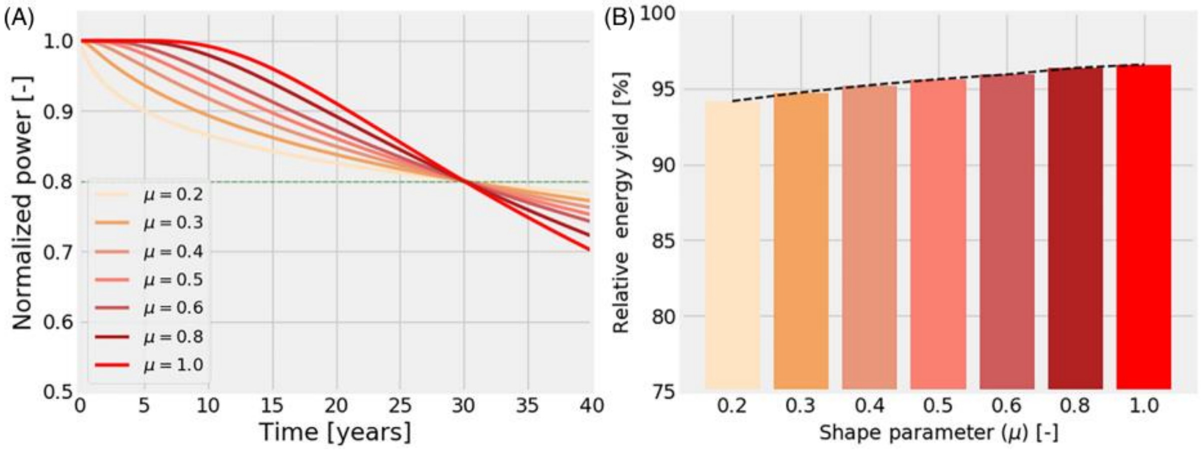

Figure 4 (A) Power degradation curves using different shape parameters and (B) correlation of the shapes with energy yield. From Kaaya et al. 2020 (*25*).

Depending on the climatic conditions of a specific location, the stress that is acting on the PV module can vary. Those specific stressors influence the degradation rates of PV modules (*23, 27*). Therefore, the PV system's service lifetime and its regarding lifetime energy yield varies from location to location and from type to type. The climatic regions can be classified according to the twelve climate zones from the widely used Köppen-Geiger (KG) (*54*) scheme which has been adapted to fit to PV specific information (KGPV) by Ascencio-Vásquez et al. (*55*) (Table 1).

Table 1 Adapted KGPV scheme (*55*). Each climate zone is defined by two letters, the first one implies the relation of temperature and precipitation (TP-zones) and the second is related to the irradiation level (H-zones).

Temperature-Precipitation (TP) Zones	**Irradiation (H) Zones**
A: Tropical climate	K: Very high irradiation
B: Desert climate	H: High irradiation
C: Steppe climate	M: Medium irradiation
E: Temperate climate	L: Low irradiation
D: Cold climate	
F: Polar climate	

Kaaya et al. 2019 (*53*) propose to include four climatic stressors (temperature, relative humidity, UV irradiation, and temperature cycles) that induce three main degradation mechanisms (hydrolysis, photo-degradation, and thermo-mechanical degradation) to estimate the degradation rates in different climates (Figure 5 A). From those, the PV specific degradation rates have been calculated (Figure 5 B) (*27*).

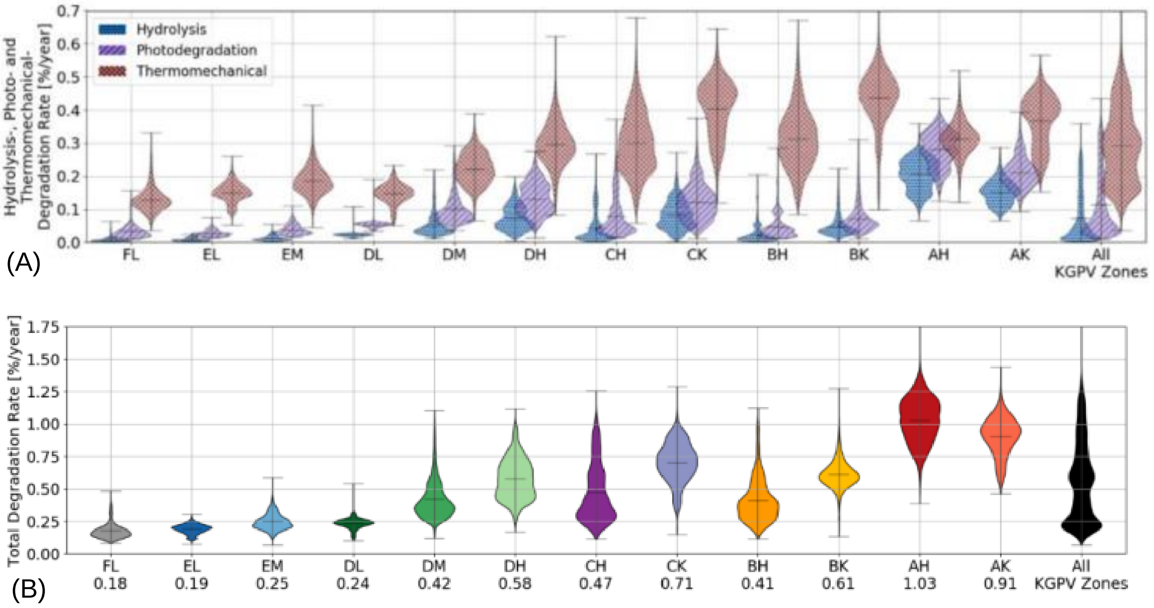

Figure 5 (A) Spatial distribution of the degradation mechanism in relation to KGPV zones. (B) Spatial distribution of the total degradation rates in relation to KGPV zones (*27*).

The baseline degradation rate in this dissertation is a linear degradation of 0.7 % per year. However, in Herceg et al. (2022a) (*49*) the above described non-linear and regionalized degradation mechanisms have been used to test their effect on the carbon emissions related to PV electricity.

2.4. Photovoltaic Repowering: Definitions and Calculation

Zimmerman (*34*) defines the repowering of wind energy converters (WEC) as “the replacement of older WEC by new state-of-the-art WEC, hereby improving the utilization of existing sites and reducing the total number of installed converters”. Whereas the term repowering is well-established for wind turbines, for PV, repowering is less common and therefore the exact definition is less distinct. The term repowering has been used in literature and industry to describe the replacement of the whole PV system, of single PV modules or other parts of the system like the inverter. For example, Rajagopalan 2021 et al. (*37*) describe the “replacement of operational, low-efficiency panels before the end of their 30-year service lifetime with newer, higher-efficiency panels” by using the term repowering. A broader definition is given in (*56*), where repowering is defined as the replacement of outdated power plants with newer ones in order to improve the power output and/or efficiency. Additionally, environmental impacts and maintenance costs are reduced according to this definition. Especially in industry and non-scientific articles, repowering is also used to describe the partial replacement of modules, inverters or other parts of BOS components (*57–59*). In contrast, the term refurbishment usually describes the repair of an existing system, with (sometimes on-site) replacement of only minor components, while partially restoring the power plants original performance capacity (*36, 60*). While for refurbishment, one or more parts of the system are generally already at their EoL through damage or wear-out, repowering typically describes the replacement of old but functioning systems with newer ones.

In the study presented here, the definition of repowering is closest to the common definition for WEC, where the whole system is replaced to reduce the total number of modules and increase the utilization of existing sites (*34*). Therefore, repowering is used here to describe the replacement of the entire PV plant with a newly manufactured system, without the reuse of parts. The earliest repowering time has been defined as the minimum time after which the impacts per kWh of the repowering case are lower than the impacts of the base case (no repowering). The calculation is based on the approach presented by Ardente and Mathieux (*29*). However, the scheme has been adjusted to fit PV as an energy producing technology (*42, 61*).

First, a base case is defined in which the sum of lifetime environmental impacts per impact category is calculated according to equation (2), where $I_{B,n}$ is the sum of the production impacts for the base case, the yearly use impacts multiplied by the system lifetime, and the EoL impacts.

Equation 2

$$I_{B,n} = P_{1,n} + U_{1,n} \cdot L + E_{1,n}$$

$P_{1,n}$= *production impacts in category n for system 1*

$U_{1,n}$= *yearly use impacts in category n for system 1*

$E_{1,n}$= *EoL impacts in category n for system 1*

L= *Lifetime of the respective system in years*

The sum of lifetime environmental impacts per category for the repowering case is calculated according to equation (3), where $I_{R,n}$ is the sum of the impacts from production and the use impacts from commissioning until repowering time. Additionally, impacts from the subsequent system 2 that is used to repower, are only considered partially. The scope of this work covers 30 years of total operation. The second system will therefore still be useful outside this scope. Hence, the impacts are only partially allocated to this calculation, considering the repowering time as well as the system lifetime. This is represented by equation 3. It is important to mention, that to reduce complexity, it is assumed that the entire PV plant is replaced with a newly manufactured system, without reusing any parts.

Equation 3

$$I_{R,n} = P_{1,n} + U_{1,n} \cdot T + E_{1,n} + \left(1 - \frac{T}{L}\right) \cdot P_{2,n} + U_{2,n} \cdot (L - T) + \left(1 - \frac{T}{L}\right) \cdot E_{2,n}$$

$P_{2,n}$= *production impacts in category n for system 2*

$U_{2,n}$= *yearly use impacts in category n for system 2*

$E_{2,n}$= *EoL impacts in category n for system 2*

T= *Repowering time in years after the installation of system 1*

According to equation (4), the repowering of a PV plant is beneficial when the sum of lifetime impacts per kWh of generated electricity in the base case are higher or equal to the sum of lifetime impact per kWh of the repowering case.

Equation 4

$$\frac{I_{B,n}}{S_B} \geq \frac{I_{R,n}}{S_R}$$

$I_{B,n}$= *Impacts in category n for Base Case*

$I_{R,n}$= *Impacts in category n for Repowering Case*

S_B= *electricity production in the Base Case*

S_R= *electricity production in the Repowering Case*

$I_{B,n}$ is the sum of the production impacts for the system, the yearly impacts caused during use multiplied by the system lifetime, and the EoL impacts. Only one system over the timespan of 30 years is considered since no repowering takes place.

To calculate the repowering time T, equations (2) and (3) can therefore be inserted into equation (4) which results in the following equation (5).

Equation 5

$$\frac{P_{1,n} + U_{1,n} \cdot L + E_{1,n}}{S_B} \geq \frac{P_{1,n} + U_{1,n} \cdot T + E_{1,n} + \left(1 - \frac{T}{L}\right) \cdot P_{2,n} + U_{2,n} \cdot (L - T) + \left(1 - \frac{T}{L}\right) \cdot E_{2,n}}{S_R}$$

Still, the electricity production in the Repowering Case S_R is dependent on the repowering time T. The sooner the system is repowered, the more electricity is generated within the investigated 30-year timeframe. To solve this problem, three more formulas need to be introduced to calculate the electricity production in both the base case and the repowering case. First, the electricity production in the first year of the plant is calculated by multiplying the irradiation, the performance ratio, the module efficiency, and the module area (see equation (6)).

Equation 6

$$S_{1|2} = Irr \cdot PR \cdot \eta \cdot A$$

$S_{1|2}$= *electricity production in year 1*

Irr = *Solar irradiation in* $\frac{kWh}{m^2 \cdot a}$
PR = *Performance Ratio*
η = *module efficiency*
A = *module area*

The electricity production in the base case S_B, is the sum of the yearly electricity production, which is constantly reduced by a degradation factor DR_1. In the base case only system 1 is considered since no repowering takes place (see equation (7)).

Equation 7

$$S_B = \sum_{t=1}^{L} S_1 - (S_1 \cdot DR_1 \cdot (t-1))$$

S_1= *electricity production of module 1 in year 1*
DR_1= *annual degradation rate of system 1*
t = *year of system use after installation*

The electricity production in the repowering case S_R is the sum of the electricity production from system 1 until it is repowered, and the electricity production of system 2 from the repowering time on until the 30-year timeframe of this study is completed (see equation 8).

Equation 8

$$S_R = \sum_{t=1}^{T} S_1 - \big(S_1 \cdot DR_1 \cdot (t-1)\big) + \sum_{t=1}^{L-T} S_2 - (S_2 \cdot DR_2 \cdot (t-1))$$

S_2= *electricity production of module 2 in year 1*
DR_2= *annual degradation rate of system 2*

The earliest repowering time can now be calculated as the minimum time after which the impacts per kWh of the repowering case are lower than the impacts of the base case (see equation 4). The optimum repowering time is reached when the impacts per electricity production in the repowering case are at their minimum.

3. Synthesis

The research questions of this cumulative dissertation have been approached with the findings from three peer-reviewed journal articles. In this chapter, the most important findings of the articles are summarized per publication.

3.1. The influence of PV module end-of-life treatment on the environmental footprint of PV electricity

To address the first sub-research question;

“How does the end-of-life treatment of PV modules affect the environmental footprint of PV electricity?”,

an LCA study has been performed to analyze the environmental performance of different EoL approaches that differ in the recovery rate of certain PV module components and materials in Herceg et al. 2020 (*48*). State-of-the-art recycling is the most basic approach in this analysis, whereas the other approaches have so far only been implemented in scientific studies. Recent LCA studies focus mainly on the emissions from PV (*9, 8*) or on the economic effects of PV recycling (*62*). Few waste management approaches for silicon PV modules have been studied but system boundaries, functional unit and study scope differ strongly, thus making a direct comparison impossible. Further, since these studies do not use a functional unit of 1 kWh of PV electricity, inclusion of the results in assessing the overall environmental footprint of PV electricity is not possible. Wambach et al. 2017 (*63*) assess the impacts of the state-of-the-art recycling of 1 kg of used module and come to the conclusion, that the recycling processes under study lead to net environmental benefits. Latunussa et al. 2016 (*64*) present a novel approach that additionally recovers silver and metallurgical grade silicon and assess the consequential impacts per 1000 kg of module waste. The authors find net benefits from recycling and identify transport and thermal treatments as the main burdens within the entire process. To identify the effect that module recycling has on the environmental footprint of PV electricity, the above-mentioned processes, in addition to other literature values for PV recycling, have been used in the scenarios analyzed in Herceg et al. 2020 (*48*). The results demonstrate that recycling has the potential to improve the environmental profile of PV electricity while state-of-the-art PV recycling is not sufficient for a drastic decrease of emissions from PV electricity. Further, parameters that have a major influence on the environmental footprint of PV electricity are identified.

Life Cycle Assessment of module recycling

The functional unit for the studied product system is the generation of 1 kWh electricity produced with a slanted-roof PV plant installed in Germany and manufactured under the approximated global market and technological conditions of 2010–2013 (*65*). The reference flow refers to the size of the system that quantifies the functional unit, which in this case is a 3 kWp plant (Table 2). Whereas Herceg et al. 2020 (*48*) show results for monocrystalline as well as multicrystalline PV modules, this paragraph will only display the results for the monocrystalline modules, since all other analysis within this dissertation are also focused on monocrystalline modules. Life cycle inventories can be found in Appendix A.

The manufacturing of the balance-of-system (BOS) components (mounting structure, cabling, inverter) is included in the calculation of the total PV electricity emissions; however, recycling of BOS has not been considered since no data have been available. Since this analysis has been performed between 2018 and 2019, the now existing PEFCR (*21*) and PVPS guidelines (*19*) on how to perform an LCA for PV systems had not yet been implemented (see chapter 2.2). Therefore, the then existing recommendations from Wade et al. 2017 (*66*) have been followed: For this reason, the LCIA method used in this analysis differs from the LCIA method described in chapter 2.2. Here, the ILCD 2011 (*67*) midpoint has been used, from which seven categories, that have been recommended for the LCA of PV electricity (*66*), are displayed.

Table 2 Module and modelling parameters (after Herceg et al. 2020 (*48*)).

	Parameter	**Mono-Si**
Location of Manufacturing (Market Share)(*65*)	China (CN)	79.6 %
	Europe (RER)	14.5 %
	Asia Pacific (APAC)	5.9 %
Module parameters	Plant size (kW$_p$)	3
	Module efficiency	14 %
	Panel capacity rate (W$_p$/m^2)	140
	Module lifetime (Years)	30
	Module weight (kg/m^2)	10
	Module Area (m^2)	1.6
Expected service lifetime (years)	Module	30
	Inverter	15
	Mounting structure	30
	Cabling	30
	Infrastructure (production / recycling facility)	30
Modelling parameters	Performance ratio	0.75
	Degradation rate	Linear, 0.7 % per year
	Conversion efficiency (primary energy to electricity)	G=30 %
	Irradiation (Germany) (kWh/m^2)	1055 (*68*)

Six waste management approaches have been assessed that differ in the recovered materials, the processes involved and the final disposal mechanism which the unrecovered materials undergo (Table 3). The state-of-the art basic recycling only includes the recovery of bulk materials such as aluminum and glass. This is, however, sufficient to comply with the European WEEE directive (*14*) which requires a recovery of 80 % in mass (approach n°1 and n°2). The state-of-the-art basic approaches are based on an LCI from Wambach et al. 2017 (*63*), which describes the current approach performed mostly in laminated glass, metal and electronic waste recycling plants where PV modules can also be processed. Approaches n°3 and n°4 describe basic recycling with additional treatment of a fluorine-free (A) and a fluorinated (B) backsheet, which is based on an LCI derived from experimental data on mass and material flows (*69*), whereas approaches n°5 and n°6 describe a more dedicated, but not yet implemented recycling approach based on Latunussa et al. 2016 (*64*).

