Changing environmental tides of Amsterdam's future PV systems

A multi-scenario projection for the environmental performance of residential PV systems in Amsterdam

MSc Industrial Ecology

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A multi-scenario projection for the environmental performance of residential PV systems in Amsterdam

by

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Preface

This master thesis has been an exceptionally challenging but insightful and exciting journey. I have had a wonderful time at TU Delft, Leiden University and AMS Institute. I would like to express my gratitude to my supervisors for their helpful support along the way. A special thank you goes to PV WORKS for sharing their data, enriching the depth of my research. Last but not least I would like to thank my family and friends for their encouragement and support. The inspiration behind choosing this topic stemmed from my discovery of the remarkable ambition of European cities in their quest for climate neutrality, under the initiative of the European Commission's Climate Neutral Cities Mission. Cities are currently not mandated to consider emissions beyond their borders, despite the majority originating externally. Focusing on solar panels, I sought to underscore the imperative of looking beyond local renewable energy generation and acknowledging the broader impact of production and the implications of early disposal. I hope that future students will be drawn to explore this topic further, as our journey towards a sustainable society presents an enormous challenge that necessitates focused attention and innovative solutions.

Sietse de Vilder
Delft, August 2023

Abstract

The municipality of Amsterdam is swiftly advancing its climate neutrality aspirations within the EU's Climate Neutral Cities Mission. To accelerate this transition, the municipality has set the target to fully utilize suitable rooftop surfaces for solar panels by 2050. Yet, economic incentives prompt households to replace PV panels prematurely, leading to functional panels being discarded for low-value recycling. This study focuses on evaluating the environmental consequences of lifetime extension strategies at city scale, using Amsterdam as a case study. Employing an innovative prospective Life Cycle Assessment (LCA) approach, this research examines net environmental impact across multiple scenarios, derived from a General Morphological Analysis (GMA). The findings indicate that, despite rapid technological advancements, retaining older panels on buildings proves environmentally preferable to early disposal. Moreover, re-installing functionally disposed panels holds the potential to drive a significant reduction of 790 to 1910 million kilograms of CO2-equivalent emissions, or 126 to 327 million euros in shadow costs. To seize the opportunity for reuse, the municipality is advised to initiate pilot projects urgently and collaborate with European end-of-life management stakeholders. Future research is needed to incorporate the influence of novel recycling practices, emerging circular technologies, regional market shifts toward Europe, and the implications of resource independence. This study underscores the need for sustainable PV panel management strategies to accelerate Amsterdam's climate-neutral journey.

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Abbreviations

Abbreviation	Definition
°C	Degrees Celsius
A_{avg}	Average module area
AC	Alternating Current
AC_{avg}	Average Aluminium consumption
AHN	Current Dutch Elevation
ALOP	Agricultural Land Occupation Potential
AMS	Advanced Metropolitan Solutions
APP	Aluminium consumption per meter perimeter
AR5	Fifth Assessment Report
BAU	Business As Usual
BGT_{avg}	Average back glass thickness
BOS	Balance Of System
BSF	Back Surface Field
CdTe	Cadmium Telluride
CED	Cumulative Energy Demand
CG_{avg}	Average glass consumption
CIGS	Copper Indium Gallium Selenide
CO2-Eq	Carbon Dioxide Equivalent
CONS	Conservative
COP	Climate Change Conference
c-Si	Crystalline Silicon
DC	Direct Current
ED_{avg}	Average electricity demand
ED_S	Electricity Demand Siemens process
EPBT	Energy Payback Time
EROI	Energy Return of Investment
FBR	Fluidized Bed Reactor process
FDP	Fossil Depletion Potential
FEP	Freshwater Eutrophication Potential
FETP	Freshwater Eco-Toxicity Potential
FGT_{avg}	Average front glass thickness
GHG	Greenhouse Gas
GIS	Geographic Information System
GMA	General Morphological Analysis
GUI	Graphical User Interface
GWP100	Global Warming Potential over 100-year time horizon
HJT	Heterojunction Technology
HTP	Human Toxicity Potential
IAM	Integrated Assessment Model
IEA	International Energy Agency
IEA-PVPS	IEA Photovoltaic Power Systems Programme
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Interngovernmental Panel on Climate Change
IRP	Ionising Radiation Potential
ISO	International Organization for Standardization
ITRPV	International Technology Roadmap of Photovoltaic
kg	kilogram
kg 1,4-DB-Eq	Kilograms of 1,4-dichlorobenzene-equivalent
kg 1,4-DCB-Eq	Kilograms of 1,4-dichlorobenzene-equivalent
kg CFC-11-Eq	Kilograms of CFC-11-equivalent

Abbreviation	Definition
kg CO2-Eq	Kilograms of CO2-equivalent
kg Fe-Eq	Kilograms of iron-equivalent
kg N-Eq	Kilograms of nitrogen-equivalent
kg NMVOC-Eq	Kilograms of non-methane volatile organic compounds-equivalent
kg oil-Eq	Kilograms of oil-equivalent
kg P-Eq	Kilograms of phosphorus-equivalent
kg PM10-Eq	Kilograms of PM10-equivalent
kg SO2-Eq	Kilograms of sulfur dioxide-equivalent
kg U235-Eq	Kilograms of uranium-235-equivalent
kW	kilo Watt
kWh	kilo Watthour
kWp	kilo Wattpeak
L_{avg}	Average module length
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCOE	Levelized Cost of Electricity
m	Meter
m^2	Square-Meter
m3 water-Eq	Cubic meters of water-equivalent
MC_f	Market share proportion framed panels
MDP	Metal Depletion Potential
MEP	Marine Eutrophication Potential
METP	Marine Eco-Toxicity Potential
MFA	Material Flow Analysis
MG-Silicon	Metallurgical Grade Silicon
mm^2	Square-Millimeter
Mono-Si	Monocrystalline Silicon
MPL	Market Penetration Level
MRL	Market Readiness Level
MS_{FBR}	Market share proportion Fluidized Bed Reactor process
MS_{FL}	Market share proportion frameless panels
MS_i	Market share proportion of form factor i
MS_j	Market share proportion of cell technology j
MS_k	Market share proportion bifacial cells
MS_S	Market share proportion Siemens process
Multi-Si	Multicrystalline Silicon
NC_i	Number of cells form factor i
NDC	Nationally Determined Contributions
NLTP	Natural Land Transformation Potential
ODP	Ozone Depletion Potential
Op. LT	Operational Lifetime
OPT	Optimistic
P_{avg}	Average module perimeter
PBL	Netherlands Environmental Assessment Agency
PERC	Passivated Emitter and Rear Contact/Cell
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Oxidation Formation Potential
PV	Photovoltaic
RCP	Representative Concentration Pathway
REAL	Realistic
ρ_g	Glass density
SC_{avg}	Average Silver consumption
SC_{ij}	Silver consumption form factor i and cell technology j
SG-Silicon	Solar Grade Silicon

Abbreviation	**Definition**
SIC_{avg}	Average Silicon consumption
Square meter-year	The product of a quantity in square meters and a time in years
SSP	Shared Socioeconomic Pathway
TAP100	Terrestrial Acidification Potential
TETP	Terrestrial Eco-Toxicity Potential
TopCon	Tunnel Oxide Passivated Contact
TRL	Technology Readiness Level
ULOP	Urban Land Occupation Potential
UN	United Nations
W_{avg}	Average module weight
Wd_{avg}	Average module width
WDP	Water Depletion Potential
WEEE	Waste of Electrical and Electronic Equipment