Those include the recovery of silver and metallurgical grade (MG-) silicon as well as backsheet pyrolysis (approach n°6).

Table 3 EoL treatment approaches under study (Herceg et al. 2020 (*48*)).

Appr.	Materials Recovered	Unrecovered Fraction Disposal Method
n°1	Glass, Aluminum, copper	Landfilling
n°2	Glass, Aluminum, copper	Landfilling / Incineration
n°3	Glass, Aluminum, copper	Landf*. / Inciner**. / Inciner. of Backsheet
n°4	Glass, Aluminum, copper	Landf. / Inciner. / Pyrol. of Backsheet
n°5	Glass, Aluminum, copper, MG-Si, Silver	Landfilling / Incineration
n°6	Glass, Aluminum, copper, MG-Si, Silver	Landfilling / Pyrolysis

*Landfilling. **Incineration

A sensitivity analysis has been performed to assess how changing industrial parameters would affect the environmental performance of the recycling approaches. A scenario for future PV module recycling in 2040 has been defined, based on technology forecasts that consider different effects that could either decrease or increase the benefits from PV recycling:

- A changing electricity mix with higher penetration of renewables (75 % renewables in 2040 (*70*) instead of 29 % in 2013 (*71*)).
- An enhanced recycling efficiency due to improved processes or bigger flows of material. An energy demand of 60 % of the value in the baseline scenario has been assumed.
- A changing primary material content due to technological improvements. It can be assumed that future PV modules will contain less primary material which decreases their environmental footprint during production. However, benefits from recycling could decrease due to less recoverable material. Therefore, the recovery rates have been changed from 48 %, 56 % and 77 % for the baseline scenario, while for 2040, these are assumed to be 41 %, 48 % and 65 % for aluminum, copper and silver respectively (*63, 72*).
- 50 % reduction in transportation efforts due to an efficient collection network.

Environmental Impacts from different recycling approaches

The impacts of the different EoL approaches have been analyzed relative to the impacts of the production of 1 kWh of electricity and are therefore displayed on a negative axis (Figure 6). All recycling approaches have a high capacity of reducing the impacts within the impact category “human toxicity (cancer effects)”, with potential reductions ranging from −6.6 % to −7.9 % of the total PV electricity emissions. Emissions in the category “resource depletion” could be reduced by about 12 % when dedicated recovery is considered, which is mainly due to the recovery of silver. The lowest effect can be seen for “freshwater ecotoxicity”, ranging from 0 % to −1.1 %. For the basic recycling approaches (n°1 to n°4) the environmental benefits are comparable in all the categories. Approaches n°5 and n°6 (dedicated recycling) also perform in a similar way in all impact categories. When metallurgical grade silicon is recovered from the PV cell, some of the initial (mostly fossil) energy needed to produce the high purity silicon can be avoided in further production processes.

This is mainly visible in the results for approaches n°5 and n°6 in the categories “climate change” and “particulate matter”.

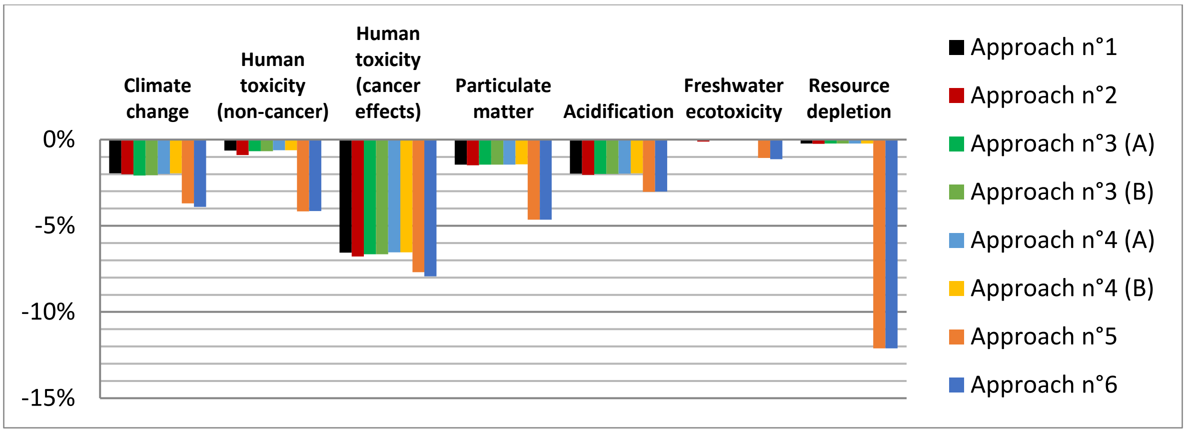

Figure 6 Potential contribution of waste management options to the environmental footprint of electricity production with mono-Si modules (Herceg et al. 2020 (*48*)).

The results of the sensitivity analysis are displayed relative to the baseline (Figure 7 A). Positive values represent improvements compared to the baseline while values on the negative axis reflect a decrease in benefits obtained from recycling. Effects for the impact category “freshwater ecotoxicity” differ an order of magnitude from the other categories, therefore the category has been plotted in an independent graph (Figure 7 B).

For the categories “human toxicity -non cancer”, “human toxicity -cancer effects”, “particulate matter”, “acidification” and “freshwater ecotoxicity” it can be seen, that the 2040 recycling scenario comes along with less environmental benefits than the baseline approaches (results relative to the impacts of PV production per kWh). This is mainly due to the reduced primary material content of the recycled modules, because the positive effects of the recovery of materials become smaller compared to the baseline approaches. For climate change, the combination of a higher share of renewables in the electricity mix, the enhanced recycling efficiency and the reduction of transport emissions overly this effect for the approaches n°1, n°4A, n°4B and n°6. Here, the positive impacts from recycling in 2040 further increase despite the reduced primary material content. For the category “Resource depletion”, a significant decrease in benefits of around 15 % compared to the baseline can be observed for the approaches n°5 and n°6, which is due to the decreased recovery of metals. For the approaches n°1 - n°4B, an increase in environmental benefits for “resource depletion” can be observed, which is due to the savings of fossil energy resources in the 2040 scenario. Here, no silver and silicon recycling are considered, hence the smaller impact of the reduced primary material content. For “freshwater ecotoxicity”; however, the horizontal −100 % line indicates that the original benefits from recycling face a reduction of 100 %. In other words, no benefits can be obtained in the 2040 scenario. Values above this line (0 to -100 %) mean that recycling will still lead to environmental benefits, but fewer than in the baseline approach. Values below -100 % mean that recycling is now leading to an additional burden on the environment, which is the case for approaches n°1, n°3A and n°3B as well as n°4A and n°4B. Here, emissions from incineration and pyrolysis are dominating the negative effects.

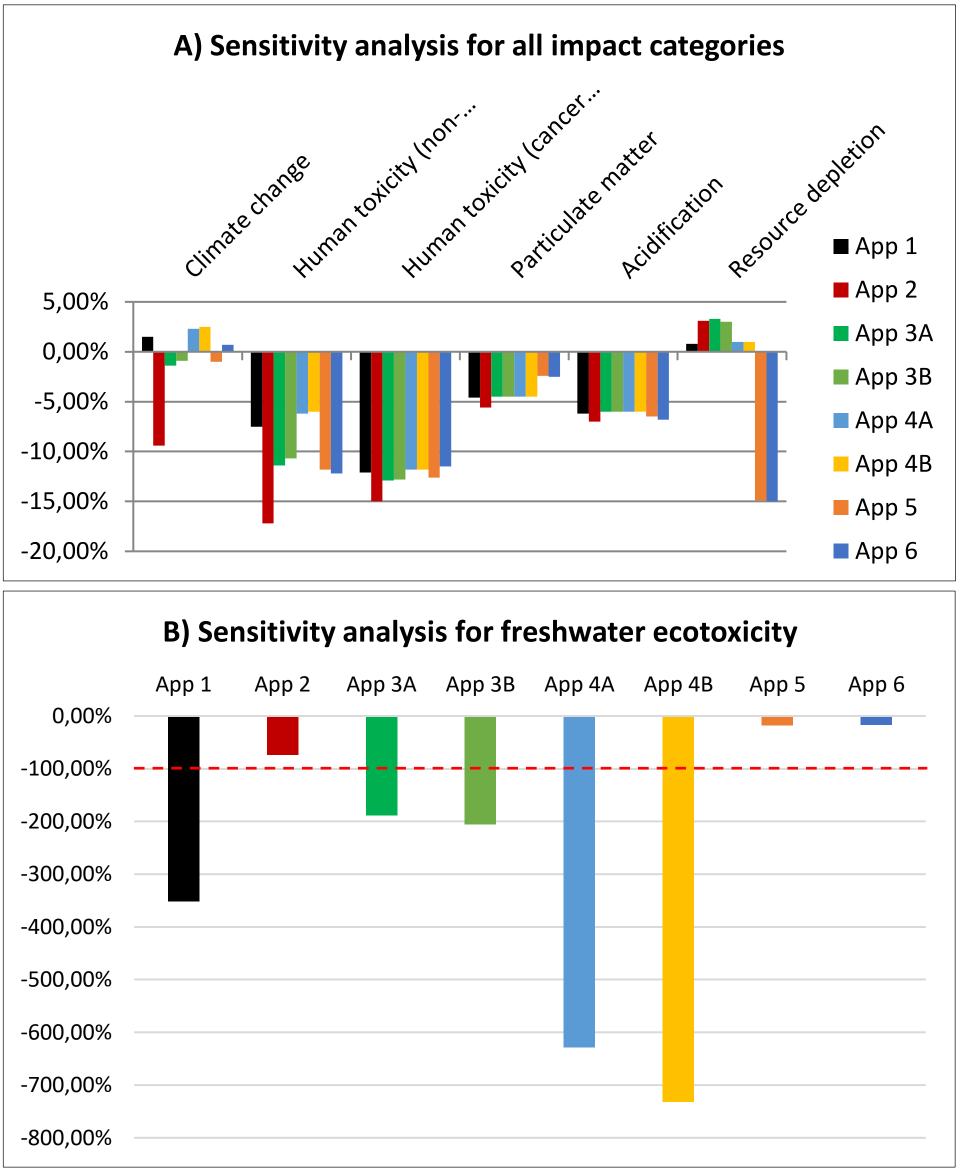

Figure 7 (A) LCIA results for the sensitivity analysis of PV recycling for all scenarios. Results for freshwater ecotoxicity are displayed separately in Figure 7 (B). After Herceg et al. 2020 (*48*).

Implementing dedicated recovery approaches could contribute to the reduction of greenhouse gas emissions (see impact category “climate change”) of PV electricity by up to 4 % in the baseline scenario and another 2.5 % in the 2040 scenario. While 4 % may seem low at a first glance, Table 4 shows the potentially avoided GHG emissions per ton of waste (*17*) until the years 2040 and 2050. Minimum and maximum values are given in consideration of the approaches with the lowest (approach n°1) and highest (approach n°6) potentials. By 2040, the avoided GHG emissions from recycled PV material in Germany could add up to two to four million tons, which equals to around 10 % of the possibly avoided average global emissions. By 2050, the same analysis results in possible emissions avoided of around three to seven million tons in Germany, accounting for 6 % of the global GHG emissions that could be avoided by PV recycling.

Table 4 Potentially avoided greenhouse gas emissions per ton of PV waste in the year 2040 and 2050 (Herceg et al. 2020 (*48*)).

Year	**Area**	**PV Waste (Million tons)**	**Cumulative Million Ton CO_2 eq**	
			MIN	**MAX**
2040	Germany	2.4	2.04	4.08
	Global	23.5	19.95	39.90
2050	Germany	4.3	3.65	7.30
	Global	69	58.57	117.16

Overall, dedicated recycling as presented in approaches n°5 and n°6 entails the highest potential to improve the environmental footprint of PV electricity production. The specific treatment of the backsheet layer, as seen in approaches n°3 and n°4, does not have a major impact on the environmental profile of recycling the modules under study due to the low mass fraction of the backsheet. It should, however, be taken into consideration that certain materials, like the fluorine in the backsheet, can become problematic when considering the forecasted increase in waste material flows. Efforts in research should focus on reducing the unrecovered fraction that is being landfilled containing polymers, silicon and metals. The development of an appropriate recycling network will not only bring benefits in environmental aspects but will also have a great impact on the economics and financial balances of the logistic schemes.

Conclusion

State-of-the-art PV recycling has a moderate effect on the overall environmental footprint of PV electricity with up to 7 % impact reductions in the category “human toxicity-cancer effects”. Only the bulk materials aluminum, glass and copper are currently being recycled, which leads to an impact reduction of 2 % from the overall impact per kWh in the category “climate change”. The recycling of additional materials, especially silver and the energy-intensive solar-grade silicon, show great potential to further increase the positive effects of PV module recycling (up to 4 % for “climate change” as well as up to 12 % for “resource depletion”). Additionally, the recycling of BOS components, which has not been considered in this study due to a lack of data, will also decrease the overall environmental footprint of PV electricity. As shown here, the recovery of solar grade silicon can be a first step to decreasing overall emissions. But since especially the production route from MG-silicon to final wafer contributes to a large amount to the PV production emissions in the category “climate change”, the recovery or effective recycling of the silicon wafer would be an attractive measure to further decrease overall emissions. The sensitivity analysis shows that future predictions on PV recycling must consider 1) different aspects of technology development and 2) the whole PV life cycle, since certain measures can have contradicting effects in different lifetime phases, like the reduction of primary material content in the PV module, which is decreasing the positive effects of PV recycling while nevertheless reducing the overall environmental burden of PV electricity.

When dedicated recycling has the potential to lower the overall environmental footprint of PV electricity, it can be assumed that the higher the benefits from recycling, the shorter the possible PV lifetime to reach an optimal environmental footprint. This hypothesis will be investigated in chapter 3.3. In combination with the second research question (“How do different degradation patterns affect the lifetime energy output and therefore the environmental footprint of PV electricity?”) the overall goal of this study, to curtail the optimal ecological lifetime of PV systems will be further approached.

3.2. The influence of different degradation patterns on the lifetime energy output and the environmental footprint of PV electricity

To address the second research question;

“How do different degradation patterns affect the lifetime energy output and consequently the environmental footprint of PV electricity?”,

the influence of different degradation characteristics on the greenhouse gas (GHG) emissions of silicon photovoltaics has been investigated in Herceg et al. 2022a (*49*). Recent studies that calculate the GHG emissions of PV electricity usually do consider performance degradation as recommended by current standards on PV LCA (*19, 21*) by assuming a linear reduction in lifetime energy output of either 0.5 % or 0.7 % per year. However, research has shown that the decrease in energy output over time does not necessarily follow a linear degradation pattern (*25, 26*). Degradation can vary at different points in the module’s lifetime (*25*) and follows different patterns in different climate zones (*52, 53, 27*). To study the effect of those degradation patterns on the GHG emissions of PV electricity, different degradation aspects have been integrated into the calculation of GHG emissions. Whereas in Herceg et al. 2022a (*49*) also the effects of changing atmospheric conditions due to climate change have been quantified, the results presented here are focused on non-linear degradation and differences in geographic location.

Non-linear degradation

By including the methodology to assess the PV system’s lifetime energy yield proposed by Kaaya et al. 2020 (*25, 53*) (see chapter 2.3) into the life cycle assessment of PV electricity, the variations in GHG emissions that can be caused by different non-linear degradation profiles at the same defined failure threshold are calculated and compared with a linear degradation profile. The degradation trends of five different PV systems (systems A–E, based on field measurements, see (*25, 53*)) have been used to simulate five different profiles in Kaaya et al. (*25, 53*) (scenarios S01 -S04 plus linear) (Table 5) by changing the values for the shape parameter μ and the model parameter Γ as shown in Table 5. The assumptions for systems A-E (Figure 8 A) are based on differences in module design and manufacturing.

Table 5 Different degradation profiles and corresponding parameters.

Scenario	Parameter (μ)	Parameter (Γ)	k (%/Year)	Lifetime (Years)
Linear	-	-	0.70	30.0
S01	1.0	0.33	0.70	30.0
S02	0.7	0.40	0.70	30.0
S03	0.3	0.93	0.70	30.0
S04	0.2	1.94	0.70	30.0

For example, it is expected that for glass–glass modules there is fewer moisture ingress compared to glass–backsheet modules. Therefore, moisture-induced degradation modes are expected to be slower at the earlier stages of the module lifetime for glass–glass modules in comparison to glass–backsheet modules (*73*). However, at the same time, the compacted design of the glass–glass modules implies that drying is also limited, causing the moisture and degradation products like acetic acid to accumulate inside the module over the years, leading to a dramatic increase in the degradation rate in later years.