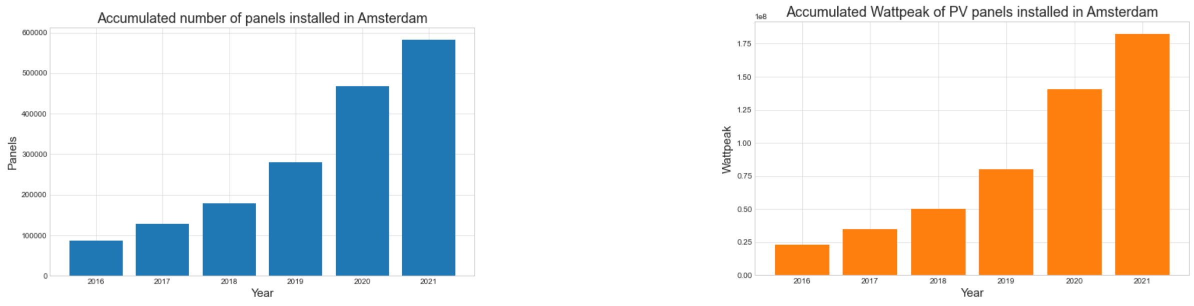
1

Introduction

The growing threat of climate change has prompted an increasing number of cities worldwide to commit to becoming carbon-neutral. In Europe, the European Commission has established targets for member states and cities to reduce their greenhouse gas (GHG) emissions by 55% by 2030. To achieve this objective, cities are adopting measures such as increasing the adoption of renewable energy technologies, including photovoltaic (PV) panels on urban rooftops. However, solely focusing on reducing GHG emissions by deploying PV panels on urban roofs overlooks the environmental consequences associated with their production and disposal. The manufacturing of PV panels requires substantial amounts of energy, water, and the use of rare and toxic materials, which can have significant environmental impacts. Additionally, the current practices for managing end-of-life PV modules primarily involve bulk recycling of aluminium and glass, while the remaining materials are shredded and used as fillers for asphalt and concrete (WEEE NL, personal communications; Ghaleb et al., 2023). Therefore, cities need to consider and anticipate the environmental impact of the entire supply chain, as well as the disposal process, for PV systems.

1.0.1. Decarbonization targets of Amsterdam

Amsterdam is actively participating in the Climate Neutral Cities Mission, a project commissioned by the European Commission. The aim of this initiative is to facilitate the rapid transition towards climate neutrality for 112 cities that have committed to achieving carbon neutrality by 2030. The local government of Amsterdam has prioritized the decarbonization of the city and has set a target of generating 80% of household electricity demand through solar and wind energy by 2030. To accomplish this, the municipality has established goals to utilize 50% of suitable roof capacity for solar energy by 2030 and eventually utilize all available capacity by 2050 (Gemeente Amsterdam, n.d.). This ambitious plan requires a significant scaling up of residential PV systems in the upcoming decades. As depicted in **Figure 1.1**, the installation of solar panels in Amsterdam has seen a substantial increase over the past decade. Considering the rising prices of the Dutch electricity grid, it is anticipated that the installation of solar panels will experience an even more rapid growth in the future.



(a) Accumulated number of panels installed in Amsterdam **(b)** Accumulated Wattpeak of PV installed in Amsterdam

Figure 1.1: Trend of PV installations expressed in total number of panels and power (Data from Gemeente Amsterdam)

1.0.2. Circularity targets of Amsterdam

In addition to emission reduction targets, the municipality of Amsterdam has also established circularity targets, including a goal to halve the use of raw materials by 2030 and achieve full circularity by 2050 (Gemeente Amsterdam, 2020). The Amsterdam Circular Strategy 2020-2025 highlights the circular processing ladder, as shown in **Figure 1.2**, which outlines the principles of a circular economy. One of the most effective strategies for creating a more circular city is to reduce the production of material and energy-intensive products. However, there is still a significant gap in aligning the deployment of PV systems with circularity targets. The European Union's Waste of Electrical and Electronic Equipment (WEEE) Directive mandates that PV panel producers supplying the EU market take financial responsibility for collecting and recycling disposed PV panels within Europe (Chowdhury et al., 2020). The directive sets a minimum recycling requirement of 90% of the electronic product's weight. However, it does not specify the type of recycling that should be employed. Consequently, producers often opt for the cheapest and lower-value recycling methods, such as shredding and using the materials as fillers for asphalt or concrete (WEEE NL, personal communications; Ghaleb et al., 2023). Moreover, the remaining 10% of PV panels, which includes valuable materials like silicon, silver, and copper, pose a challenge. While the recovery of silicon cells from status-quo PV modules has been achieved at the laboratory scale (Hoseinpur et al., 2023), industrial-scale recovery is not yet feasible. Without economic or institutional incentives, producers and installers tend to choose the cheapest end-of-life management option, which involves low-value recovery of 90% of the PV system's weight.

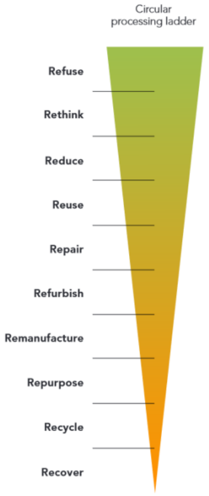


Figure 1.2: The circular processing ladder (Gemeente Amsterdam, 2020)

1.0.3. Priorities for Technological Development

Novel PV technologies with a circular design focus are currently being developed by research institutes, companies, and start-ups in the Netherlands, such as TNO, Solarge, and Biosphere Solar. However, the dominant PV producers have primarily optimized their production processes to create the most cost-competitive PV systems available in the market. These producers prioritize minimizing the Levelized Cost of Energy (LCOE) to offer attractive products to consumers, who are primarily driven by the desire to save on their electricity bills (Vasseur & Kemp, 2015). **Equation 1.1** provides a simplified definition of the LCOE:

$$LCOE = \frac{\text{Sum of costs over lifetime}}{\text{Sum of electricity produced over lifetime}} \tag{1.1}$$

The sum of costs mainly consists of capital costs, which includes the production and installation of the system. The sum of electricity produced over lifetime depends on the yearly electricity yield and operational lifetime. Considering this driver, the ideal panel has the highest module efficiency, lowest degradation rate and longest product lifetime. Because of this, producers put a power warranty on their products, guaranteeing a minimal degradation rate and maximum technical lifetime. To guarantee a high maximum technical lifetime, tests are required over a long period of time and typically the most well-established companies can guarantee the best maximum lifetime. This makes it harder for emerging technologies to compete with the status quo, unless subsidization by institutions allow for the development of these technologies at industrial scale.

Trends for Technological Development of PV Modules

Based on projections by the International Technology Roadmap for Photovoltaic (ITRPV, 2022), the contemporary well-established PV technologies have reduced and will reduce further considerably in material and energy consumption during production. An in depth analysis of these trends can be found in **Section 3.4**. Furthermore, the peak power and related electricity yield have increased considerably over the last decade, as shown in **Figure 1.3**. This trend is likely to continue, based on projections of the module efficiency (ITRPV, 2022).

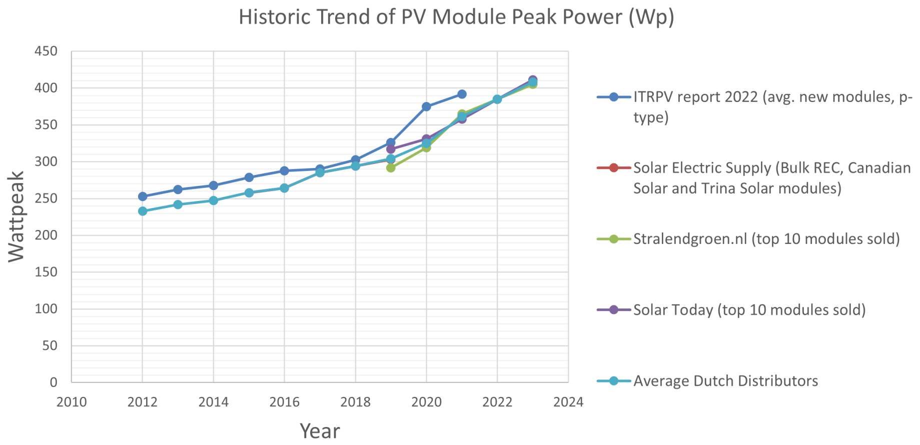


Figure 1.3: Market trend for the average peak power of PV modules (ITRPV & market research)

1.0.4. Operational lifetime of PV modules

To claim the lowest LCOE, producers put a power warranty on their products, guaranteeing a minimal degradation rate and a maximum technical lifetime. The newest modules with the most advanced cell technologies in 2023 have a linear power degradation rate of only 0.25% and a power warranty of 25 years (Meyer Burger - Mono N-type HJT 390). Standard modules are made to operate at least 25 years. However, the technical lifetime does not necessarily reflect the operational lifetime, which is also dependent on various other factors:

1. **Technical lifetime of inverters**: Currently, most string inverters last for 10 to 15 years (Choi & Lee, 2020; European Commission, 2018). If the string inverter breaks, installers will likely advice the consumer to upgrade to a full new set of panels besides the inverter(s) (personal communication, PV installer).

2. **Technological development of PV modules**: The average electricity yield of PV modules has increased substantially over the last few years and is expected to increase much further.

3. **Electrification**: Because of high gas prices, many households are expected to switch to heat pumps in the near future. Furthermore, electric vehicles will also overtake fossil fuelled vehicles, which are often charged at home. As a result, households will have a higher electricity demand. However, many residential PV systems are installed based on current electricity consumption (personal communication, PV installer). If households choose to install a system with a string inverter, which is currently the most common inverter, the set of panels cannot be supplemented with additional panels with different specifications. Because of rapid technological development, it will be difficult to find panels with the same specifications in the future. Additionally, installers will advise to upgrade the entire system since they are responsible for the performance of the system and upgrading the entire system is a much less risky and cost effective option (personal communication, PV installer).

4. **Increasing electricity prices:** Because of high electricity prices, people who install a PV system to cover the full electricity demand are likely to have returned their investment already within 3 to 7 years, neglecting net metering (Sodhi et al., 2022). Because of this, it is easier for people to install a new PV system in the future. A recent study conducted by Sodhi et al. (2022) performed a break-even financial analysis on the replacement of solar panels, estimating the optimal replacement year based on the module performance, annual degradation, electricity price, panel costs, subsidies and system costs, including installation. Their results show that PV panels installed in 2012 can be profitably replaced in 2018 and panels installed in 2018 could already be profitably replaced by 2025.

1.1. Research Gap and Problem Definition

In light of international decarbonization ambitions and the rapidly decreasing costs of solar energy, the expansion of PV systems is accelerating at a pace set to increase further (Ashmelash & Prakash, 2019). The well-established contemporary design PV industry is optimising its production line and technology performance to lower the LCOE of PV (ITRPV, 2022). This leads to a reduction in energy and material consumption during production and an increase in performance. The increase in electricity prices from the grid, reduction in PV system costs and increase in module performance make it more attractive for consumers to replace their old panels within in a much smaller time-frame than is anticipated by most studies (Sodhi et al., 2022). The literature review in the next chapter systematically identifies studies that have focused on future projections of the environmental impact of PV systems. All these studies take into account an operational lifetime of around 30 years, as is recommended by the IEA Methodology Guidelines on Life Cycle Assessment of Photovoltaic (IEA, 2020). Furthermore, none of these studies focus on the environmental impact at city-scale, which may produce different results than assessments at a smaller scale.

Trade-off Induced Impact and Avoided Impact

Differences in operational lifetime may have a substantial effect on the environmental impact and electricity yield of PV systems deployed at city scale. The quick re-installation of high performance PV modules results in a higher total electricity yield, considering technological development and degradation rates. If this electricity displaces the use of the grid, which also consists of non-renewable energy sources, it may result in a higher avoided impact. However, the higher production and disposal rate may also lead to a higher induced environmental impact. The trade-off between avoided impact, while not only considering GHG emissions but also other critical impact categories, in different operational lifetimes is still unexplored.

Alignment Decarbonization and Circularity Targets

Interventions, such as the reuse of PV modules or simple economic incentives to not replace the PV modules, are classified as lifetime extension strategies in this study. Municipalities may have the leverage to initiate these interventions if they pursue a circular economy, such as Amsterdam. This city highlights the circular processing ladder in their Circular Strategy report (Gemeente Amsterdam, n.d.), which shows that refuse, rethink and reduce strategies are more impactful than material recovery and recycling strategies, from a circular economy perspective. Understanding the interplay between operational lifetimes of PV systems, their environmental impact, and the alignment with circular economy goals is vital. This study takes Amsterdam as a case study and seeks to address these aspects.

Study Focus and Objective

This study focuses on Amsterdam as a case study, considering its well-defined residential rooftop PV deployment targets. The primary objective is to evaluate the environmental implications of residential PV systems when deployed to match the city's deployment targets. This evaluation encompasses different operational lifetimes of the systems, taking into account both the advantageous electricity yield and the potential negative environmental effects throughout the complete lifecycle of the systems. Furthermore, this study examines the potential environmental benefits associated with the reuse of disposed functional PV panels. The outcomes of this assessment have the potential to strengthen the rationale for implementing lifetime extension strategies. Additionally, by exploring the environmental impact of PV systems at operational lifetimes lower than their technical lifetimes in a city-wide context, novel insights and contributions to the theoretical field may emerge.

1.2. Research questions

The aim of this study is to analyse the effects of lifetime extension strategies on the net environmental impact of residential rooftop PV systems. Amsterdam is taken as a case study, since it has set concrete upscaling targets of utilizing 50% of the suitable rooftop capacity by 2030 and 100% by 2050. Furthermore it has also set circularity targets of being '50% circular by 2030 and 100% circular by 2050' (Gemeente Amsterdam, n.d.). The timeframe is set on 2012 until 2050, since PV starting gaining momentum in the study since 2012 (Alliander, 2022). Based on this information the following main research question is determined:

What is the effect of operational lifetime extension strategies on the net environmental impact of residential rooftop PV systems, upscaled to the maximum rooftop capacity of Amsterdam by 2050?

To address this research question comprehensively, a model needs to be developed that integrates key factors including electricity yield, the environmental impact of PV system production and disposal, and the deployment rate at city-wide scale. However, projecting these aspects until 2050 introduces numerous uncertainties within the socio-technical system governing PV system production, deployment, and the associated technological advancements. Given these uncertainties, the study will incorporate a range of scenarios to account for potential variations. The initial sub-research question, therefore, aims to identify and derive the scenarios essential for capturing these future uncertainties. These scenarios will subsequently be integrated into the model to address the second sub-research question effectively. Both questions are highlighted below. The temporal scope of 2012 to 2050 will be further explained in **Chapter 3**.

SQ1: What are relevant socio-technical and technological development scenarios to account for uncertainty in long-term projections of the net environmental impact of rooftop PV systems?

SQ2: What is the total net environmental impact of residential rooftop PV systems installed on the roofs of Amsterdam between 2012 to 2050, considering each relevant socio-technical, technological development and operational lifetime scenario?

In the upcoming chapter, a systemic literature review is conducted to refine the research scope by drawing insights from previous studies. This review also facilitates the identification of appropriate research methods that can effectively address the research questions.

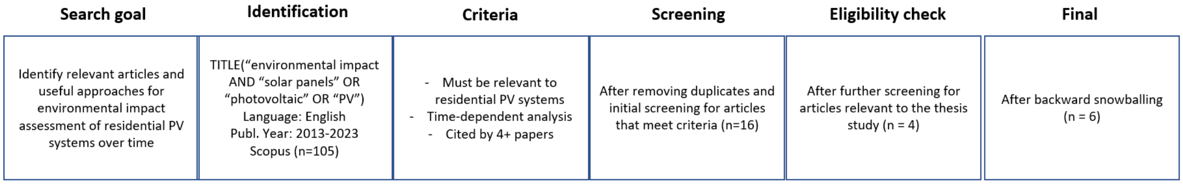
2

Theoretical Framework

The purpose of this study is to evaluate the effects of operational lifetime extension strategies on the environmental impact of scaling up residential PV systems in Amsterdam to meet the rooftop capacity goals established by the municipality. This chapter covers the systemic literature review which is conducted to further define the research scope, select methods to answer the research questions based on earlier studies and provide background information on these methods. A summary and synthesis of the findings can be found in **Section 2.1.5**.