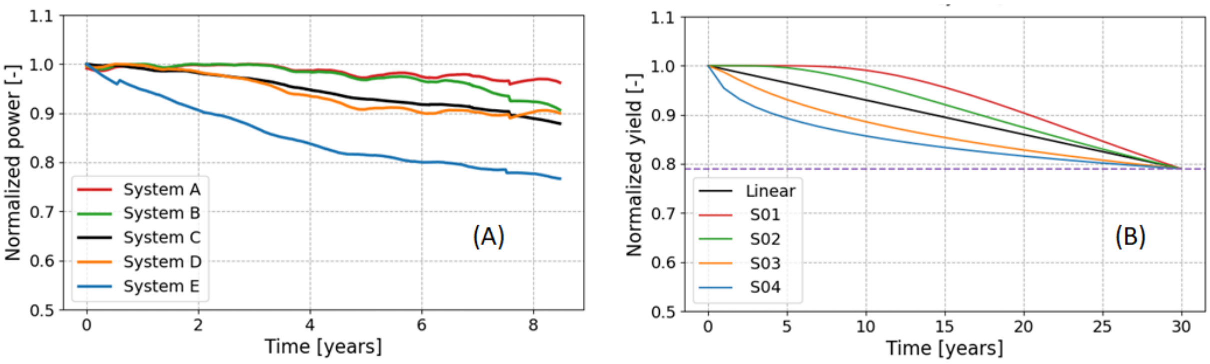

Figure 8 (A) Different degradation profiles for different PV systems. (B) Simulated degradation scenarios based on the different degradation profiles. See Herceg et al. 2022 a (*49*).

Results are presented in kg CO_2 eq./kWh for a 3 kWp slanted-roof PV plant installed in the EU (baseline scenario, see Table 6). The four degradation scenarios (S01–S04) have been benchmarked to the baseline scenario.

Table 6 Baseline scenario of a 3 kWp slanted-roof PV plant installed in the EU.

Parameter	Values
Solar irradiation	1331 kWh/(m^2·a) (baseline)
Performance ratio	0.85
Degradation rate	0.7 %/year (baseline)
Plant size	3000 Wp
Module efficiency	20.11 %
Module area	1.85 m^2
Maximum power	372.3 Wp
Power/Area	201.24 Wp/m^2

Effect of non-linear performance degradation on the GHG emissions of PV electricity

The results for the non-linear performance degradation scenarios differ from the linear degradation (0.7 % annually) scenario by up to 6 % (Figure 9 A). Absolute values range from 20.3 g CO_2 eq. per kWh for S01 to 22.3 g CO_2 eq. for S04 (Figure 6 B). The analysis shows that using a linear approximation would lead to an over- or underestimation of GHG emissions for most systems observed in the field. To improve the accuracy of GHG emission calculation for PV electricity, more detailed information about the PV system under study should be considered.

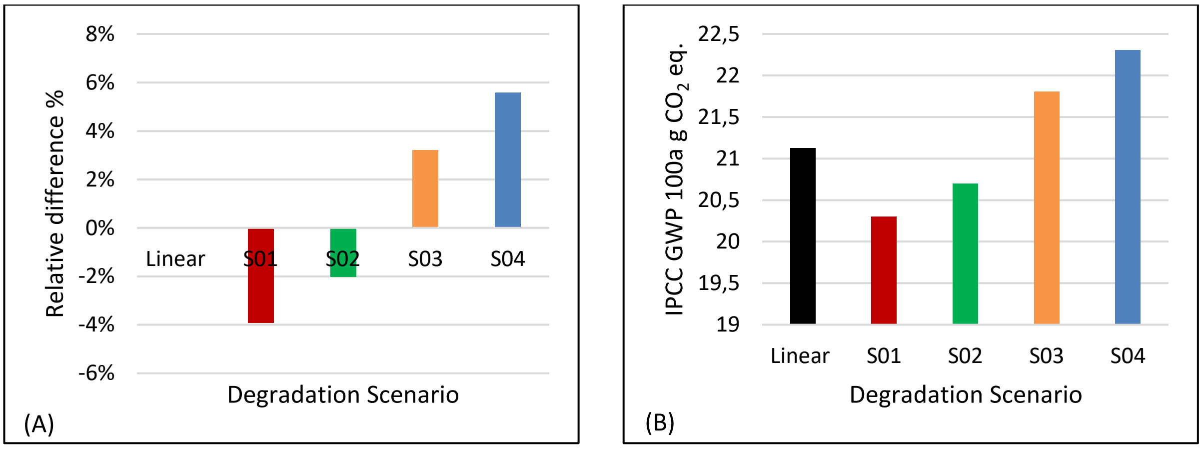

Figure 9 (A) Relative difference of the GHG emissions for all four degradation scenarios in relation to linear degradation. (B) GHG emissions per 1 kWh PV electricity in g CO_2 eq. for all four degradation scenarios and linear degradation.

Climate Specific Degradation

To assess the deviation of the climate specific GHG emissions of 1 kWh of PV electricity from the GHG emissions of 1 kWh of PV electricity with constant degradation (0.7 % annually), degradation rate and irradiation have been adapted according to the spatial distribution of the degradation mechanism in relation to KGPV zones (*27*) (see chapter 2.3). Lifetime electricity yield has been calculated and GHG emissions have been assessed accordingly via LCA. GHG emissions have been assigned to different climate zones according to the KGPV scheme (*27*) (see chapter 2.3) . Again, the results show that assuming linear degradation leads to an over- or underestimation of GHG emissions in most cases (Figure 10). The only climate zone that resembles a linear degradation behavior is CK (steppe climate, very high irradiation, see chapter 2.3) In most of the climate zones (FL, EL, EM, DL, DM, CH, BH and BK), the degradation rates are calculated to be lower than 0.7 %/year, thus the GHG emissions are overestimated when using linear degradation as a default. This is the case for all temperature-precipitation zones (B: Desert climate, C: Steppe climate, E: Temperate climate, D: Cold climate, F: Polar climate) in combination with different irradiation zones (K: Very high irradiation, H: High irradiation, M: Medium irradiation, L: Low irradiation) except for Tropical climate (A). On the contrary, in tropical areas with high and very high irradiation (i.e., AH and AK), where the degradation rates are calculated to be higher than 0.7 %/year, the GHG emissions are underestimated when using linear degradation as a default. In the AH zone (Tropical climate, High irradiation) using linear degradation would lead to comparably low GHG emissions of 17.4 g CO_2 eq. per kWh, which is mainly caused by the underlying high irradiation value. Instead, when the climate specific degradation is being used in the calculation, the GHG emissions almost double to 30.2 g CO_2 eq. per kWh. In this case, the effect of the high irradiation is overshadowed by the high degradation and resulting shorter system lifetime.

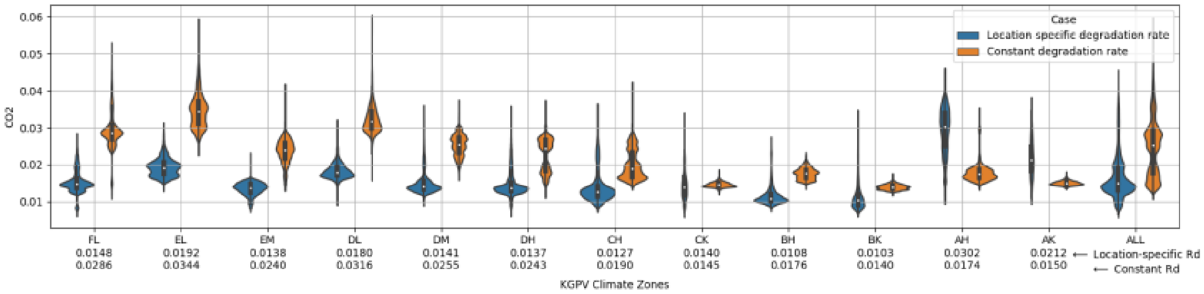

Figure 10 Spatial distribution of GHG emissions (IPCC GWP 100a kg CO_2 eq.) in view of the KGPV climate zones. The average GHG emissions in kg CO_2 eq. per climate zone is indicated below each label for the two cases (Rd: degradation rate).

To further visualize this trend, the respective GHG emissions have been plotted into world maps of the regionalized GHG emissions (Figure 11). Figure 11 A shows the emissions related to 1 kWh PV electricity calculated from climate-based degradation rates (lifetime adapted to climate-based degradation), whereas Figure 11 B shows the GHG emissions of 1 kWh PV electricity calculated using a constant linear degradation rate (lifetime of 30 years). If linear degradation is considered (Figure 11 B), the carbon footprint follows the irradiation pattern: the higher the irradiation, the lower the carbon footprint. Regardless of the expected lower degradation rates in temperate climates with low irradiation (EL zone), the evaluated GHG emissions only depend on the lower values of solar irradiation in these areas. However, when assuming climate-based degradation rates (Figure 11 A), high irradiation does not automatically lead to a lower carbon footprint since high irradiation is often accompanied by strong degradation factors and hence a shorter system lifetime. Similarly, the temperate climates with low irradiation (EL zone) show lower GHG emissions regardless of the lower irradiation because lower degradation and longer system lifetimes have been calculated.

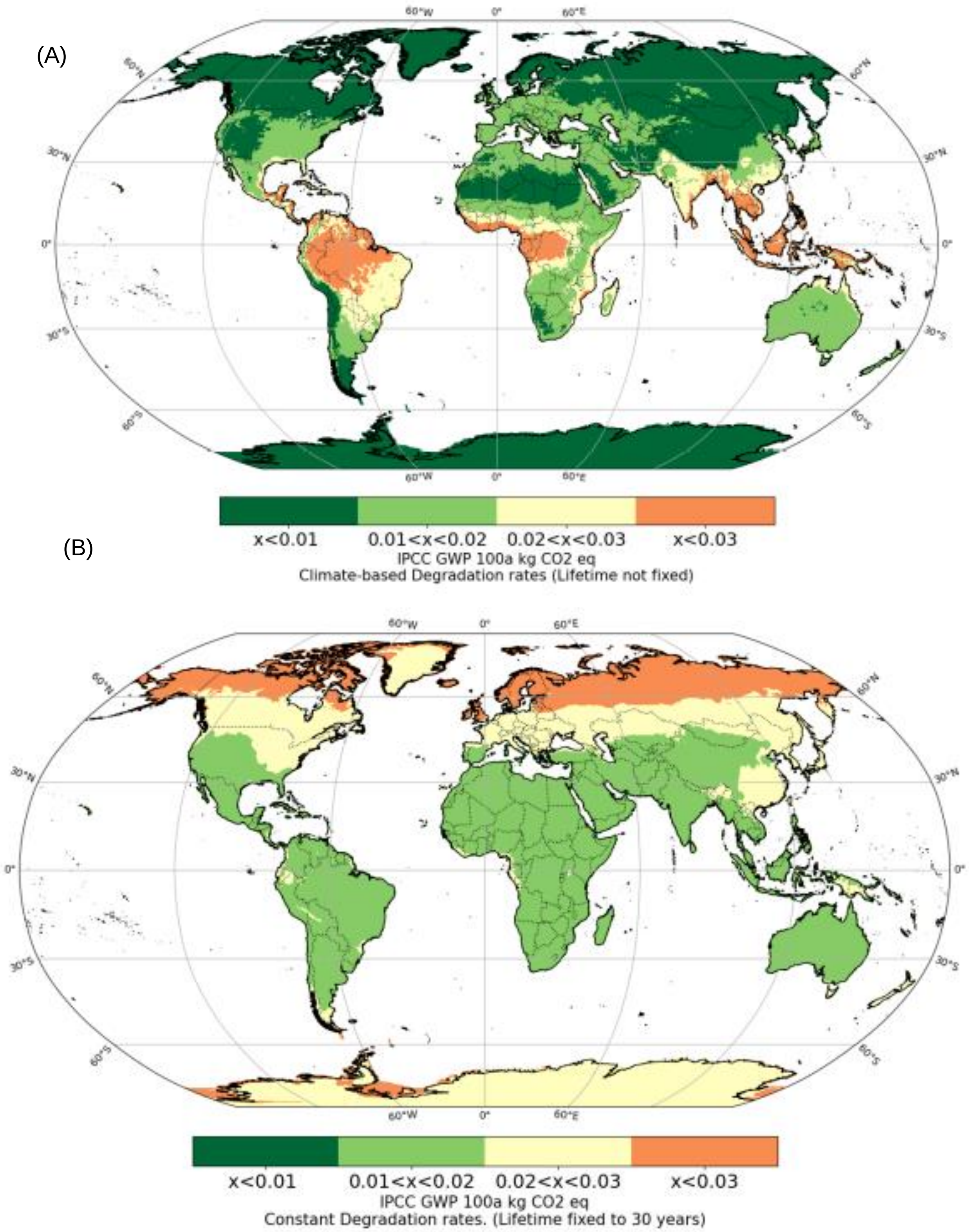

Figure 11 (A) World map of the GHG emissions of 1 kWh PV electricity calculated from climate-based degradation rates (lifetime not fixed) (B) World map of the GHG emissions of 1 kWh PV electricity calculated using a constant degradation rate (lifetime fixed to 30 years).

Conclusion

Degradation is reducing the lifetime energy output of a PV system irreversibly. The inclusion of degradation effects in LCA calculations is an area that still needs optimization since assuming linear performance degradation can lead to an over- or under estimation of GHG emissions for systems that do not follow a linear degradation pattern of around 4 % to 6 %, which in the analysis presented here is a variation of around 0.8 to 1 g of CO_2 eq. per kWh of PV electricity. Moreover, in regions where climatic stressors like temperature, humidity and corrosion are high, the GHG emissions per kWh almost double in the calculations presented here when climate-specific degradation rates are used. If a linear degradation is applied, the GHG emissions follow the global irradiation pattern: the higher the irradiation, the lower the carbon footprint. When using regional climatic degradation, this pattern changes to higher or lower degradation rates as well as longer or shorter module lifetimes.

Linear degradation can serve as a proxy to calculate average emissions of PV electricity. However, the accurate financial and environmental assessment of specific PV projects is gaining more and more interest by investors and insurance companies as well as political regulations, that make the assessment of a system's carbon footprint a prerequisite of financial incentives (*44, 74–76*). Therefore, not only technology and project specific parameters, but also technology and project specific degradation values should be considered to predict accurate values. This is important to forecast costs as well as emissions of a PV system, but also an indicator of the point in time at which the systems reach their technical, financial and ecological EoL. In chapter 2.1, different PV lifetime definitions are presented. The most used definition is, that the EoL is reached when a system has degraded down to 80 % of its initial efficiency. Assuming a constant linear degradation of 0.7 % per year, this point is reached after 30 years. However, the analysis presented here has shown that according to this definition, the lifetime of a PV system can vary at different climatic locations. In combination with the findings from Herceg et al. 2022b (*42*), which will be presented in the following chapter, this information can be used to predict the optimum ecological PV system lifetime.

3.3. The optimal lifetime of PV systems to minimize the environmental footprint of PV electricity

To address the third sub-research question;

"What is the optimal lifetime of PV systems to minimize the environmental footprint of PV electricity?",

the point in the lifetime of a PV system has been calculated at which the benefits of premature replacement of an existing PV system with a new and more efficient one outweighs the additional environmental impacts from the production and end-of-life treatment of the new system. A life cycle assessment has been performed for a 3 kWp rooftop silicon PV plant and for a 1.07 MWp open field silicon PV plant for the two reference-production years of 2004 and 2020. The earliest and the optimum points in time, at which a premature replacement can be ecologically beneficial have been calculated at midpoint for the indicators "climate change", "ecotoxicity, freshwater", "land use" and "resource use, minerals and metals". Detailed results have been published in Herceg et al. 2022b (*42*).

Due to an ongoing rise in average module efficiencies (from about 14.7 % in 2010 to 19.2 % in 2019 for mono silicon PV modules (*77*)), it can be expected, that the early replacement of PV systems before their expected 30-year lifetime, can be not only financially but also environmentally beneficial. This so-called repowering is common practice for wind farms and is gaining relevance for PV systems (see chapter 2.4). Further, energy and material demand in the module production have significantly decreased, for example using thinner silicon wafers or advanced wafering technologies (*8, 77*). The land use efficiency of ground-mounted systems has increased accordingly, from 4.1 ha per MWp in 2004 to 1.5 ha per MWp in 2017 (*78*).

Only few studies try to assess the impacts associated with PV repowering, and those studies follow different definitions of "repowering" (see chapter 2.4). For example, Jean et al. (*35*) argue that a frequent replacement of modules of different types of technologies has both financial and environmental benefits as well as a positive effect on the development of new and innovative technologies, while shorter lifetimes or higher degradation rates would allow manufacturers to use less material and invest less in reliability testing. Curtis et al. (*36*) find an improved performance through updated technologies, continued use of existing infrastructure and arrangements as well as low maintenance costs as benefits of PV repowering, but stress the higher capital investment. However, Rajagopalan et al. (*37*) conclude that early repowering is not environmentally beneficial in comparison to a longer lifetime when comparing LCA results for different repowering cases of a multi-Si PV-plant over a fixed period of 30 years.