Literature Selection Procedure

The literature review article selection was conducted in four steps: identification, screening, eligibility check and final selection. **Figure 2.1** shows the four step procedure. In the first step, the search goal is defined and keywords are chosen to find relevant articles in Scopus. Duplicates, articles published before 2013, irrelevant articles and articles with less than 4 citations are then filtered out in the initial screening process. In the eligibility check the articles are thoroughly examined to check for relevance of this thesis study. In the final step, additional relevant articles are added through backward snowballing. In the literature review, additional references to other relevant reports or literature are added where useful.



Search goal	Identification	Criteria	Screening	Eligibility check	Final
Identify relevant articles and useful approaches for environmental impact assessment of residential PV systems over time	TITLE("environmental impact AND "solar panels" OR "photovoltaic" OR "PV") Language: English Publ. Year: 2013-2023 Scopus (n=105)	- Must be relevant to residential PV systems - Time-dependent analysis - Cited by 4+ papers	After removing duplicates and initial screening for articles that meet criteria (n=16)	After further screening for articles relevant to the thesis study (n = 4)	After backward snowballing (n = 6)

Table 2.1: Overview of systemic literature selection procedure

Literature Review Objective

The objective of the literature review is to find other studies that have performed environmental impact assessments on residential photovoltaic systems and analyse their methodology. In the screening process additional focus is placed on studies which perform a time-dependent analysis, making future projections or looking at multiple different production years. The relevant articles found through the systemic search procedure have been thematically analysed in the literature review. Based on the literature review, the research scope and research gap is further defined and the methods used to answer the research questions are adopted.

2.1. Time-dependent impact assessments of PV systems

By means of the systemic literature selection procedure, 6 articles were identified that perform a time-varying or prospective environmental impact assessment of residential PV systems. All studies use a Life Cycle Assessment (LCA) methodology, which is used to evaluate the environmental impact of a product or service within a predetermined scope of its life cycle. **Section 3.1** provides all relevant information about this method. **Figure 2.2** gives an overview of the goal, method(s), scope, data sources and parameters taken into account to create a time-dependent assessment of the system's environmental impact.

Article	Goal	Method(s)	Tech. included	Processes included	Functional unit	Op. lifetime	Data source(s)	Time-dependent parameters
Fthenakis & Leccisi (2021)	Assess the environmental improvements of a PV system between 2015 and 2020	Static Life Cycle Assessment (LCA) and Net Energy Analysis (NEA)	Mono-Si & Multi-Si modules, BOS (including mechanical and electric components)	Manufacturing and operations (excluding End-of-Life management)	1 kWh electricity generated at location of deployment	30 years	IEA PVPS Task 12 LCI Report (2015 & 2020)	Technological development, electricity mix at manufacturing country
Antonanzas & Quinn (2021)	Assess the net environmental impact of the PV industry between 2000-2025	LCA with dynamic Life Cycle Inventory (LCI)	Mono-Si, Multi-Si, a-Si, CdTe modules and BOS	Manufacturing and operations (excluding End-of-Life management)	X kWh electricity generated by PV systems worldwide (Each year)	25-30 years	Ecoinvent, literature and IEA PVPS reports	Technological development,market shares and electricity mixes at manufacturing countries
Van der Hulst et al. (2020)	Apply built framework for LCA of emerging technologies to CIGS PV laminate case-study	Ex-ante LCA	CIGS PV laminate	Simplified case-study including all processes	1 kWp CIGS laminate production	30 years	Literature	Technological development, production efficiency, electricity grid projections
Frischknecht et al. (2015)	Assess the environmental performance of PV systems in 2030 & 2050	Scenario-based prospective LCA	Mono-Si & CdTe modules, BOS including mechanical and electric components	Manufacturing, operations, End-of-Life management	1 kWh of electricity supplied to the grid in the long-term future	30-40 years	IEA PVPS Task 12 LCI Report (2015), ITRPV reports, data manufacturers	Technological development, electricity mix at manufacturing country and metal industry changes
Marini & Blanc (2014)	Apply built framework to account for uncertainty in prospective LCA of PV system in 2050	Scenario-based prospective LCA	CdTe module, BOS including mechanical and electric components	Manufacturing and operations (excluding End-of-Life management)	Technological development, electricity mix at manufacturing country	30 years	Ecoinvent and literature	Technological, electricity mix, market and environmental developments
Fthenakis & Leccisi (2020)	Critical assessment of literature on ex-ante LCA emerging technologies (Perovskite solar cells)	Literature review on ex-ante LCA literature	single-junction and tandem perovskite PVs	Manufacturing	N.A.	N.A.	Literature	Technological development

Table 2.2: overview of goal, method(s), scope, sources and time-dependent parameters of articles

2.1.1. Ex-ante LCA or Prospective LCA

Van der Hulst et al. (2020) propose a systemic approach to evaluate the environmental impact of emerging technologies, with CIGS photovoltaic laminate as case-study. The authors introduce the ambiguity in literature regarding the definition of "prospective" or "ex-ante" LCA. The assessments of emerging technologies, which are technologies at an early stage of development and not yet produced at an industrial scale, are typically labelled either "prospective" or "ex-ante" LCA. However, van der Giesen et al. (2020) argue that "ex-ante" indicates assessment before market introduction of a technology, whereas prospective LCA can also be conducted on technologies which have already been introduced in the market. To avoid misinterpretation, this thesis study adopts the definitions proposed by van der Giesen et al. (2020) and defines "ex-ante LCA" as the assessment of technologies which are not produced yet at industrial scale (TRL < 9) and "prospective LCA" as the assessment of technologies in the future, not constrained by their scale in production or technological development.

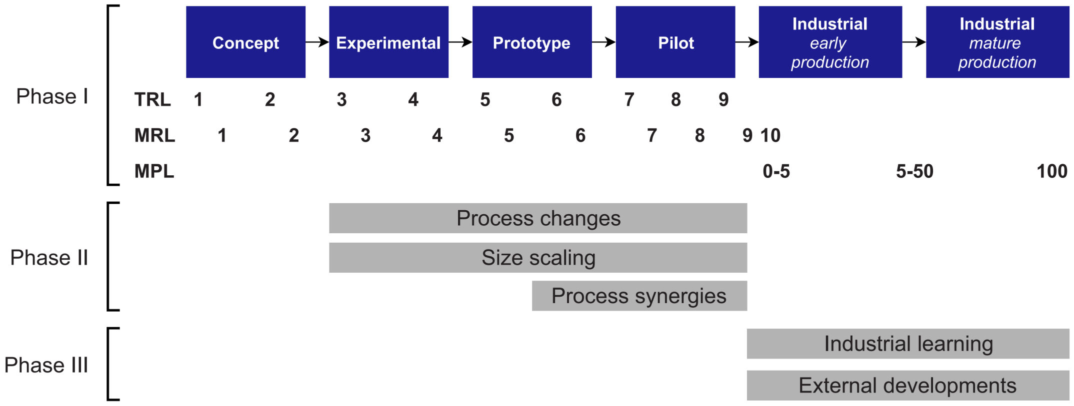


Figure 2.1: Levels and mechanisms in technology development (van der Hulst et al, 2020).

2.1.2. Uncertainty of ex-ante LCA on emerging PV technologies

As visualized **Table 2.1**, van der Hulst et al (2020) show that the environmental impact of emerging technologies can be attributed to different parameters in different phases of development. In their ex-ante LCA framework, the first phase merely involves the definition of the development stage which can be characterized according to technology readiness levels (TRLs), manufacturing readiness levels (MRLs) and market penetration levels (MPLs), which are all measures of readiness or development of the product towards mature industrial scale production.

Development of Emerging Technologies

The second phase encompasses the development stages from 'experimental lab' via 'prototype' to 'pilot' scale. There are various methods that researchers can undertake to forecast the environmental impact of products that are still under development in these stages, such as: assessing the effect of production process changes or process synergies through deduction from already existing industrial processes or size scaling through engineering geometry calculations and log-linear regression of scaling curves. However, the results of ex-ante LCAs focussing on emerging technologies can widely vary depending on data availability, different modelling assumptions and methodological errors (Leccisi & Fthenakis, 2020). An example in the context of emerging photovoltaic technologies is the different outcomes in literature for the global warming impact of Perovskite-Silicon tandem cells. Although this technology has a high chance of penetrating the market by the end of this decade, it is currently still under development at lab-scale (ITRPV, 2022). In 2017 two research groups estimated the global warming potential of Perovskite-Silicon tandem cells (Lunardi et al, 2017; Celik et al, 2017). Lunardi et al. derived 1800 kg CO2-equivalent emissions per square meter of cell whereas Celik et al. estimated roughly 200 kg CO2-equivalent emissions per square meter of cell. Lecissi & Fthenakis (2020) argue that the variations in global warming impact are mainly caused by the difference in process energy assumed for the manufacturing of Perovskite-Silicon tandem cells. This study underlies the importance of transparency in modelling assumptions and conducting uncertainty analyses.

Development of Contemporary Technologies

The third phase comprises the assessment of developments for industrially produced technologies. At this phase, learning by doing is the dominant mechanism for reducing environmental impacts (van der Hulst et al., 2020). However, size scaling and process synergies can also occur on the industrial level. To account for complex entanglements in learning mechanisms, learning and experience curves of a company, technology or industry can be used. Learning curves illustrate the empirical relationship between the decrease in labor time or costs per unit produced and the cumulative quantity of production (van der Hulst et al., 2020). The International Technology Roadmap for Photovoltaic (ITRPV) presents such a curve for crystalline Silicon PV modules in their yearly report, as shown in **Figure 2.2**. Based on the learning rate and extensive discussions with industry leaders, the ITRPV projects technological developments of c-Si PV modules covering material consumption, manufacturing improvements and product performance. Besides technological developments the ITRPV also projects market dynamics within the c-Si industry. The ITRPV reports can therefore be used as input for prospective LCA of c-Si PV modules.

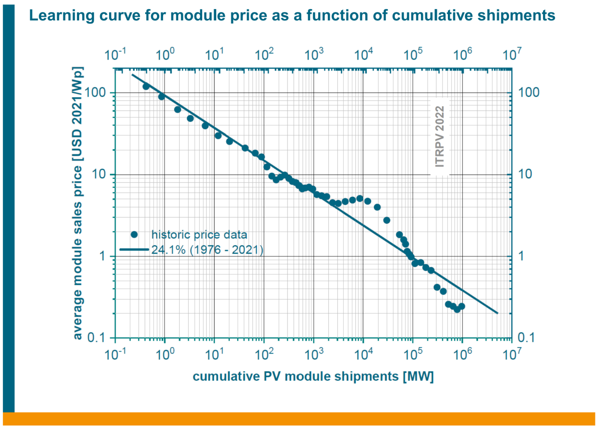


Figure 2.2: Learning curve for price of c-Si panels (ITRPV, 2022)

2.1.3. Prospective LCA on contemporary PV systems

Several articles were found that focus on contemporary PV technologies in their prospective LCA. Marini & Blanc (2014) conducted a prospective Life Cycle Assessment (LCA) to evaluate the environmental impact of a PV system installed in the South of Spain in 2050. Their study employed a scenario-based approach, which combined predictive and exploratory elements to account for the uncertainties associated with the future-oriented nature of the analysis. One of the challenges encountered when conducting quantitative impact assessments of future energy pathways is the inherent uncertainty stemming from critical environmental, technological, and economic factors. Factors such as the energy source supply during technology production or the availability of resources can significantly influence the environmental footprint of the assessed technology. To address this issue, Marini & Blanc (2014) argue that scenario analysis is crucial in prospective assessments.

Scenario-Based Prospective LCA

In a scenario-based LCA approach, different types of scenarios can be employed based on the study's objectives: (1) Predictive scenarios: These scenarios are based on the likelihood of their occurrence and are often referred to as forecasts. They are used to anticipate and evaluate potential future developments. (2) Exploratory scenarios: These scenarios are strategic in nature and are used to analyze the effects of specific interventions or changes. They help in understanding the potential impacts of different actions or decisions. (3) Normative scenarios: These scenarios are designed to determine how a specific target or goal can be achieved. They provide insights into the necessary steps and strategies to reach a desired outcome. Marini & Blanc (2014) argue that many studies define scenarios using single values for each parameter within a predefined range, and environmental impacts are assessed deterministically. However, this approach fails to account for the uncertainties associated with prospective assumptions. To address this limitation, the authors suggest identifying key parameters and their associated uncertainties to explore different potential future developments. By considering these uncertainties, researchers can avoid underestimating the uncertainties of its results.

Example 1: Exploratory Scenario-Based Prospective LCA

The LCA study conducted by Marini & Blanc (2014) follows a standard ISO14040 procedure, as detailed further in **Section 3.1**. However, the study introduces modifications to several parameters in the life cycle inventory (LCI) for the prospective LCA of the PV system. This modification is visualized in **Figure 2.3**. Within the LCI, numerous input parameters are altered to account for projections in 2050, influenced by both technological advancements (module efficiency, PV system lifetime, etc.) and external developments (module manufacturing origin, electricity mix of countries, irradiation, etc.). These alterations lead to significant changes in both the system's electricity yield and its environmental impact during production. The cumulative effect of these modifications is encapsulated in a final model parameter, representing the environmental performance of the electricity generated by the PV system.

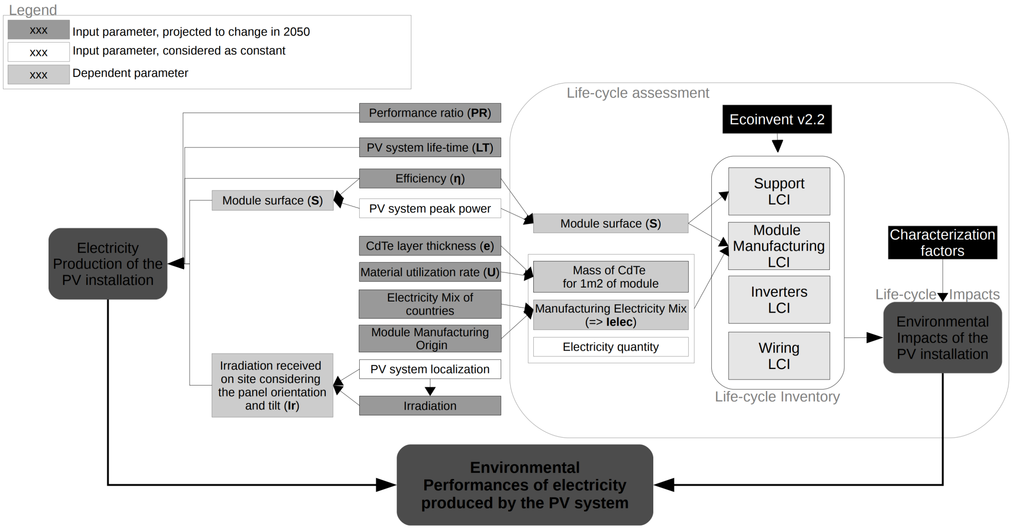


Figure 2.3: flowchart of parameterization model for prospective LCA (Marini & Blanc, 2014)

Module Area and Peak Power Considerations

Notably, the system's peak power remains constant while efficiency increases, causing a logical reduction in module area. This decrease in size impacts the environmental impact during production. However, the recent ITRPV projections (ITRPV, 2022) indicate a substantial increase in the average module area of residential PV systems. This observation is driven by economic incentives for households to enhance their renewable energy generation by contributing excess electricity to the grid. Consequently, accounting for the rise in module area and the corresponding increase in peak power becomes crucial when assessing the maximum roof capacity for PV in urban areas.