To calculate the earliest and the optimum repowering time for PV systems, a calculation approach has been developed which is presented in chapter 2.4. The approach is based on the methodology presented by Ardente and Mathieux (*29*) for energy using products and has been adapted to fit PV as an energy producing technology. For further details see chapter 2.4.

PV system and scenario description

For LCA, the methodological approach described in chapter 2.2 has been followed regarding functional unit, LCIA method and calculation of lifetime and degradation. Six different mono-crystalline silicon PV systems (passivated emitter and rear cell, PERC) are modelled from cradle to grave. The impacts of mounting structure, electrical installation components and the inverter (inverter efficiency stays constant) are included in the analysis. The functional unit (FU) is 1 kWh of produced DC electricity.

A small-scale rooftop system of 3 kWp and a large-scale ground mounted silicon PV plant with 1.07 MWp rated capacity (for system specifications see Table 7) are modelled as the base case systems (which are to be repowered) after a life cycle inventory (LCI) from silicon PV panel production in 2004 (*79*). A further system (which is assumed to repower the old system) is modelled after the current state-of-the-art technology (reference year 2020) (*9*). The geographical focus of the study is Europe: the systems are assumed to be produced in Europe and installed in average irradiation locations in Europe (1391 kWh/m^2/a) (*80*). Life cycle inventories can be found in Appendix B.

Table 7 PERC PV system specifications. Three systems are modelled for the rooftop scale and the open field- scale: one for 2004, and two for 2020, while the 4.01 kWp system (2020) is extrapolated from the 3 kWp system (2020) and the 4.39 MWp system (2020) is extrapolated from the 1.07 MWp system (2020) (*42*).

		Rooftop Systems			**Open-Field Systems**		
	Identifier	[u]	[v]	[w]	[x]	[y]	[z]
System	reference year	2004	2020	2020	2004	2020	2020
	rated power [kWp]	3	3	4.01	1 070 (*81*)	1 070	4 390
	plant area [m²]	20.27	15.16	20.27	43 900	10 700	43 900
	module area [m²]	20.27	15.16	20.27	7 230	5 408	22 175
	area demand [ha/MWp]	-			4.1	1	
	technology	mono-Si					
	system lifetime [a]	30					
Module	module efficiency	14 % (*82*)	19.79 % (*9*)		14 % (*82*)	19.79 % (*9*)	
	module weight (framed) [kg/m²]	16.24 (*79*)	12.09 (*9*)		16.24 (*79*)	12.09 (*9*)	
	module area [m²]	1.25 (*82*)	1.85 (*9*)		1.25 (*82*)	1.85 (*9*)	
	module power [Wp]	185 (*83*)	366 (*9*)		185 (*83*)	366 (*9*)	
	annual degradation rate	0.7 %					
BOS	material of mounting structure	aluminum (*84, 13*)			aluminum (*85*)	steel (*13*)	
	inverter power [kW]	2.5			500		

Based on the technical system specifications presented in Table 7, six scenarios have been developed. Scenarios RT basic, RT EoL and RT capacity show a small-scale rooftop (RT) silicon PV plant, whereas scenarios OF basic, OF EoL and OF capacity show a large-scale open-field (OF) silicon PV plant. The EoL treatment pathways and the repowering goal vary among the scenarios. System 1 is the system to be repowered. It is either a rooftop (u) or an open-field system (x) and it’s LCI is based on the reference year 2004.

The scenarios for the EoL treatment are the following:

- State-of-the-art recycling based on the LCI data for silicon PV modules from (*63*). These include the takeback and recycling efforts as well as the avoided burdens due to the recovery of glass, copper and aluminum (recycling rates for metals, plastics and electronic components can be found in Appendix C).
- A best-case scenario is based on the information given in (*86, 64, 87*).
- In a worst-case scenario, all materials are landfilled and not treated any further.

Scenarios RT basic and OF basic as well as RT EoL and OF EoL represent a repowering to the original plant capacity (3 kWp / 1.07 MWp), leading to a decreased area demand of the plant due to efficiency increases in the new system. Scenarios RT capacity and OF capacity represent a repowering with a plant capacity increase to fill the entire available area. For the open field PV plant, this leads to a significant increase of the rated power. This is since the area demand for open field PV plants has decreased and leads to a substantial increase in total module area from 7230 to 22175 m^2 in the OF capacity-scenario (see systems [x] and [z] in Table 7).

Table 8 Six different scenarios are investigated. Three scenarios consider a small-scale rooftop silicon PV plant (scenarios 1a-c), while the other three focus on a large-scale open-field silicon PV plant (scenarios 2a-c). RT = rooftop, OF = open-field (*42*).

Scenario		**1a**	**1b**	**1c**	**2a**	**2b**	**2c**
Acronyms		RT basic	RT EoL	RT capacity	OF basic	OF EoL	OF capacity
system identifiers for cross-referencing with Table 7	System 1	[u]			[x]		
	System 2	[v]	[v]	[w]	[y]	[y]	[z]
end of life treatment of system 1		State of the Art	Landfill	State of the Art	State of the Art	Landfill	State of the Art
end of life treatment of system 2		Best Case	State of the Art	Best Case	Best Case	State of the Art	Best Case
repowering goal		original capacity	original capacity	filling entire available area	original capacity	original capacity	filling entire available area

In Herceg et al. 2022b (*42*), a sensitivity analysis is conducted to further validate the impact of the system lifetime and the module efficiency. The results of the sensitivity analysis will be briefly discussed later, but not presented here.

Calculated Repowering Times: Rooftop System

If the calculated repowering time T is lower than 30 years, repowering can be considered beneficial from an environmental point of view, as the expected lifetime of the PV plant is 30 years. A calculated repowering time lower than 30 years therefore means that the combined environmental impact of the two systems is lower at a point in time before the technical EoL is reached after 30 years. Two values have been calculated: The *earliest repowering time*, after which repowering is environmentally favorable (compared to not repowering) and the *optimum repowering time*, when the impacts per kWh are at their minimum. The calculated repowering times vary significantly among the scenarios and impact categories (Table 9).

Table 9 Earliest and optimal repowering times in years (a) after the commissioning of the original system, according to scenario and impact category (*42*).

Acronyms		**RT basic**	**RT EoL**	**RT capacity**	**OF basic**	**OF EoL**	**OF capacity**
climate change	earliest (a)	9	21	1	26	30	1
	optimum (a)	20	25	6	28	30	1
eco-toxicity	earliest (a)	30	12	1	30	12	1
	optimum (a)	30	21	16	30	21	7
land use	earliest (a)	8	22	1	30	30	1
	optimum (a)	19	26	6	30	30	1
resource use	earliest (a)	7	8	1	13	14	1
	optimum (a)	19	19	5	22	22	1

The optimum repowering times are the lowest for “resource use, minerals and metals” with an average of 15 years, whereas they are highest for “ecotoxicity” with 21 years, on average. Optimum average repowering times for “climate change” and “land use” are 18 and 19 years, accordingly. Repowering times lower than 17 years must be handled with caution since the reference years for the underlying LCA calculation are 17 years apart (2004 and 2021). Therefore, it cannot be concluded that repowering timers lower than 17 years would have met the technological standards needed for optimum repowering.

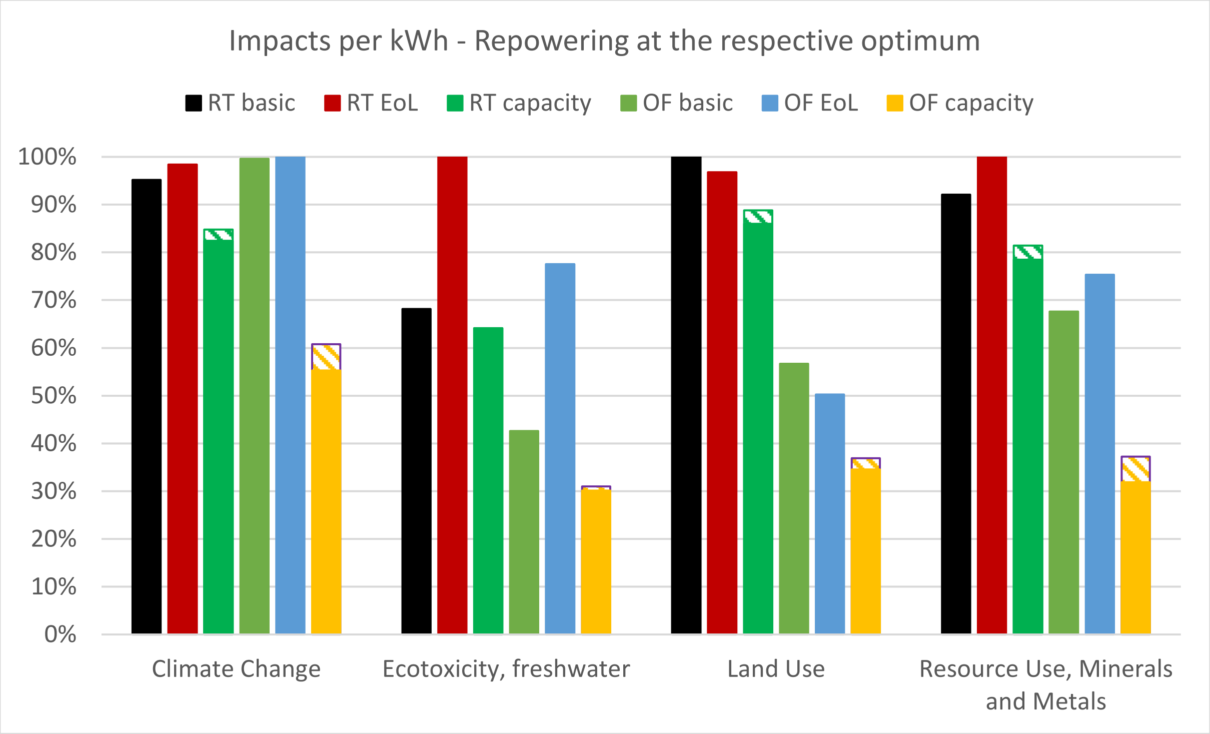

Figure 12 Characterization results per impact category and scenario of the repowered system, when repowered at the optimum repowering time. The results are presented relative to each other: the highest impact value per category is defined to be 100 %. All other impacts in the same category are presented relative to this. Stacked columns in the capacity scenarios: the calculated optimum repowering time is earlier than 17 years, therefore the additional impacts when repowered after 17 years are included. Functional unit: 1 kWh of produced electricity.

Figure 12 presents the characterization results for all scenarios at their optimum repowering time. A trend for decreasing repowering times from the basic to the capacity scenarios can be observed. In the RT and OF basic scenario, the system is repowered to its original capacity, the old system is treated with the current state of the art EoL treatment pathway, and the new system will be treated in a best-case scenario once it reaches its EoL in the future.

For a better understanding, results will be further illustrated for RT basic, “climate change”, in the following.

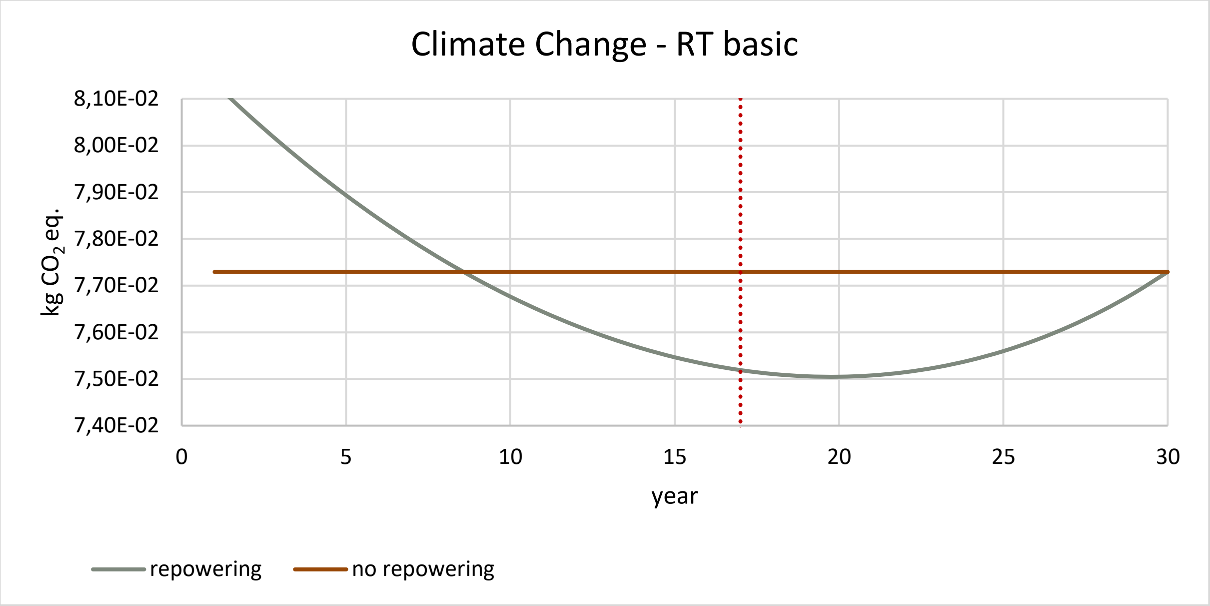

Figure 13 Impacts of the RT basic scenario in the category “climate change” in kg CO_2 eq. per kWh. The vertical line marks year 17, which is the interval between the two reference years.

For RT basic, the earliest repowering time for “climate change” is at 9 years, whereas the optimum repowering time is at 20 years (Figure 13). At the optimum repowering time, the difference between the relative increase in electricity production and the relative increase in environmental impacts reaches its maximum. After this point, the relative change in electricity production declines more steeply than the relative change in impacts (Figure 14). The carbon footprint per kWh is the quotient of the total impacts divided by the total electricity production and is therefore dependent on the changes of those two variables. A break-even point marks the earliest point in time, after which repowering is ecologically beneficial. Here, the gain from the additional electricity production due to repowering offsets the burdens from the additional impacts after 9 years. The impacts for all other categories and scenarios have been calculated accordingly, additional figures can be found in Herceg et al. 2022 b (*42*).

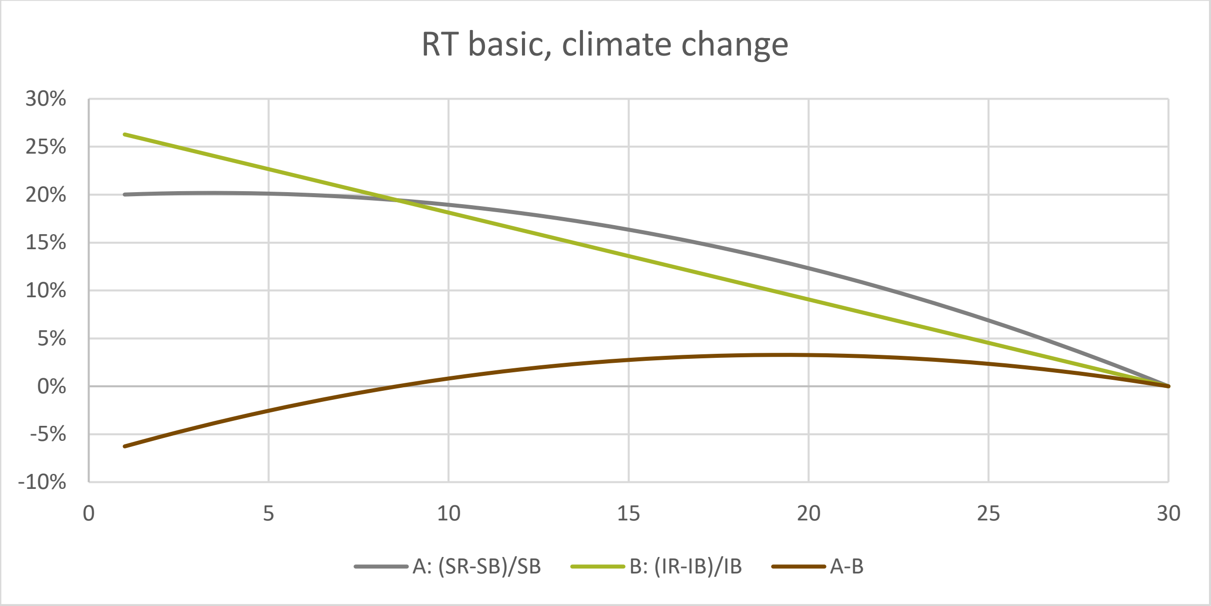

Figure 14 Relative changes of total impact (CO_2 eq.) over time of the repowering case depending on the repowering time (B: (IR− IB)/IB; see also chapter 2.1) in the category climate change as well as relative changes of electricity production of the repowering case over time (A: (SR-SB)/SB). The variables are calculated according to equations (1), (2), (6) and (7) in chapter 2.4.