Operational Lifetime Considerations

Additionally, the study assumes an operational lifetime aligned with the technical lifespan, initially set at 30 years and later extended to 35 years. However, this operational lifetime might not necessarily align with the owner's decision influenced by economic incentives, as explained in **Section 1.0.4** of the introduction.

Example 2: Exploratory Scenario-Based Prospective LCA

A similar scenario-based prospective LCA approach was used by the IEA PVPS Task 12 research group (Frischknecht et al., 2015). The aim of this study is to provide scenario-based information about the environmental performance of Mono-Si and CdTe PV modules produced and operated in the far future (2030 to 2050). Like Marini & Blanc (2014), scenario dependent projections are made of key parameters, as shown in **Table 2.3**. Interestingly, the operational lifetime is again assumed to be equal to the estimated module technical lifetime.

Parameter	Single-Si				CdTe			
	TODAY	BAU	REAL	OPT	TODAY	BAU	REAL	OPT
Cell efficiency	16.5 %	25.0 %	27.0 %	29.0 %	15.6 %	22.8 %	24.4 %	26.0 %
Derate cell to module efficiency	8.5 %	8.5 %	6.8 %	5.0 %	13.9 %	10.0 %	7.5 %	5.0 %
Module efficiency	15.1 %	22.9 %	25.2 %	27.6 %	13.4 %	20.5 %	22.6 %	24.7 %
Wafer thickness / layer thickness	190 µm	150 µm	120 µm	100 µm	4.0 µm	2.0 µm	1.0 µm	0.1 µm
Electricity demand in CdTe laminate manufacture	-	-	-	-	100 %	86 %	81 %	74 %
Kerf loss	190 µm	150 µm	120 µm	100 µm	-	-	-	-
Silver per cell	9.6 g/m^2	9.6 g/m^2	5.0 g/m^2	2.0 g/m^2	-	-	-	-
Fluidized-bed reactor (FBR) Share of Poly Si Production	0 %	20 %	40 %	100 %		-	-	
Glass thickness	4.0 mm	4.0 mm	3.0 mm	2.0 mm	3.5 mm	3.5 mm	3.0 mm	2.0 mm
Operational lifetime	30 years	30 years	35 years	40 years	30 years	30 years	35 years	40 years

Table 2.3: Input values of technological parameters for the prospective LCA of Frischknecht et al. (2015)

External System Developments

Besides technological developments of the PV module, projections are made of the electricity mixes in main manufacturing countries and of basic material production in the far future. By doing this, Frischknecht et al. (2015) account for the external developments mentioned by van der Hulst et al. (2020). The avoided impact is determined by assessing the environmental impact of the grid's electricity, which is displaced by the electricity generated by the PV system.

Exploratory Scenarios Used

For all mentioned parameters, three exploratory future scenarios were used: "business as usual" (BAU), "realistic improvement" (REAL) and "optimistic improvement" (OPT). These scenarios are used to account for uncertainty in predictive modelling. However, it should be noted that the life cycle inventory data is outdated and recent technological development of c-Si and CdTe modules has led to some of the key parameters nearly being exceeded. For example, the kerf loss has been reduced to only 52 μm, which is 48% lower than the most optimistic scenario used by Frischknecht et al. (2015).

2.1.4. LCA on historic PV developments (non-prospective)

A more recent study by Antonanzas & Quinn (2021) assesses the net environmental impact of all PV installed globally, considering the PV yield during operation, the environmental impact during manufacturing and, similarly to Frischknecht et al. (2015), the environmental effects for displacing other energy sources. The authors argue that Although the pollutants emitted during the manufacturing and installation of individual PV systems can be offset within a few years, the rapid expansion of the PV industry may have led to temporary pollutant sinks. This hypothesis is verified in their analysis, which shows that the PV industry achieved greenhouse gas emissions payback between 2012 and 2016, depending on the energy sources displaced.

Unrealistic Assumptions

The study also includes technological and external developments but assumes no efficiency increase nor reduction of material and energy use after 2019. Based on the latest technological developments of contemporary design PV technologies (ITRPV, 2022), this is a critical assumption that likely diverges from realistic LCA outcomes in this time period. Interestingly, the authors also do not consider the end of life stage, given its uncertainty. Furthermore, they argue that the decommissioning of PV panels is outside of the time horizon of the study (2000-2025), because the average life of PV panels is 25-30 years.

Importance of Large-Scale LCAs on PV Systems

Although Antonanzas & Quinn don't use prospective modelling, as no technological developments or external developments after 2019 are considered, they do consider the increase of PV deployment rather than constraining the scope to one PV system. In the context of upscaling PV systems in Amsterdam, the results of their research highlight the importance of taking a wider approach.

Different Assessment Metrics

Finally, Fthenakis & Leccisi (2021) conduct a life cycle assessment and net energy analysis of crystalline-based photovoltaic (PV) systems. The goal of the study is to assess the difference in global warming impact, cumulative energy demand (CED), the energy payback time (EPBT) and Energy Return on Investment (EROI) of a crystalline-based photovoltaic (PV) system manufactured in 2015 or 2020. In LCAs, global warming is an impact category that quantifies the global warming effect of the greenhouse gas emissions emitted within a specified scope of the lifecycle of the system. It is the most frequently assessed impact category, since global developments currently mainly focus on mitigating climate change. However, it is important to not neglect other impact categories, since they also pose a substantial threat to the environment. CED covers all energy requirements of the system during its lifecycle. The EPBT also incorporates the electricity yield of the system over its lifetime and determines at what moment the electricity yield has compensates the energy required during its lifecycle. The EROI can be calculated by dividing the total energy delivered by the energy required to deliver that energy.

Historic Developments in Global Warming Impact of c-Si Modules

Like the aforementioned studies, this study also assess contemporary design PV modules (Mono-Si or Multi-Si) and includes mechanical and electrical components. This study also did not include End-of-Life management and recycling. They argue that there is insufficient data on optimized recycling scenarios that accurately represent realistic collection rates and material recovery fractions on a large scale. Several technological parameters are considered including the module efficiency, wafer thickness, kerf losses and electricity demand during wafer production. Furthermore, external developments are taken into account by updating the Chinese electricity mix from the 2015 mix to the 2020 mix. Based on these developments, the study concludes that the global warming potential has decreased from 2000 kg CO2-Eq emissions per kWp in 2015, to only 1000 kg in 2020.

2.1.5. Summary and synthesis of findings

Several studies have been found with a big overlap in research objectives, considering the prospective or time-dependent nature of the environmental impact assessment of PV systems. All studies use a Life Cycle Assessment (LCA) approach to quantify the environmental impact in multiple impact categories, across the lifecycle of the PV system. An Ex-ante LCA approach can be used for emerging technologies that have not penetrated the market and a prospective LCA can also be used to account for future developments of contemporary PV systems. Van der Hulst et al. (2020) introduce the different mechanisms that come into play during the development of PV technologies and what mechanisms should be integrated in the ex-ante/prospective LCA, depending on the development phase. Leccisi & Fthenakis (2020) show the high uncertainty of ex-ante LCAs of emerging technologies and give the example of Perovskite-Silicon tandem Global Warming impact assessments, which can differ by a factor of 10. All other articles in this literature review focus on time-dependent modelling of contemporary PV systems. As mentioned by van der Hulst et al. (2020), the main parameters considered are technological developments (based on industrial scaling, size scaling and process synergies) and external developments (mainly considering the changes in electricity mixes).