For the category “ecotoxicity” (RT basic), the additional impacts from the manufacturing and EoL treatment of the second system cannot be offset by the increase in electricity production (Table 9), which means early repowering is not beneficial. For “land use”, the repowering time calculation shows environmental benefits after 8 years and an optimum after 19 years, where the land use impacts per kWh are at their minimum. For the indicator “resource use, minerals and metals”, the earliest repowering time is calculated at 7 years, whereas the optimum is reached after 19 years (Table 9).

For the RT EoL scenario, repowering is environmentally beneficial in all four impact categories (Table 9) and the optimum repowering time lies between 19 years for “resource use, minerals and metals” and 26 years for “land use”. This scenario differs from the RT basic scenario in the less dedicated EoL treatment of both systems. This leads to a later repowering time, except for “ecotoxicity”. The positive effect on “ecotoxicity” can be traced back to the landfilling of system 1. By treating system 1 with the current state-of-the-art recycling pathway, environmental credits are accounted for, mainly due to the copper recovery. However, when the same system is landfilled, it causes significant “ecotoxicity” impacts. The overall life cycle emissions of the system are increased. At the same time the impacts of the EoL treatment of system 2, which is changed from the best-case treatment to the current state-of-the-art, increase only marginally.

For the RT capacity scenario, repowering can be beneficial from year one in all four impact categories (Table 9). The optimum repowering time, however, lies between 5 and 6 years for “climate change”, “land use” and “resource use, minerals and metals” and at 16 years for “ecotoxicity”. In this scenario, not only dedicated recycling is considered but also the repowering goal is changed to filling up the entire available land area instead of repowering to the plant’s original capacity. This leads to an increased rated capacity of the new plant from 3 kWp to 4.01 kWp.

Calculated Repowering Times: Open-field systems

In the OF basic scenario, repowering cannot be considered beneficial for the indicators “ecotoxicity” and “land use” (Table 9). For “climate change”, the earliest beneficial repowering time is at 26 years, whereas the optimal repowering time would be after 28 years. In the category “resource use, minerals and metals”, the earliest repowering is calculated at 13 years, whereas optimum repowering time is 22 years after the commissioning of the original plant. In comparison to the rooftop system, repowering times are delayed. This is because the relative differences between the impacts of the 2004 reference case and 2020 reference case are lower than compared to the rooftop systems. This can be traced back to the respective changes of the bill of materials (BOM) for the mounting structure [35, 36] (LCI in Appendix B).

In the OF EoL scenario, repowering is not beneficial for “climate change” as well as “land use”. For “resource use, minerals and metals” the calculated repowering times are 4 and 22 years (earliest and optimum, respectively). For “ecotoxicity”, the earliest repowering is at 12 and the optimum at 21 years. As for the RT EoL scenario, the negative impacts of landfilling system 1 outweigh the only marginal benefits of recycling system 2 with the state-of-the-art recycling scenario.

Comparable to the RT capacity scenario, repowering can be beneficial in the OF capacity scenario from year one in all four impact categories. The optimum repowering time is after 1 year, except for “ecotoxicity”, where the optimum repowering time is after 7 years. By filling up the entire available land of 4.4 ha, the rated capacity of the plant increases from 1.07 MWp in 2004 to 4.4 MWp in 2020.

Sensitivity Analysis

In a sensitivity analysis, the influence of the system lifetime and the module efficiency has been tested. As research and development is aiming at increasing system lifetimes to more than 30 years in the future, an increase in the lifetime of the second system to 40 years with an adjusted degradation rate of 0.5 % annually has been assumed. The results show a decreased repowering time for all categories. For the rooftop plants, the optimum repowering time is decreased by 6 years on average, for the open-field plants, by at about 3.7 years.

Secondly, the influence of the module efficiency has been evaluated by increasing the efficiency of the module that is to be repowered from 14 % to 16 %. The resulting higher lifetime electricity output of system 1 leads to a delayed repowering time in all categories by 7 and 3 years on average for the rooftop systems and the open-field systems, respectively. Hence, the higher the module efficiency of the older system (and, consequently, the lower the difference in module efficiencies of systems 1 and 2), the lower the benefits from repowering.

Conclusion

The calculated repowering times vary significantly among the scenarios and impact categories. However, it can be said that the more determined the EoL treatment pathway, the earlier the optimum repowering time, except for “ecotoxicity”. Here, the landfilling in the EoL scenarios has a major influence. Still, the impact of the repowered system at its optimum repowering time is 47 % higher in the RT EoL scenario than in the RT basic scenario, which means that more dedicated recycling lowers the overall impacts of the two systems combined. The same tendency applies in the corresponding open-field scenarios (+82 %). This shows that the EoL phase has significant influence on the environmental footprint and therefore the repowering time. By repowering the entire available area, the increase in capacity outweighs the additional environmental burdens from production and recycling. The impacts per kWh are 6–53 % lower in the capacity scenarios than they are in the respective basic scenarios if the repowering takes place at the calculated optimum times. Overall, the results indicate that repowering can be more beneficial for rooftop plants than for open field plants. This is mainly due to the materials used for the open field mounting structure. However, this analysis does not consider a re-use of the already existing mounting structure but a replacement of all system components. The sensitivity analysis shows, that with further increasing improvements of future PV modules, like decreasing degradation rates and longer modules lifetimes, an early replacement of old modules becomes more and more environmentally friendly. However, while there have been major improvements in production and operation efficiencies, it cannot be expected that this trend continues at the same speed in the future, due to natural restrictions of the efficiency increase for this PV technology. The Auger limit of a normal silicon cell is 29.4 % (*88*). Still, new technologies, such as heterojunction and tandem solar cells are promising to reach higher efficiencies while having a comparable environmental impact (*35, 89, 90*). Still, the findings from this study suggest that the development of easily recyclable modules with a standard system lifetime of 20-25 years should be prioritized over systems with extremely long lifetimes of 40-50 years. Simultaneously, systems with longer lifetimes will be tying up valuable resources aggravating the threat of a resource scarcity in renewable energy deployment.

Premature repowering of PV plants can be environmentally beneficial under certain conditions, namely dedicated EoL treatment as well as an efficient use of available land. The analysis shows that replacing old modules with state-of-the-art highly efficient modules has the potential to lower the overall carbon footprint of PV electricity. Especially for “resource use, minerals and metals” repowering has shown to be environmental beneficial in this analysis. This is effect is gaining relevance, the more dedicated the EoL treatment. This can be a valuable indicator to address the issue of resource and material scarcity in the future, where old modules can be used as a supply of materials to produce new modules. Dedicated recycling in combination with repowering will also further decrease the impacts of PV electricity in the category “ecotoxicity”. For the category “land use”, repowering of open field PV systems is only recommended in combination with a capacity increase, while repowering only to the original capacity is not ecologically beneficial according to this analysis.

4. Discussion and Conclusion

The overall goal of this study has been to evaluate how different stages of the PV system's life cycle can affect its overall life cycle emissions and therefore influence its optimal ecological lifetime, as expressed in the research question:

"What is the optimal ecological lifetime of PV systems and how do different effects throughout their life cycle influence the environmental footprint of PV electricity?".

The three influencing factors (1) non-linear and regionalized performance degradation, (2) end-of-life (EoL) treatment and (3) actual operational time have been assessed using LCA methodology. The results have been published in three peer-reviewed journal articles. These studies improve the accurateness and comparability of the assessment of emissions related to PV electricity generation and can be used to further optimize PV deployment strategies by providing a better understanding of the environmental implications of the above-mentioned influencing mechanisms.

To answer **the first sub-research question**, the status quo as well as more dedicated approaches of PV module recycling have been analyzed regarding their impact on the emissions of PV electricity in different environmental impact categories in Herceg et al. 2020 (*48*). By using the electricity output in kWh as functional unit instead of a mass-based FU, the results can be related to the overall life cycle emissions of the PV system. Further, the results are in accordance with international guidelines for PV LCA and therefore improve the comparability and compatibility of PV LCA results. It could be shown that state-of-the-art PV module recycling only has a small impact of 2 % in relation to the production emissions of the PV system ("climate change"). However, the more parts of a module are being recycled, the higher the positive effect of recycling (despite the higher effort for waste treatment). The impact in relation to the production emissions for the most dedicated treatment approach increases to 4 % for the category "climate change" and to 12 % for "resource depletion". In conclusion, dedicated recycling has the potential to lower the overall environmental footprint of PV electricity. It can further be concluded that the higher the benefits from recycling, the shorter the possible PV lifetime to reach an optimal environmental footprint. These findings are also mirrored in the results from **the third sub-research question**, which show that in most cases, PV repowering is environmentally beneficial when a more dedicated EoL treatment is implemented (*42*). Strategic recycling, especially of older PV modules which contain high amounts of materials like silver and silicon, can be used to tackle resource scarcity for production in the near future, where new PV installations will grow vastly. Still, PV technologies are facing constant development, like the reduction of primary material content, making the assessment of EoL strategies an ongoing task.

To answer **the second sub-research question**, the effects of non-linear PV module degradation as well as climate specific degradation on the overall GHG emissions of PV electricity have been assessed (*49*). Instead of using a constant linear degradation to calculate life cycle emissions in the PV LCA, a non-linear degradation rate adapted to PV module and system design has been used.

The results with non-linear degradation vary up to -4 % to +6 % from the linear degradation, which in the analysis presented here is a variation of around 0.8 to 1 g of CO_2 eq. per kWh of PV electricity produced. While today, calculated emissions of modern PV systems are below 20 g/kWh, assessing technology and system specific emissions can make a major difference regarding the specific system components, design and financing. The impact is even more significant for site specific assessments, where GHG emissions can almost double when using regionalized degradation rates. The results lead to the conclusion, that a longer system lifetime might be more recommendable from an environmental perspective in temperate climates with low irradiation since the energy output stays higher over a longer period due to slower degradation. On the other hand, due to a faster decrease in energy output and therefore a higher carbon footprint per kWh, an early replacement of modules seems to be environmentally beneficial in locations with high irradiation and high environmental stress. Overall, these results can be helpful not only to optimize PV deployment strategies regarding decisions on system and site, but also to assess the optimal lifetime of a specific system in a certain location.

For answering **the third sub-research question**, a new approach to identify the earliest and the optimum repowering time has been presented (*42*). The emissions of PV electricity influenced by repowering a rooftop as well as an open-field system with fixed degradation but varying recycling scenarios have been assessed via LCA. The results show an optimum environmental repowering time of between 15 and 21 years in most cases. It was also shown that a dedicated recycling as well as a repowering of the whole available area are decisive to make repowering environmentally beneficial. In general, the repowering times are earlier for the rooftop system under study in comparison to the open field system. Here, it should be kept in mind, that the analysis considers the replacement of all system components. It could be, however, possible to keep parts of the BOS components, like mounting system or cabling, in place to further reduce the environmental impact of repowering. This analysis comes closest to answering the overall research question regarding the optimal ecological lifetime of a PV system, yet it is so far limited to two systems and a fixed location. Additional scenarios must be assessed to give recommendations on site and technology specific repowering goals. In this analysis, a linear degradation of 0.7 % and an average European irradiation level of 1391 kWh/m^2/a is used. However, findings from **the second sub-research question** (*49*) demonstrate, that the specific GHG emissions per kWh could be lower for temperate climates with low to medium irradiation (EL and EM zones), therefore repowering times could be delayed when using location specific degradation rates in this analysis.

When looking at the results of the individual studies separately, the results for different scenarios might seem minor in some cases. Firstly, the results must be seen in the context of the massive scale up of PV installations worldwide. Secondly, in combination, the findings from the above analysis can help to optimize and improve the assessment of the emissions from PV electricity production over the whole PV lifecycle. An integration of the separate findings to investigate interdependencies and interactions of the individual effects has not been part of the scope of this thesis but should be addressed in future studies. Further, the data availability for life cycle inventories of the PV module has been better than for BOS components throughout all studies, therefore, the results bear an uncertainty when projected to the whole PV system. For example, little is known on the weathering or replacement of wiring, inverters or mounting structure. Also, no useful information is available on the recycling of BOS components. Still, it is valid to focus on the PV module as the main part to curtail the question regarding the PV systems optimal ecological lifetime, since the PV module is the crucial part of the PV plant. Further, the PV module is the most energy and resource intensive part to produce and recycle and because of its central function to convert solar energy into electricity, its lifetime power degradation is decisive.

Overall, the rapid decarbonization of the energy supply is a pressing issue, while simultaneously resource scarcity as well as the vulnerability of global supply chains became obvious over the past years. These circumstances not only call for new and innovative circularity policies but also for regionalized and customized deployment strategies for renewable energies. By providing an approximation of the optimal ecological lifetime of a PV system, the findings from this thesis can help to pursue these objectives. Repowered PV modules could be a valuable source for raw materials for today’s PV industry, therefore, an assessment of the environmental performance of the existing PV plants as well as a forecast for projected PV production can help in developing smart strategies to further lower the overall emissions of PV electricity.

Lastly, this study is trying to curtail the optimal PV system lifetime from an environmental point of view by addressing different measures and effects that influence the overall emissions of PV electricity and concludes that an early replacement (before the technical EoL) is beneficial under certain circumstances. From these findings, it can be concluded that the development of easily recyclable modules with a standard system lifetime of 20-25 years should be prioritized, as other studies have also suggested for economical optimization. Systems with extremely long lifetimes of 40-50 years will not be favorable while also tying up valuable resources. However, the importance of a general rapid massive deployment of renewable energies for the decarbonization of the whole electricity grid should be stressed after all.

5. Outlook

Based on a thorough literature evaluation, a dedicated assessment of the life cycle emissions of PV electricity (in contrast to production emissions) has been identified as a research gap which has been addressed in this thesis. An approach to curtail the optimal ecological lifetime of PV systems has been introduced and demonstrated for an average European installation location for a rooftop and an open field system with a fixed degradation rate. Additionally, the influence of different EoL scenarios on the PV life cycle emissions has been quantified and the influences of varying degradation scenarios has been shown. Thus, it could be demonstrated that a PV system’s optimal ecological lifetime can be evaluated when all life cycle phases are integrated in the assessment, since degradation and EoL treatment was shown here to significantly influence the environmental footprint of PV electricity.

Future research should focus on the integration of the methodologies, definitions and results presented here. A site-specific assessment of a PV system’s life cycle emissions is possible when using the approach presented in this thesis, which can not only improve the forecast of the emissions of new PV installations but also help to identify the optimal lifetime of a specific PV plant from an environmental point of view. To minimize complexity, the classification of reference climate zones and corresponding degradation patterns could be combined with regionalized EoL scenarios and installation conditions. This can facilitate the inclusion of non-linear degradation rates and EoL scenarios in the assessment of PV system life cycle emissions, while still improving the accuracy of the overall LCA results. Developing new and improved technical EoL management strategies for PV systems is a topic that is currently widely addressed in research and industry. Therefore, the environmental assessment of these approaches is a task that should be continued. Also, a combination of the findings from the environmental assessment with an economic assessment should be addressed to identify the most sustainable lifetime. By applying these studies results, PV modules and systems can be designed in a way that improves their resource efficiency, while being in accordance with environmental and economical optimization.

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Appendix

Appendix A: Life Cycle Inventories of recycling approaches as in Herceg et al. 2020 (*48*)

Product			**Comment**
App 1 Takeback and recycling 1Kg cSi pv module (current state) (w/o incineration)	1	kg	
Avoided products			
Copper {RER}| production, primary	0,00185	kg	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	0,0864	kg	
Avoided burdens, Glass cullet, Foam glass {GLO}| production	0,63	kg	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,03886	MJ	Energy recovery from cable incineration
Electricity, medium voltage {DE}	0,019162	kWh	Energy recovery from cable incineration
Inputs			
Diesel, burned in building machine {GLO}| market for	0,0648	MJ	
Waste preparation facility {CH}| waste preparation facility construction	2E-09	p	
Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction	8E-10	p	
Electricity, 2013 mix medium voltage {DE}	1,11E-01	kWh	
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5	0,12	tkm	
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5	0,0813	tkm	
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5	0,4	tkm	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill	0,18	kg	

Waste wire plastic {CH}| treatment of, municipal incineration	0,0067	kg	
Product			**Comment**
App 2 Takeback and recycling 1Kg cSi pv module (current state) (+incineration/landfill)	1	kg	
Avoided products			
Copper {RER}| production, primary	0,00185	kg	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	0,0864	kg	
Avoided burdens, Glass cullet, Foam glass {GLO}| production	0,63	kg	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,503	MJ	Energy recovery from cable incineration
Electricity, medium voltage {DE}	0,249	kWh	Energy recovery from cable incineration
Inputs			
Diesel, burned in building machine {GLO}| market for	0,0648	MJ	
Waste preparation facility {CH}| waste preparation facility construction	2E-09	p	
Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction	8E-10	p	
Electricity, medium voltage {DE}	0,111	kWh	
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5	0,12	tkm	
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5	0,4	tkm	
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5	0,0813	tkm	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, municipal incineration	0,066	kg	6,6% = 5,1% eva + 1,5% BS PET
Waste plastic, mixture {CH}| treatment of, sanitary landfill	0,114	kg	7% contaminated glass + 4,4% cells

Waste wire plastic {CH}| treatment of, municipal incineration	0,0067	kg	

Product			**Comment**
App 3 Takeback and recycling 1Kg cSi pv module (current state+incineration BS) -fluorinated -	1	kg	
Avoided products			
Copper {RER}| production, primary	0,00185	kg	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	0,0864	kg	
Electricity, medium voltage {DE}	0,0714	kWh	Incineration backsheet
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,168	MJ	Incineration backsheet
Avoided burdens, Glass cullet, Foam glass {GLO}| production	0,63	kg	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,03886	MJ	energy recovery from cable incineration
Electricity, 2013 mix medium voltage {DE}	0,019162	kWh	energy recovery from cable incineration
Inputs			
Diesel, burned in building machine {GLO}| market for	0,0648	MJ	
Diesel {Europe without Switzerland}| market for	0,000721	kg	Incineration backsheet
Waste preparation facility {CH}| waste preparation facility construction	2E-09	p	
Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction	8E-10	p	
Electricity, medium voltage {DE}	0,111	kWh	
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5	0,12	tkm	
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5	0,4	tkm	

Electricity, medium voltage {DE}	0,00768	kWh	Incineration backsheet
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5	0,0813	tkm	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill	0,18	kg	
Waste polyvinylfluoride {CH}| treatment of, municipal incineration	0,00036	kg	Incineration backsheet
Waste wire plastic {CH}| treatment of, municipal incineration	0,0067	kg	
Product			**Comment**
App 3 Takeback and recycling 1Kg cSi pv module (current state+incineration BS) -fluorin free -	1	kg	
Avoided products			
Copper {RER}| production, primary	0,00185	kg	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	0,0864	kg	
Electricity, medium voltage {DE}	0,0829	kWh	Incineration Backsheet
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,189	MJ	Incineration Backsheet
Avoided burdens, Glass cullet, Foam glass {GLO}| production	0,63	kg	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,03886	MJ	Energy recovery from cable incineration
Electricity, 2013 mix medium voltage {DE}	0,019162	kWh	Energy recovery from cable incineration
Inputs			
Diesel, burned in building machine {GLO}| market for	0,0648	MJ	
Diesel {Europe without Switzerland}| market for	0,000451	kg	Incineration Backsheet
Waste preparation facility {CH}| waste preparation facility construction	2E-09	p	

Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction	8E-10	p	
Electricity, medium voltage {DE}	0,111	kWh	Incineration Backsheet
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5	0,12	tkm	
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5	0,4	tkm	
Electricity, 2013 mix medium voltage {DE}	0,00614	kWh	
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5	0,0813	tkm	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill	0,18	kg	
Waste polyethylene terephtalate {CH}| treatment of, municipal incineration with fly ash extraction	0,000029	kg	Incineration Backsheet
Waste wire plastic {CH}| treatment of, municipal incineration	0,0067	kg	

Product			**Comment**
App 4 Takeback and recycling 1Kg cSi pv module (current state+pyrolysis BS) -fluorinated -	1	kg	
Avoided products			
Copper {RER}| production, primary	0,00185	kg	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production | APOS, U	0,0864	kg	
Heat, district or industrial, natural gas {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, U	0,00284	MJ	Pyrolysis (Gas)
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | APOS, U	0,141429	MJ	Pyrolysis (Oil)
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | APOS, U	0,31071	MJ	pyrolysis (char)
Avoided burdens, Glass cullet, Foam glass {GLO}| production | APOS, U	0,63	kg	

Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | APOS, U	0,03886	MJ	Energy recovery from cable incineration
Electricity, 2013 mix medium voltage {DE}| APOS, U	0,019162	kWh	Energy recovery from cable incineration
Inputs			
Diesel, burned in building machine {GLO}| market for | APOS, U	0,0648	MJ	
Diesel {Europe without Switzerland}| market for | APOS, U	0,000721	kg	
Lime, hydrated, packed {CH}| production | APOS, U	0,022464	kg	Pyrolysis
Waste preparation facility {CH}| waste preparation facility construction | APOS, U	2E-09	p	Pyrolysis
Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction | APOS, U	8E-10	p	
Electricity, medium voltage {DE}| APOS, U	0,111	kWh	
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, U	0,12	tkm	
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	0,4	tkm	
Electricity, medium voltage {DE}| APOS, U	0,00154	kWh	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | APOS, U	0,0126	MJ	
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | APOS, U	0,0813	tkm	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill | APOS, U	0,18	kg	
Waste wire plastic {CH}| treatment of, municipal incineration | APOS, U	0,0067	kg	
Emissions to air			
Nitrogen, atmospheric	0,000336	kg	Pyrolysis
Hydrogen fluoride	0,000012	kg	Pyrolysis

Final waste flows			
Calcium fluoride waste	0,023679	kg	Pyrolysis

Product			**Comment**
App 4 Takeback and recycling 1Kg cSi pv module (current state+pyrolysis BS) -fluorinated free -	1	kg	
Avoided products			
Copper {RER}| production, primary	0,00185	kg	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	0,0864	kg	
Heat, district or industrial, natural gas {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical	0,252	MJ	Pyrolysis
Heat, district or industrial, other than natural gas {CH}| heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction	0,312	MJ	Pyrolysis
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,102857	MJ	Pyrolysis
Avoided burdens, Glass cullet, Foam glass {GLO}| production	0,63	kg	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,03886	MJ	Energy recovery from cable incineration
Electricity, 2013 mix medium voltage {DE}	0,019162	kWh	Energy recovery from cable incineration
Inputs			
Diesel, burned in building machine {GLO}| market for	0,0648	MJ	
Diesel {Europe without Switzerland}| market for	0,000326	kg	Pyrolysis
Waste preparation facility {CH}| waste preparation facility construction	2E-09	p	
Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction	8E-10	p	
Electricity, medium voltage {DE}	0,111	kWh	
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5	0,12	tkm	

Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5	0,4	tkm	
Electricity, 2013 mix medium voltage {DE}	0,0123	kWh	pyrolysis
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,0101	MJ	pyrolysis
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5	0,0813	tkm	
Emissions to air			
Nitrogen, atmospheric	0,00269	kg	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill	0,18	kg	
Waste wire plastic {CH}| treatment of, municipal incineration	0,0067	kg	

Product			**Comment**
App 5 Takeback and recycling 1Kg cSi pv module (innovative - incineration) Packaging glass	1	kg	
Avoided products			
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,50284	MJ	
Electricity, 2013 mix medium voltage {DE}	0,24884	MJ	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	0,0877	kg	
Copper {RER}| production, primary	0,00245	kg	
Silicon, metallurgical grade {GLO}| market for	0,03468	kg	
Silver {GLO}| market for	0,000385	kg	
Avoided burdens, Glass cullet, packaging glass, white {GLO}| packaging glass production, white	0,686	kg	
Inputs			
Diesel, burned in building machine {GLO}| market for	0,04104	MJ	1,14 L forklift, 36 MJ/L
Water, completely softened {RER}| water production, completely softened	0,30971	kg	

Nitric acid, without water, in 50% solution state {RER}| nitric acid production, product in 50% solution state	0,00708	kg	
Lime, hydrated, loose weight {CH}| production	0,0365	kg	Ca(OH)2
Waste preparation facility {CH}| waste preparation facility construction	2E-09	p	
Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction	8E-10	p	
Electricity, 2013 mix medium voltage {DE}	0,114	kWh	
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5	0,142	tkm	
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5	0,4	tkm	
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5	0,141	tkm	
Emissions to air			
Nitrogen oxides	0,002	kg	
Waste to treatment			
Waste glass {CH}| treatment of, inert material landfill	0,014	kg	
Used cable {GLO}| treatment of	0,01	kg	
Waste plastic, mixture {CH}| treatment of, municipal incineration	0,051	kg	
Waste polyvinylfluoride {CH}| treatment of, municipal incineration	0,015	kg	
Waste wire plastic {CH}| treatment of, municipal incineration	0,0067	kg	
Average incineration residue {CH}| treatment of, residual material landfill	0,002	kg	
Limestone residue {CH}| treatment of, inert material landfill	0,30613	kg	
Blast furnace sludge {CH}| treatment of blast furnace sludge, residual material landfill	0,05025	kg	

Product			**Comment**
App 6 Takeback and recycling 1Kg cSi pv module (innovative - pyrolysis) Packaging glass	1	kg	
Avoided products			

Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	0,315	MJ	different energy recovery from pyrolysis + heat from cable incineration
Electricity, medium voltage {DE}	0,01916	MJ	no electricity production from pyrolysis, only from cable incineration
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	0,0877	kg	
Copper {RER}| production, primary	0,00245	kg	
Silicon, metallurgical grade {GLO}| market for | APOS, U	0,03468	kg	
Silver {GLO}| market for	0,000385	kg	
Avoided burdens, Glass cullet, packaging glass, white {GLO}| packaging glass production, white	0,686	kg	
Inputs			
Diesel, burned in building machine {GLO}| market for	0,04104	MJ	1,14 L forklift, 36 MJ/L
Water, completely softened {RER}| water production, completely softened	0,30971	kg	
Nitric acid, without water, in 50% solution state {RER}| nitric acid production, product in 50% solution state	0,00708	kg	
Lime, hydrated, loose weight {CH}| production	0,0365	kg	Ca(OH)2
Nitrogen, liquid {RER}| market for	0,001032	kg	For pyrolysis
Waste preparation facility {CH}| waste preparation facility construction	2E-09	p	
Mechanical treatment facility, waste electric and electronic equipment {GLO}| construction	8E-10	p	
Electricity, medium voltage {DE}	0,127	kWh	includes electricity for pyrolysis
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5	0,142	tkm	evaluation transport for incineration
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5	0,4	tkm	

Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5	0,141	tkm
Emissions to air		
Nitrogen oxides	0,002	kg
Waste to treatment		
Waste glass {CH}| treatment of, inert material landfill	0,014	kg
Used cable {GLO}| treatment of	0,01	kg
Waste wire plastic {CH}| treatment of, municipal incineration	0,0067	kg
Limestone residue {CH}| treatment of, inert material landfill	0,30613	kg
Blast furnace sludge {CH}| treatment of blast furnace sludge, residual material landfill	0,05025	kg

Appendix B: Life Cycle Inventories for repowered PV Systems as in Herceg et al. 2022b (*42*)

Modelled foreground processes as published in Herceg et al. 2022b (supporting information)

B1: Production

Product			**Comment**
[2004] 00_1_Photovoltaic plant, 3kWp, Single-Si, slanted roof installation | production {RER}	1.00E+00	p	
Inputs			
[2004] 01_0_Photovoltaic panel, Single-Si wafer | production {RER}	2.03E+01	m^2	
[2004] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | production {RER}	2.03E+01	m^2	
[2004] 03_1_Electric Installation, for 3kWp Photovoltaic plant, slanted roof installation | production {RER}	1.00E+00	p	
04_Inverter, 2.5kW | production {RER}	2.40E+00	p	The lifetime of the inverter is assumed with 15 years.
Electricity, low voltage {DE}| market for	2.30E-01	kWh	
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for	4.97E+02	tkm	1000 km

Product			**Comment**
[2004] 00_2_Photovoltaic plant, 1.07MWp, Single-Si, on open ground | production {RER}	1.00E+00	p	
Inputs			
[2004] 01_0_Photovoltaic panel, Single-Si wafer | production {RER}	7.23E+03	m^2	
[2004] 02_2_Mounting System, for Photovoltaic plant, on open ground | production {RER}	7.23E+03	m^2	
[2004] 03_2_Electric Installation, for 570kWp Photovoltaic plant, on open ground | production {RER}	1.88E+00	p	
04_Inverter, 500kW | production {RER}	5.87E+00	p	
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for	2.19E+05	tkm	1000 km
Diesel, burned in building machine {GLO}| market for	1.44E+04	MJ	
Electricity, low voltage {DE}| market for	6.77E+01	kWh	

Products			**Comment**

[2020] 00_1_Photovoltaic plant, 3kWp, Single-Si, slanted roof installation | production {RER}	1.00E+00	p	
Inputs			
[2020] 01_0_Glass-Backsheet Photovoltaic panel, Single-Si wafer | production {RER}	1.52E+01	m^2	
[2020] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | production {RER}	1.52E+01	m^2	
[2020] 03_1_Electric Installation, for 3kWp Photovoltaic plant, slanted roof installation | production {RER}	8.00E-01	p	Calculated value. Assumption: 20% efficiency increase.
04_Inverter, 2.5kW | production {RER}	1.20E+00	p	Calculated value. Assumption: 50% weight reduction. The lifetime of the inverter is assumed with 15 years.
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for	3.19E+02	tkm	1000 km
Electricity, low voltage {DE}| market for	2.30E-01	kWh	(*91*)

Products			**Comment**
[2020] 00_2_Photovoltaic plant, 4 kWp, Single-Si, slanted roof installation | production {RER}	1.00E+00	p	
Inputs			
[2020] 01_0_Glass-Backsheet Photovoltaic panel, Single-Si wafer | production {RER}	2.03E+01	m^2	
[2020] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | production {RER}	2.03E+01	m^2	
[2020] 03_1_Electric Installation, for 3kWp Photovoltaic plant, slanted roof installation | production {RER}	1.01E+00	p	Extrapolated from 3 kWp System 2020.
04_Inverter, 2.5kW | production {RER}	1.52E+00	p	Extrapolated from 3 kWp System 2020.
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for	4.30E+02	tkm	1000 km
Electricity, low voltage {DE}| market for	2.91E-01	kWh	Extrapolated from 3 kWp System 2020.

Products			**Comment**

[2020] 00_3_Photovoltaic plant, 1.07MWp, Single-Si, on open ground | production {RER}	1.00E+00	p	
Inputs			
[2020] 01_0_Glass-Backsheet Photovoltaic panel, Single-Si wafer | production {RER}	5.41E+03	m^2	
[2020] 02_2_Mounting System, for Photovoltaic plant, on open ground | production {RER}	5.41E+03	m^2	
[2020] 03_2_Electric Installation, for 570kWp Photovoltaic plant, on open ground | production {RER}	1.50E+00	p	Calculated value. Assumption: 20% efficiency increase.
04_Inverter, 500kW | production {RER}	2.93E+00	p	Calculated value. Assumption: 50% weight reduction. The lifetime of the inverter is assumed with 15 years.
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for	8.28E+04	tkm	1000 km (*92*)
Diesel, burned in building machine {GLO}| market for	1.44E+04	MJ	
Electricity, low voltage {DE}| market for	6.77E+01	kWh	

Products			**Comment**
[2020] 00_4_Photovoltaic plant, 4.4MWp, Single-Si, on open ground | production {RER}	1.00E+00	p	
Inputs			
[2020] 01_0_Glass-Backsheet Photovoltaic panel, Single-Si wafer | production {RER}	2.22E+04	m^2	Calculated value.
[2020] 02_2_Mounting System, for Photovoltaic plant, on open ground | production {RER}	2.22E+04	m^2	Calculated value.
[2020] 03_2_Electric Installation, for 570kWp Photovoltaic plant, on open ground | production {RER}	6.16E+00	p	Extrapolated from 1.07 MWp System 2020.
04_Inverter, 500kW | production {RER}	1.20E+01	p	Extrapolated from 1.07 MWp System 2020.
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for	3.39E+05	tkm	1000 km
Diesel, burned in building machine {GLO}| market for	5.91E+04	MJ	Extrapolated from 1 MWp System 2020.
Electricity, low voltage {DE}| market for	2.77E+02	kWh	Extrapolated from 1 MWp System 2020.

Products			**Comment**
[2004] 02_2_Mounting System, for Photovoltaic plant, on open ground | production {RER}	1.00E+00	m^2	Dataset from (*93*). Transport moved to system process.
Resources			
Transformation, from grassland/pasture/meadow	6.07E+00	m^2	Calculated value. Entire area requirement.
Transformation, to industrial area, built up	2.00E+00	m^2	Calculated value. 1/3 of total area demand. (Ratio consistent with original dataset.)
Transformation, to industrial area, vegetation	4.07E+00	m^2	Calculated value. 2/3 of total area demand. (Ratio consistent with original dataset.)
Inputs			
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for	3.98E+00	kg	
Concrete, normal {CH}	5.37E-04	m^3	
Corrugated board box {RER}| production	8.64E-02	kg	
Polyethylene, high density, granulate {RER}| production	9.09E-04	kg	
Polystyrene, high impact {RER}| production	4.55E-03	kg	
Reinforcing steel {RER}| production	7.21E+00	kg	
Section bar extrusion, aluminium {RER}| processing	3.98E+00	kg	
Section bar rolling, steel {RER}| processing	6.15E+00	kg	
Steel, chromium steel 18/8 {RER}| steel production	2.47E-01	kg	
Wire drawing, steel {RER}| processing	1.06E+00	kg	
Zinc coat, coils {RER}| zinc coating, coils	1.09E-01	m^2	
Zinc coat, pieces {RER}| zinc coating, pieces	1.56E-01	m^2	
Waste to treatment			
Waste paperboard {CH}| treatment of, municipal incineration	8.64E-02	kg	Disposal of packaging.