Time-Dependent Parameters Considered

Marini & Blanc (2014); Frischknecht et al. (2015) both consider the following parameters in their time-dependent LCA model:

1. Technological development: wafer thickness
2. Technological development: operational lifetime
3. Technological development: material utilization during production
4. Technological development: module efficiency
5. External development: electricity mix changes
6. External development: market share of production regions

Marini & Blanc (2014) also consider environmental developments by integrating future irradiation scenarios in their model. Frischknecht et al. (2015) also include external developments in production of metals. Antonanzas & Quinn (2021) do not specify on the tech. development parameters used, but address developments through different lifecycle inventories provided by the ecoinvent database and published papers. Fthenakis & Leccisi (2021) also integrate the above mentioned parameters in their impact assessment of crystalline Silicon-based PV systems between 2015 and 2020 but does not change the electricity mix and restricts the analysis to production in China.

Large-Scale Assessment

Antonanazas & Quinn (2021) determine the net-environmental impact of global PV installations between 2000-2025, by comparing the renewable electricity yield gains to the environmental impact of non-renewable electricity generation. Although the Energy Payback Time presented in other studies only ranges between a few months to a couple of years (Fthenakis & Lecissi, 2021; Frischknecht et al, 2015), the greenhouse gas emissions payback time on a global system scale may take much longer.

Consistency in Operational Lifetime

All studies except for Fthenakis & Lecissi (2021) include the environmental impact during operations, by estimating the electricity yield during the system's operational lifetime. Interestingly, these studies all assume an operational lifetime equal to the technical lifetime, within a range of 25 to 40 years. However, as explained in **Section 1.0.4** of the introduction, the operational lifetime is likely to be much lower. A lower operational lifetime could have a substantial effect on the net environmental impact.

End-of-Life Management

Only Frischknecht et al. (2015) take into account the end-of-life management because of the high uncertainty and lack of data, due to the currently low disposal rate of PV systems. Frischknecht et al. (2015) have made an estimated LCI based on current disposal practices, but do not consider other emerging disposal or recycling practices.

Scenario-Based Prospective LCA

Both Marini & Blanc (2014) & Frischknecht et al. (2015) adopt multiple scenarios to take into account the uncertainty of prospective modelling. Three different type of scenario-based approaches can be used in prospective LCAs: predictive scenarios, exploratory scenarios and normative scenarios. Both studies use partial predictive/exploratory scenarios based on possible technological and socio-technical global developments.

2.1.6. Research Methods and Scope Based on Findings

This thesis study will adopt a scenario-based prospective LCA approach to determine the net environmental impact of upscaling residential PV systems in Amsterdam to full capacity by 2050. Full capacity is regarded as the total suitable roof area, and the LCA study will therefore focus on roof capacity rather than electricity capacity. Because of recent increases in module area (ITRPV, 2022), this study will also take into account developments in module area and the accompanied peak power deevelopments. Because of the high uncertainty of ex-ante LCAs of emerging technologies and data and time limitations, this thesis study will only focus on contemporary PV systems, which include Mono-Si, Multi-Si and CdTe modules and the current BOS. The environmental impact is assessed from raw material extraction to disposal and electricity yield estimates are modelled. Like the other prospective LCA studies of contemporary design PV systems, technological developments and external developments will be taken into account. However, all the aforementioned studies assume an operational lifetime of 25-40 years. This thesis will incorporate different operational lifetime scenarios, based on technical and economic incentives. Due to lack of data and uncertainty of emerging recycling practices, this study assumes the current low-value recycling procedure to remain dominant in the coming decades.

3

Methodology

This chapter covers the methodology, including all the research methods and general steps to answer each sub-research question. This study takes a unique four-phase approach, as visualized in **Figure 3.1**, to systematically build the scenario-based prospective Life Cycle Assessment (LCA) of PV systems at city-wide scale. However, to ensure consistency with academic LCA studies of PV systems, the general LCA methodology is first covered in **Section 3.1**. The subsequent sections describes all specific methods and data used per research phase.

Outline Four-Phase Research Approach

In the first phase, a static LCA is conducted for three different types of PV modules and the system elements that are part of the balance of system (BOS). All elements except for the inverter are normalized to one square meter of PV module. The inverter is normalized to 2.5 kW power capacity. In the second phase an in-depth technology analysis of the PV modules is performed, accompanied with a socio-technical analysis of global developments in the context of PV system production and future electricity mixes in general. The results of this analysis are used as input for the General Morphological Analysis (GMA) to determine relevant development narratives and quantified scenarios in the third phase. In the final phase the life cycle inventory (LCI) that was used for the normalized baseline LCA is transformed based on the quantified scenarios derived from the GMA, to develop a normalized LCA of each system element produced in each year between 2012 and 2050. Finally, The optimal number of panels for each specific residential building in Amsterdam is derived with the PV WORKS model. Besides the number of panels, this model can also accurately calculate the electricity yield for each building. By integrating both the normalized LCAs and the accompanied electricity yield, a yearly city-wide environmental impact assessment can be conducted for 2012-2050.

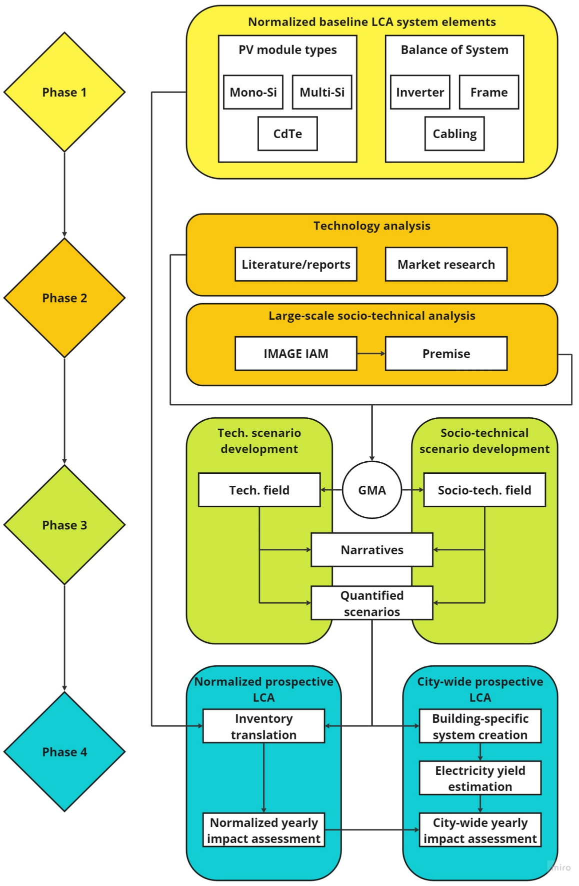


Figure 3.1: Visualization of research approach

3.1. LCA methodology

The research approach of this study consists of four distinct phases, wherein the normalized baseline Life Cycle Assessment (LCA) and the prospective LCA are dissected into two sequential segments. However, in alignment with global academic standards for LCA studies, this section comprehensively presents the essential details of the LCA process. This includes the goal and scope definition, life cycle inventory methods and data, impact assessment methods and interpretation methods.

What is a Life Cycle Assessment?

A Life Cycle Assessment (LCA) is a widely used methodology for evaluating the environmental impacts of products or services within a predefined scope of their lifecycle. It provides a systematic approach to identify and quantify the environmental burdens associated with various stages, including raw material extraction, manufacturing, use, and disposal/recycling. One of the key benefits of LCA is its ability to assess the environmental implications of different choices, allowing for informed decision-making and the identification of improvement opportunities (Guinée, 2002). Guinée et al. (2010) define LCA as: "a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle".