B2:

Products			**Comment**
Use phase of PV module, Cleaning per m^2 and year	1.00E+00	p	Impacts per m^2 and year. Rooftop Plant.

Inputs			
Tap water {RER}| market group for	6.66E-01	kg	
Emissions to air			
Water/m^3	3.34E-04	m^3	
Waste to treatment			
Wastewater, from residence {CH}| market for wastewater, from residence	3.34E-04	m^3	

Products			**Comment**
[2004] use phase, roof top plant, 3 kWp, cleaning 20 m^2 per year {RER}	1.00E+00	p	Impacts per year.
Inputs			
Use phase of PV module, Cleaning per m^2 and year	2.03E+01	p	Module Area.

Products			**Comment**
[2020] use phase, roof top plant, 3 kWp, cleaning 15 m^2 per year {RER}	1.00E+00	p	Impacts per year.
Inputs			
Use phase of PV module, Cleaning per m^2 and year	1,52E+01	p	Module Area.

Products			**Comment**
[2020] use phase, roof top plant, 4 kWp, cleaning 20 m^2 per year {RER}	1.00E+00	p	Impacts per year.
Inputs			
Use phase of PV module, Cleaning per m^2 and year	2.03E+01	p	Module Area.

Products			**Comment**
Use phase of PV module, Cleaning per m^2 and year {RER}	1.00E+00	p	Impacts per m^2 and year. open-field plant.
Inputs			
Tap water {RER}| market group for	3.35E-03	kg	
Emissions to air			
Water/m^3	5.02E-07	m^3	
Waste to treatment			
Wastewater, from residence {CH}| market for wastewater, from residence	3.35E-06	m^3	

Products			**Comment**
[2004] use phase, open-field plant, 1.07 MWp, cleaning 7200m^2 per year {RER}	1.00E+00	p	Impacts per year.
Inputs			

Occupation, industrial area, vegetation	2.92E+04	m^2a	Calculated value. 2/3 of total area demand.
Occupation, industrial area, built up	1.46E+04	m^2a	Calculated value. 1/3 of total area demand.
Use phase of PV module, Cleaning per m^2 and year {RER}	7.23E+03	p	Module Area.

Products			**Comment**
[2020] use phase, open-field plant, 1.07 MWp, cleaning 5500 m^2 per year {RER}	1.00E+00	p	Impacts per year.
Inputs			
Occupation, industrial area, vegetation	5.29E+03	m^2a	Calculated value. Difference between total area demand and module area.
Occupation, industrial area, built up	5.41E+03	m^2a	Calculated value. Module Area.
Use phase of PV module, Cleaning per m^2 and year {RER}	5.41E+03	p	Module Area.

Products			**Comment**
[2020] use phase, open-field plant, 4.4 MWp, cleaning 22500m^2 per year {RER}	1.00E+00	p	Impacts per year.
Inputs			
Occupation, industrial area, built up	2.22E+04	m^2a	Module Area.
Occupation, industrial area, vegetation	2.17E+04	m^2a	Calculated value. Difference between total area demand and module area.
Use phase of PV module, Cleaning per m^2 and year {RER}	2.22E+04	p	Module Area.

B3: End-of-life

Products			**Comment**
[2004] 00_1_Photovoltaic plant, 3 kWp, mono-Si, slanted roof installation | EoL Landfill {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2004] 01_Photovoltaic Panel, Single-Si wafer | EoL Landfill {RER}	2.03E+01	m^2	Module Area.
[2004] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL Landfill {RER}	2.03E+01	m^2	Module Area.

[2004] 03_1_Electric Installation, for 3 kWp Photovoltaic plant, slanted roof installation | EoL Landfill {RER}	1.00E+00	p	
04_Inverter, 2.5kW | EoL Landfill {RER}	2.40E+00	p	
Electricity, low voltage {DE}| market for	2.30E-01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 7.5-16 metric ton, euro5 {RER}| market for	9.94E+01	tkm	200 km
Products			Comment
[2004] 00_2_Photovoltaic plant, 1.07 MWp, mono-Si, on open ground | EoL Landfill {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2004] 01_Photovoltaic Panel, Single-Si wafer | EoL Landfill {RER}	7.23E+03	m^2	Module Area.
[2004] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL Landfill {RER}	7.23E+03	m^2	Module Area.
[2004] 03_2_Electric Installation, for 570 kWp Photovoltaic plant, on open ground | EoL Landfill {RER}	1.88E+00	p	
04_Inverter, 500kW | EoL Landfill {RER}	5.87E+00	p	
Diesel, burned in building machine {GLO}| market for	1.44E+04	MJ	Assumption: Energy demand for disassembly is the same as for assembly.
Electricity, low voltage {DE}| market for	6.77E+01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 7.5-16 metric ton, euro5 {RER}| market for	4.37E+04	tkm	200 km
Products			**Comment**
[2004] 01_Photovoltaic Panel, Single-Si wafer | EoL Landfill {RER}	1.00E+00	m^2	
Waste to treatment			
Hazardous waste, for underground deposit {DE}| treatment of	4.07E+00	kg	Calculated according to bill of materials. PV Sandwich.
Waste aluminum {CH}| treatment of, sanitary landfill	3.04E+00	kg	Calculated according to bill of materials. Aluminum Frame.
Waste glass {GLO}| treatment of, sanitary landfill	9.12E+00	kg	Calculated according to bill of materials. Solar Glass.
Products			**Comment**
[2004] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL Landfill {RER}	1.00E+00	m^2	
Waste to treatment			

Waste aluminium {CH}| treatment of, sanitary landfill	2.83E+00	kg	Calculated according to bill of materials.
Scrap steel {Europe without Switzerland}| treatment of, inert material landfill	1.50E+00	kg	Calculated according to bill of materials.
Waste plastic, mixture {CH}| treatment of, sanitary landfill	1.40E-03	kg	Calculated according to bill of materials.
Waste polystyrene {CH}| treatment of, sanitary landfill	7.01E-03	kg	Calculated according to bill of materials.
Products			**Comment**
[2004] 03_1_Electric Installation, for 3 kWp Photovoltaic plant, slanted roof installation | EoL Landfill {RER}	1.00E+00	p	
Waste to treatment			
Scrap copper {Europe without Switzerland}| market for scrap copper	2.00E-02	kg	Calculated according to bill of materials. Proxy for brass treatment. [Landfill process not available.]
Scrap steel {Europe without Switzerland}| treatment of, inert material landfill	8.60E-01	kg	
Waste electric wiring {CH}| treatment of, collection for final disposal	3.25E+01	kg	Calculated according to bill of materials. All materials used in and for wires are summed up in this value.
Waste polyethylene/polypropylene product {CH}| treatment of, collection for final disposal	2.02E-01	kg	Calculated according to bill of materials. Proxy for the treatment of epoxy and polycarbonate.
Waste polyvinylchloride {CH}| treatment of, sanitary landfill	2.13E+00	kg	Calculated according to bill of materials.
Products			**Comment**
04_Inverter, 2.5kW | EoL Landfill {RER}	1.00E+00	p	
Waste to treatment			
Used printed wiring boards {GLO}| market for	1.56E+00	kg	
Waste paperboard {CH}| treatment of, inert material landfill	2.29E+00	kg	
Waste polyethylene {CH}| treatment of, sanitary landfill	5.50E-02	kg	
Waste polystyrene {CH}| treatment of, sanitary landfill	2.84E-01	kg	
Products			**Comment**
[2004] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL Landfill {RER}	1.00E+00	m^2	
Waste to treatment			

Waste aluminum {CH}| treatment of, sanitary landfill	3.98E+00	kg	Calculated according to bill of materials.
Scrap steel {Europe without Switzerland}| treatment of, inert material landfill	6.40E+00	kg	Calculated according to bill of materials.
Waste reinforced concrete {Europe without Switzerland}| treatment of, collection for final disposal	8.45E+00	kg	Calculated according to bill of materials.
Waste polystyrene {CH}| treatment of, sanitary landfill	4.55E-03	kg	Calculated according to bill of materials.
Waste plastic, mixture {CH}| treatment of, sanitary landfill	9.09E-04	kg	Calculated according to bill of materials.
Products			**Comment**
[2004] 03_2_Electric Installation, for 570 kWp Photovoltaic plant, on open ground | EoL Landfill {RER}	1.00E+00	p	
Waste to treatment			
Scrap copper {Europe without Switzerland}| market for scrap copper	1.16E+00	kg	Calculated according to bill of materials. [Landfill process not available.]
Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill	4.73E+01	kg	Calculated according to bill of materials.
Waste electric wiring {CH}| treatment of, collection for final disposal	1.24E+03	kg	Calculated according to bill of materials.
Waste polyethylene/polypropylene product {CH}| treatment of, collection for final disposal	2.32E-01	kg	Calculated according to bill of materials.
Waste polystyrene {CH}| treatment of, sanitary landfill	3.82E+01	kg	Calculated according to bill of materials.
Products			**Comment**
04_Inverter, 500kW | EoL Landfill {RER}	1.00E+00	p	
Waste to treatment			
Used printed wiring boards {GLO}| market for	4.75E+01	kg	
Waste mineral oil {Europe without Switzerland}| market for	8.56E+02	kg	
Waste paperboard {CH}| treatment of, inert material landfill	1.32E+01	kg	
Waste plastic, mixture {CH}| treatment of, sanitary landfill	2.23E+02	kg	
Waste polyethylene {CH}| treatment of, sanitary landfill	1.55E+00	kg	
Waste polystyrene {CH}| treatment of, sanitary landfill	1.55E+00	kg	
Products			**Comment**

[2004] 00_1_Photovoltaic plant, 3kWp, Single-Si, slanted roof installation | EoL state-of-the-art {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2004] 01_0_Photovoltaic panel, Single-Si wafer | EoL state-of-the-art {RER}	2.03E+01	m^2	Module Area.
[2004] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	2.03E+01	m^2	Module Area.
[2004] 03_1_Electric Installation, for 3kWp Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	1.00E+00	p	
04_Inverter, 2.5kW | EoL state-of-the-art {RER}	2.40E+00	p	
Electricity, low voltage {DE}| market for	2.30E-01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	1.99E+02	tkm	400 km
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	4.97E+01	tkm	100 km to collection point
Products			**Comment**
[2004] 00_2_Photovoltaic plant, 1.07MWp, Single-Si, on open ground | EoL state-of-the-art {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2004] 01_0_Photovoltaic panel, Single-Si wafer | EoL state-of-the-art {RER}	7.23E+03	m^2	Module Area.
[2004] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL state-of-the-art {RER}	7.23E+03	m^2	Module Area.
03_2_Electric Installation, for 570kWp Photovoltaic plant, on open ground | EoL state-of-the-art {RER}	1.88E+00	p	
04_Inverter, 500kW | EoL state-of-the-art {RER}	5.87E+00	p	
Diesel, burned in building machine {GLO}| market for	1.44E+04	MJ	Assumption: Energy demand for disassembly is the same as for assembly.
Electricity, low voltage {DE}| market for	6.77E+01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	8.75E+04	tkm	400 km
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	2.19E+04	tkm	100 km to collection point

Products			**Comment**
[2004] 01_0_Photovoltaic panel, Single-Si wafer | EoL state-of-the-art {RER}	1.00E+00	m^2	
Inputs			
[2004] 01_1_Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Avoided Burden {RER}	1.62E+01	kg	
Products			**Comment**
[2004] 01_1_Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Avoided Burden {RER}	1.00E+00	kg	All data adjusted to bill of materials of 2004 panel.
Avoided products			
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	6.83E-01	MJ	
Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, heavy fuel oil, at industrial furnace 1MW	4.42E-01	MJ	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	6.22E-02	kg	
Copper {GLO}| market for	4.22E-02	kg	
Silica sand {DE}| production	2.88E-01	kg	
Sodium bicarbonate {RER}| soda production, solvay process	1.14E-01	kg	
Limestone, crushed, for mill {CH}| market for	1.99E-01	kg	
Inputs			
Copper {GLO}| treatment of used cable	4.22E-02	kg	
Aluminium, cast alloy {RER}| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner	6.22E-02	kg	
[2020] 01_2_Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Takeback and Recycling {RER}	1.00E+00	kg	
Emissions to air			
Carbon dioxide, fossil	-1.04E-01	kg	
Products			**Comment**
[2004] 01_2_Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Takeback and Recycling {RER}	1.00E+00	kg	All adjusted to bill of materials of 2004 panel.
Inputs			
Electricity, medium voltage {ENTSO-E}| market group for	1.11E-01	kWh	

Diesel, burned in building machine {GLO}| processing	6.48E-02	MJ	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, municipal incineration	1.49E-01	kg	
Waste plastic, mixture {CH}| treatment of, sanitary landfill	2.60E-02	kg	
Products			**Comment**
[2004] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	1.00E+00	m^2	
Avoided products			
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	3.43E-01	kg	Calculated value. Recycling rate: 12.1% (*94*).
Steel, low-alloyed, hot rolled {RER}| production	1.48E+00	kg	Calculated value. Recycling rate: 99%
Electricity, medium voltage {ENTSO-E}| market group for	2.05E-02	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	4.17E-02	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, municipal incineration	1.77E-04	kg	
Waste polystyrene {CH}| treatment of, municipal incineration	7.01E-03	kg	
Scrap aluminium {Europe without Switzerland}| market for scrap aluminium	2.83E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Scrap steel {Europe without Switzerland}| market for scrap steel	1.50E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Products			**Comment**
[2004] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL state-of-the-art {RER}	1.00E+00	m^2	
Avoided products			
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	4.82E-01	kg	Calculated value. Recycling rate: 12.1%
Steel, low-alloyed, hot rolled {RER}| production	2.45E-01	kg	Calculated value. Recycling rate: 99%
Electricity, medium voltage {ENTSO-E}| market group for	1.56E-02	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg

Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	3.17E-02	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, municipal incineration	9.09E-04	kg	
Waste polystyrene {CH}| treatment of, municipal incineration	4.55E-03	kg	
Waste reinforced concrete {CH}| treatment of, collection for final disposal	8.45E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Scrap steel {Europe without Switzerland}| market for scrap steel	2.47E-01	kg	Added to harmonize datasets. Calculated according to bill of materials.
Scrap aluminium {Europe without Switzerland}| market for scrap aluminium	3.98E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Products			**Comment**
[2004] 03_1_Electric Installation, for 3kWp Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	1.00E+00	p	
Avoided products			
Electricity, medium voltage {ENTSO-E}| market group for	5.78E+01	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	1.17E+02	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Copper {RER}| production, primary	6.47E-01	kg	Calculated value. Recycling rate: 4.4%
Steel, low-alloyed, hot rolled {RER}| production	8.51E-01	kg	Calculated value. Recycling rate: 99%
Waste to treatment			
Waste plastic, industrial electronics {CH}| treatment of, municipal incineration	2.02E+01	kg	
Waste electric wiring {CH}| treatment of, collection for final disposal	6.00E-02	kg	
Scrap copper {Europe without Switzerland}| market for scrap copper	1.47E+01	kg	Added to harmonize datasets. Calculated according to bill of materials.
Scrap steel {Europe without Switzerland}| market for scrap steel	8.60E-01	kg	Added to harmonize datasets. Calculated according to bill of materials.
Products			**Comment**

03_2_Electric Installation, for 570kWp Photovoltaic plant, on open ground | EoL state-of-the-art {RER}	1.00E+00	p	
Avoided products			
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	2.23E+02	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Electricity, medium voltage {ENTSO-E}| market group for	1.10E+02	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Steel, low-alloyed, hot rolled {RER}| production	4.68E+01	kg	Calculated value. Recycling rate: 99%
Copper {RER}| production, primary	5.10E-02	kg	Calculated value. Recycling rate: 4.4%
Waste to treatment			
Scrap copper {Europe without Switzerland}| market for scrap copper	1.16E+00	kg	
Scrap steel {Europe without Switzerland}| market for scrap steel	4.73E+01	kg	
Waste electric wiring {CH}| treatment of, collection for final disposal	1.24E+03	kg	
Waste plastic, mixture {CH}| treatment of, municipal incineration	2.32E-01	kg	
Waste polyvinylchloride {CH}| treatment of, municipal incineration	3.82E+01	kg	
Products			**Comment**
04_Inverter, 2.5kW | EoL state-of-the-art {RER}	1.00E+00	p	
Avoided products			
Electricity, medium voltage {ENTSO-E}| market group for	9.70E-01	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	1.97E+00	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Waste to treatment			
Used printed wiring boards {GLO}| market for	1.56E+00	kg	
Waste paperboard, unsorted {GLO}| market for waste paperboard, unsorted	2.29E+00	kg	
Waste polyethylene {CH}| treatment of, municipal incineration	5.50E-02	kg	
Waste polystyrene {CH}| treatment of, municipal incineration	2.84E-01	kg	

Products			
04_Inverter, 500kW | EoL state-of-the-art {RER}	1.00E+00	p	
Avoided products			
Electricity, medium voltage {ENTSO-E}| market group for	6.48E+02	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	1.31E+03	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Waste to treatment			
Used printed wiring boards {GLO}| market for	4.75E+01	kg	
Waste mineral oil {Europe without Switzerland}| market for waste mineral oil	8.56E+02	kg	
Waste paperboard, unsorted {GLO}| market for waste paperboard, unsorted	1.32E+01	kg	
Waste plastic, industrial electronics {CH}| treatment of, municipal incineration	2.23E+02	kg	
Waste polyethylene {CH}| treatment of, municipal incineration	1.55E+00	kg	
Waste polystyrene {CH}| treatment of, municipal incineration	1.55E+00	kg	

Products			Comment
[2020] 00_1_Photovoltaic plant, 3kWp, Single-Si, slanted roof installation | EoL state-of-the-art {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2020] 01_0_Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL state-of-the-art {RER}	1.52E+01	m^2	Module Area.
[2020] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	1.52E+01	m^2	Module Area.
[2020] 03_1_Electric Installation, for 3kWp Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	8.00E-01	p	
04_Inverter, 2.5kW | EoL state-of-the-art {RER}	1.20E+00	p	
Electricity, low voltage {DE}| market for	2.30E-01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	1.28E+02	tkm	400 km to recycler

Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	3.19E+01	tkm	100 km to recycler
Products			**Comment**
[2020] 00_3_Photovoltaic plant, 1.07MWp, Single-Si, on open ground | EoL state-of-the-art {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2020] 01_0_Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL state-of-the-art {RER}	5.41E+03	m^2	Module Area.
[2020] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL state-of-the-art {RER}	5.41E+03	m^2	Module Area.
03_2_Electric Installation, for 570kWp Photovoltaic plant, on open ground | EoL state-of-the-art {RER}	1.50E+00	p	
04_Inverter, 500kW | EoL state-of-the-art {RER}	2.93E+00	p	
Diesel, burned in building machine {GLO}| market for	1.44E+04	MJ	Assumption: Energy demand for disassembly is the same as for assembly.
Electricity, low voltage {DE}| market for	6.77E+01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	3.31E+04	tkm	400 km to recycler
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	8.28E+03	tkm	100km to collection point
Products			**Comment**
[2020] 01_0_Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL state-of-the-art {RER}	1.00E+00	m^2	
Inputs			
[2020] 01_1_Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Avoided Burden {RER}	1.21E+01	kg	
Products			**Comment**
[2020] 01_1_Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Avoided Burden {RER}	1.00E+00	kg	All data from and adjusted to bill of materials of 2020 panel.
Avoided products			
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	8.05E-01	MJ	

Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, heavy fuel oil, at industrial furnace 1MW	5.21E-01	MJ	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	4.05E-02	kg	
Copper {GLO}| market for	3.89E-02	kg	
Silica sand {DE}| production	3.40E-01	kg	
Sodium bicarbonate {RER}| soda production, solvay process	1.34E-01	kg	
Limestone, crushed, for mill {CH}| market for	2.35E-01	kg	
Inputs			
Copper {GLO}| treatment of used cable	3.89E-02	kg	
Aluminium, cast alloy {RER}| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner	4.05E-02	kg	
[2020] 01_2_Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Takeback and Recycling {RER}	1.00E+00	kg	
Emissions to air			
Carbon dioxide, fossil	-1.24E-01	kg	
Products			**Comment**
[2020] 01_2_Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL state-of-the-art: Takeback and Recycling {RER}	1.00E+00	kg	All data from (*94*) and adjusted to bill of materials of 2020 panel.
Inputs			
Electricity, medium voltage {ENTSO-E}| market group for	1.11E-01	kWh	
Diesel, burned in building machine {GLO}| processing	6.48E-02	MJ	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, municipal incineration	1.60E-01	kg	
Waste plastic, mixture {CH}| treatment of, sanitary landfill	2.79E-02	kg	
Products			**Comment**
[2020] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	1.00E+00	m^2	
Avoided products			
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	3.42E-01	kg	Calculated value. Recycling rate: 12.1%
Electricity, medium voltage {ENTSO-E}| market group for	2.02E-02	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg

Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	4.09E-02	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Steel, low-alloyed, hot rolled {RER}| production	1.49E+00	kg	Calculated value. Recycling rate: 99%
Waste to treatment			
Scrap aluminium {Europe without Switzerland}| market for scrap aluminium	2.83E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Scrap steel {Europe without Switzerland}| market for scrap steel	1.50E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Waste plastic, mixture {CH}| treatment of, municipal incineration	4.56E-05	kg	
Waste polystyrene {CH}| treatment of, municipal incineration	7.01E-03	kg	
Products			**Comment**
[2020] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL state-of-the-art {RER}	1.00E+00	m^2	
Avoided products			
Electricity, medium voltage {ENTSO-E}| market group for	1.83E-01	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	3.71E-01	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Steel, low-alloyed, hot rolled {RER}| production	2.48E+00	kg	Calculated value. Recycling rate: 99%
Waste to treatment			
Scrap steel {Europe without Switzerland}| market for scrap steel	2.51E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Waste concrete {CH}| treatment of, inert material landfill	4.87E+01	kg	
Waste fibreboard {CH}| treatment of, collection for final disposal	6.79E-01	kg	
Waste glass pane in burnable frame {CH}| treatment of, sorting plant	7.21E-03	kg	
Waste mineral wool {Europe without Switzerland}| treatment of waste mineral wool, sorting plant	1.92E-02	kg	
Waste plastic, mixture {CH}| treatment of, municipal incineration	5.28E-02	kg	

Waste polyurethane foam {CH}| treatment of, collection for final disposal	9.94E-02	kg	
Waste polyvinylchloride {CH}| treatment of, municipal incineration	1.11E-02	kg	
Waste reinforcement steel {CH}| treatment of, sorting plant	3.95E+01	kg	
Products			**Comment**
[2020] 03_1_Electric Installation, for 3kWp Photovoltaic plant, slanted roof installation | EoL state-of-the-art {RER}	1.00E+00	p	
Avoided products			
Copper {RER}| production, primary	7.49E-04	kg	Calculated value. Recycling rate: 4.4%
Electricity, medium voltage {ENTSO-E}| market group for	5.68E+00	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	1.15E+01	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Steel, low-alloyed, hot rolled {RER}| production	7.58E-01	kg	Calculated value. Recycling rate: 99%
Waste to treatment			
Scrap copper {Europe without Switzerland}| market for	1.70E-02	kg	
Scrap steel {Europe without Switzerland}| market for	7.66E-01	kg	
Waste electric wiring {CH}| treatment of, collection for final disposal	2.50E+01	kg	
Waste plastic, mixture {CH}| treatment of, municipal incineration	1.98E+00	kg	
Products			**Comment**
[2020] 00_1_Photovoltaic plant, 3kWp, mono-Si, slanted roof installation | EoL BestCase {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2020] 01_ Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL best-case {RER}	1.52E+01	m^2	Module Area.
[2020] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL best-case {RER}	1.52E+01	m^2	Module Area.
[2020] 03_1_Electric installation, for 3kWp Photovoltaic plant, slanted roof installation | EoL best-case {RER}	8.00E-01	p	

04_Inverter, 2.5kW | EoL state-of-the-art {RER}	1.20E+00	p	LCI unchanged from State-of-the-Art Process.
Electricity, low voltage {DE}| market for	2.30E-01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	1.28E+02	tkm	400 km to recycler
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	2.38E+01	tkm	100 km scraps to recycling
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	3.19E+01	tkm	100 km to collection point
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	1.30E+01	tkm	200 km to incineration
Transport, freight, lorry 7.5-16 metric ton, euro5 {RER}| market for	2.90E+00	tkm	100 km to landfill
Products			**Comment**
[2020] 00_1_Photovoltaic plant, 4 kWp, mono-Si, slanted roof installation | EoL BestCase {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2020] 01_ Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL best-case {RER}	2.03E+01	m^2	Module Area.
[2020] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL best-case {RER}	2.03E+01	m^2	Module Area.
[2020] 03_1_Electric installation, for 3kWp Photovoltaic plant, slanted roof installation | EoL best-case {RER}	1.01E+00	p	
04_Inverter, 2.5kW | EoL state-of-the-art {RER}	1.52E+00	p	LCI unchanged from State-of-the-Art Process.
Electricity, low voltage {DE}| market for	2.91E-01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	1.72E+02	tkm	400 km to recycler
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	3.13E+01	tkm	100 km scraps to recycling
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	4.30E+01	tkm	100 km to collection point
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	1.69E+01	tkm	200 km to incineration
Transport, freight, lorry 7.5-16 metric ton, euro5 {RER}| market for	3.69E+00	tkm	100 km to landfill
Products			**Comment**

[2020] 00_3_Photovoltaic plant, 1.07 MWp, mono-Si, on open ground | EoL best-case {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2020] 01_ Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL best-case {RER}	5.41E+03	m^2	Module Area.
[2020] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL best-case {RER}	5.41E+03	m^2	Module Area.
[2020] 03_2_Electric installation, for 570kWp Photovoltaic plant, on open ground | EoL best-case {RER}	1.50E+00	p	
04_Inverter, 500kW | EoL state-of-the-art {RER}	2.93E+00	p	LCI unchanged from State-of-the-Art Process.
Diesel, burned in building machine {GLO}| market for	1.44E+04	MJ	
Electricity, low voltage {DE}| market for	6.77E+01	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	3.31E+04	tkm	400 km to recycler
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	7.41E+03	tkm	100 km scraps to recycling
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	8.28E+03	tkm	100 km to collection point
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	3.28E+03	tkm	200 km to incineration
Transport, freight, lorry 7.5-16 metric ton, euro5 {RER}| market for	2.74E+03	tkm	100 km to landfill
Products			**Comment**
[2020] 00_3_Photovoltaic plant, 4.4 MWp, mono-Si, on open ground | EoL best-case {RER}	1.00E+00	p	Composition same as in the production of this system.
Inputs			
[2020] 01_ Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL best-case {RER}	2.22E+04	m^2	Module Area.
[2020] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL best-case {RER}	2.22E+04	m^2	Module Area.
[2020] 03_2_Electric installation, for 570kWp Photovoltaic plant, on open ground | EoL best-case {RER}	6.16E+00	p	
04_Inverter, 500kW | EoL state-of-the-art {RER}	1.20E+00	p	LCI unchanged from State-of-the-Art Process.

Diesel, burned in building machine {GLO}| market for	5.91E+04	MJ	
Electricity, low voltage {DE}| market for	2.77E+02	kWh	Assumption: Energy demand for disassembly is the same as for assembly.
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	1.36E+05	tkm	400 km to recycler
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for	3.04E+04	tkm	100 km scraps to recycli(*86*)ng
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	3.39E+04	tkm	100 km to collection point
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for	1.34E+04	tkm	200 km to incineration
Transport, freight, lorry 7.5-16 metric ton, euro5 {RER}| market for	1.12E+04	tkm	100 km to landfill
Products			**Comment**
[2020] 01_ Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL best-case {RER}	1.00E+00	m^2	
Inputs			
[2020] Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL best-case {RER} [per kg]	1.21E+01	kg	
Products			**Comment**
[2020] Glass-Backsheet Photovoltaic panel, Single-Si wafer | EoL best-case {RER} [per kg]	1.00E+03	kg	All data from (*86*) and adjusted to bill of materials of 2020 panel.
Avoided products			
[2020] 12 MG-silicon at plant {NO} | PVPS LCI 2020	7.34E+01	kg	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	1.19E+02	kg	
Copper {RER}| production, primary	1.18E+01	kg	
Electricity, medium voltage {ENTSO-E}| market group for	2.70E+02	MJ	Calculated value. Recovered energy from incineration of polymers:2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	5.48E+02	MJ	Calculated value. Recovered energy from incineration of polymers: 5.8 MJ/kg
Packaging glass, white {DE}| production	5.83E+02	kg	
Silver {GLO}| market for	2.56E-01	kg	
Inputs			
Diesel, burned in building machine {GLO}| market for	5.13E+02	kWh	Calorific value: 9.8 kWh/l

Electricity, medium voltage {ENTSO-E}| market group for	1.51E+02	kWh	
Graphite {RER}| production	2.30E+00	kg	
Lime, hydrated, loose weight {CH}| production	6.41E+01	kg	
Nitric acid, without water, in 50% solution state {RER}| market for nitric acid, without water, in 50% solution state	1.20E+01	kg	
Water, completely softened {RER}| water production, completely softened	4.49E+02	kg	
Emissions to air			
Nitrogen oxides	3.18E+00	kg	
Waste to treatment			
Average incineration residue {CH}| treatment of, residual material landfill	6.37E+00	kg	
Limestone residue {CH}| treatment of, inert material landfill	4.93E+02	kg	
blast furnace sludge {CH}| treatment of blast furnace sludge, residual material landfill	8.09E+01	kg	
Waste glass {CH}| treatment of, inert material landfill	1.32E+01	kg	
Products			**Comment**
[2020] 02_1_Mounting System, for Photovoltaic plant, slanted roof installation | EoL best-case {RER}	1.00E+00	m^2	
Avoided products			
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production	2.66E+00	kg	Calculated value. Recycling rate: 94%
Electricity, medium voltage {ENTSO-E}| market group for	2.02E-02	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	4.09E-02	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Steel, low-alloyed, hot rolled {RER}| production	1.49E+00	kg	Calculated value. Recycling rate: 99%
Waste to treatment			
Scrap aluminium {Europe without Switzerland}| market for scrap aluminium	2.83E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.
Scrap steel {Europe without Switzerland}| market for scrap steel	1.50E+00	kg	Added to harmonize datasets. Calculated according to bill of materials.

Waste plastic, mixture {CH}| treatment of, municipal incineration	4.56E-05	kg	
Waste polystyrene {CH}| treatment of, municipal incineration	7.01E-03	kg	
Products			**Comment**
[2020] 03_1_Electric installation, for 3kWp Photovoltaic plant, slanted roof installation | EoL best-case {RER}	1.00E+00	p	
Avoided products			
Copper {RER}| production, primary	1.53E-02	kg	Calculated value. Recycling rate: 90%
Electricity, medium voltage {ENTSO-E}| market group for	5.68E+00	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	1.15E+01	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Steel, low-alloyed, hot rolled {RER}| production	7.58E-01	kg	Calculated value. Recycling rate: 99%
Waste to treatment			
Scrap copper {Europe without Switzerland}| market for scrap copper	1.70E-02	kg	
Scrap steel {Europe without Switzerland}| market for scrap steel	7.66E-01	kg	
Waste electric wiring {CH}| treatment of, collection for final disposal	2.50E+01	kg	
Waste plastic, mixture {CH}| treatment of, municipal incineration	1.98E+00	kg	
Products			**Comment**
[2020] 02_2_Mounting System, for Photovoltaic plant, on open ground | EoL best-case {RER}	1.00E+00	m^2	
Avoided products			
Electricity, medium voltage {ENTSO-E}| market group for	1.83E-01	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	3.71E-01	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg
Steel, low-alloyed, hot rolled {RER}| production	2.48E+00	kg	Calculated value. Recycling rate: 99%
Waste to treatment			
Waste concrete {CH}| treatment of, inert material landfill	4.87E+01	kg	

Waste fibreboard {CH}| treatment of, collection for final disposal	6.79E-01	kg	
Waste glass pane in burnable frame {CH}| treatment of, sorting plant	7.21E-03	kg	
Waste mineral wool {Europe without Switzerland}| treatment of waste mineral wool, sorting plant	1.92E-02	kg	
Waste plastic, mixture {CH}| treatment of, municipal incineration	5.28E-02	kg	
Waste polyurethane foam {CH}| treatment of, collection for final disposal	9.94E-02	kg	
Waste polyvinylchloride {CH}| treatment of, municipal incineration	1.11E-02	kg	
Waste reinforcement steel {CH}| treatment of, sorting plant	3.95E+01	kg	
Products			**Comment**
[2020] 03_2_Electric installation, for 570kWp Photovoltaic plant, on open ground | EoL best-case {RER}	1.00E+00	p	
Avoided products			
Copper {RER}| production, primary	1.04E+00	kg	Calculated value. Recycling rate: 90% (*86*)
Electricity, medium voltage {ENTSO-E}| market group for	1.10E+02	MJ	Calculated value. Recovered energy from incineration: 2.86 MJ/kg (*87*).
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW	2.23E+02	MJ	Calculated value. Recovered energy from incineration: 5.8 MJ/kg (*87*).
Steel, low-alloyed, hot rolled {RER}| production	4.68E+01	kg	Calculated value. Recycling rate: 99% (*95*)
Waste to treatment			
Scrap copper {Europe without Switzerland}| market for scrap copper	1.16E+00	kg	
Scrap steel {Europe without Switzerland}| market for scrap steel	4.73E+01	kg	
Waste electric wiring {CH}| treatment of, collection for final disposal	1.24E+03	kg	(*91*)
Waste plastic, mixture {CH}| treatment of, municipal incineration	2.32E-01	kg	
Waste polyvinylchloride {CH}| treatment of, municipal incineration	3.82E+01	kg	

Appendix C: Recycling Rates per treatment and material as in Herceg et al. 2022b (*42*)

Material	State of the art	Best Case
aluminum	12.1 %	94 %
copper	4.4 %	90 %
glass	-	88 %
silicon	-	95 %
silver	-	94 %
steel	99 % (*95*)	99 % (*95*)