Global Standards for LCA Studies

ISO 14040 and ISO 14044 are the international leading standard for performing an LCA (Guinée et al., 2010). It offers guidelines for performing LCA in a consistent manner. As visualized in **Figure 3.2**, a standard LCA consists of four procedures: (1) the goal and scope definition; this phase covers the goal of the study, the functional unit(s), the research question and sets the regional, technological and temporal scope and system boundaries. (2) Inventory analysis (LCI); at this stage, foreground and background data should be collected to create the model within the scope as defined in the G&S definition. (3) Impact assessment; at this phase the impact of the system is assessed based on the characterization factors that translate the inventory of environmental flows into predicted impact within the family of impact categories chosen. This means that a complete set of relevant impact categories can be chosen. (4) Interpretation; at this stage the results are analysed to derive valuable conclusions for the research question. Although the steps are generally chronologically followed, a life cycle assessment is an iterative process which often requires modifications, based on inconsistencies found in the impact assessment or interpretation.

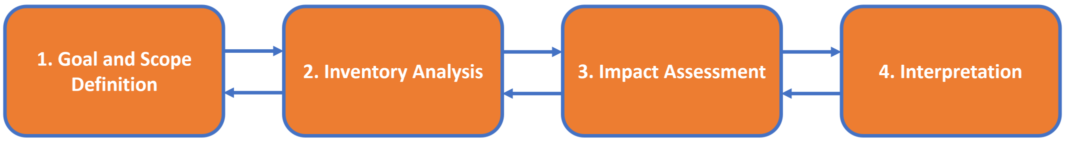


Figure 3.2: Standard LCA research approach

General Guidelines for LCA Studies of PV Systems

Besides the ISO 14040 14044 standards, the IEA Photovoltaic Power Systems Programme (IEA PVPS) provides further guidelines for LCAs of PV systems (Frischknecht et al., 2020). This study is conducted according to the general LCA ISO standards and follows the PV specific guidelines of the IEA PVPS, where deviations are explicitly mentioned. All required information for the four LCA procedures are given in the subsequent sections.

3.1.1. Goal and scope definition

The goal and scope phase of an LCA is meant to set the objective of the study and determine the technological, system, regional and temporal scope and boundaries. According to ISO 14040, the goal of an LCA states: the intended application, the reasoning for carrying out the study, the intended audience and whether the results are intended to be disclosed to the public (Curran, 2017). Furthermore, the scope should include: the product system to be analysed, the functions of the product system, the functional unit(s), the system boundary, impact categories selected and the methodology of impact assessment and subsequent interpretation, data requirements, assumptions and limitations (Curran, 2017).

Goal of the study

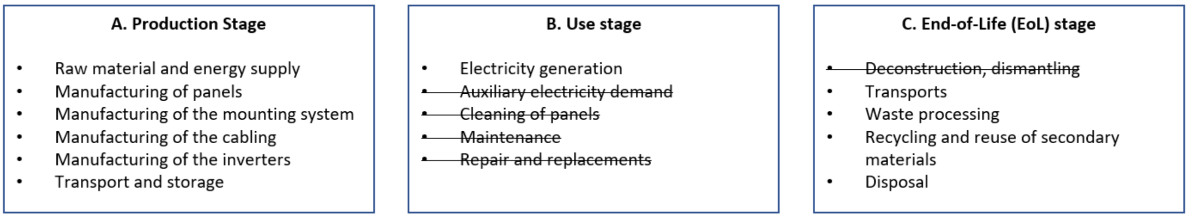
The goal of this study is to assess the net environmental impact of contemporary residential PV systems deployed on the roofs in Amsterdam between 2012 and 2050, under different technological development, socio-technical and operational lifetime scenarios. The reason for carrying out this study is the high ambition set by the municipality for upscaling PV systems in Amsterdam and the relative unknowns, related to the environmental impact of different upscaling routes that the city could take. On an academic level, multiple prospective LCAs have been performed, at system scale and global scale. Each of these studies assume an operational lifetime equal to the technical lifetime of the PV system. However, no study uses exploratory scenarios related to operational lifetime and technological development for PV systems at city scale. In this study, exploratory scenarios are used to provide insight in possible interventions that the municipality of Amsterdam could undertake and to account for uncertainty in future outlooks. The target audience of this study is therefore the municipality of Amsterdam. The study will only use publicly available data for the life cycle inventory (LCI) of the product system and will be supplemented by rooftop area data and electricity yield estimates from PV WORKS. The findings are intended to be disclosed to the public as a master thesis report.

Technological scope

Although new types of materials and technologies may emerge in the market, due to high uncertainty as described in the theoretical framework, this study focusses on contemporary technologies. The residential PV system technologies chosen for the LCA are: single-crystalline Silicon (Mono-Si), multi-crystalline Silicon (Multi-Si) and Cadmium Telluride (CdTe) PV modules, a string inverter, an Aluminium on-roof mounting system (flat roof and slanted roof) and copper cabling. Crystalline Silicon (c-Si) modules, also known as first generation modules, have dominated and are likely to continue dominating the PV market (Fraunhofer Institute, 2023; Ballif et al., 2022). Thin-film PV modules, or second generation PV modules, are the second biggest established industry for photovoltaics with a 5% global market share in 2022 (Fraunhofer Institute; 2023). CdTe modules account for 80% of the thin-film production, with First Solar as the biggest producer (IEA Trend Report, 2022). String inverters are currently the most widely used and cheapest type of inverter for residential PV systems (PV installer, personal communications).

System boundaries and functional units

Figure 3.3 gives an overview of the scope considered in the analysis of the product system of PV, in accordance with the IEA PVPS methodology guidelines (Frischkknecht et al., 2020). However, due to negligibility and lack of data several processes have been excluded in the use and end-of-life stages.



A. Production Stage

- Raw material and energy supply
- Manufacturing of panels
- Manufacturing of the mounting system
- Manufacturing of the cabling
- Manufacturing of the inverters
- Transport and storage

B. Use stage

- Electricity generation
- ~~Auxiliary electricity demand~~
- ~~Cleaning of panels~~
- ~~Maintenance~~
- ~~Repair and replacements~~

C. End-of-Life (EoL) stage

- ~~Deconstruction, dismantling~~
- Transports
- Waste processing
- Recycling and reuse of secondary materials
- Disposal

Figure 3.3: Lifecycle stages considered in the LCA

Avoided Impact

Since the goal of the study is to analyse the net environmental impact, both the negative environmental impact during production and end-of-life as well as the positive impact during operation are considered.

However, electricity yield (kWh) is not directly classified under an impact category. Therefore the electricity generated is translated into 'avoided' impact by displacing certain energy sources. Because of the high uncertainty in the future electricity mix and methodological constraints, multiple displacement scenarios have been considered: The projected future European electricity mix, the current Dutch electricity mix and the current European electricity mix. More information on these scenarios can be found in **Section 3.5**.

Building-Specific System Scaling

The number of panels, electricity yield and required inverter size interdependently varies per building. The number of panels is dependent on the available and suitable rooftop area. The electricity yield depends on several factors such as the amount of shadow, as further explained in **Section 3.7**. The required inverter is dependent on the peak power of the entire system. Therefore, to determine the net environmental impact at city-scale, the system should first be specified per building. The municipality of Amsterdam has set the target of utilizing 50% of the suitable rooftop capacity by 2030, and 100% by 2050 (Gemeente Amsterdam, n.d.). The constraint can therefore be regarded as the available rooftop area. Because of this, the system elements that are required are all normalized to one m^2 module area. Since the inverter size is dependent on the peak power of the PV system, it is first normalized to 2.5 kW and changed in size based on the building-specific PV system power capacity. How this sizing is done, is shown through an example in **Section A.2.1**. These normalized system elements are used as building blocks for the building-specific system, as visualized in **Figure 3.4**. The functional units within the scope of the PV system manufacturing to regional storage are shown in **Table 3.1**. In this study, regional storage refers to the storage of the system elements after long-distance transport and before the installation.

System Element	Functional Unit
Mono-Si Module	1m^2 Mono-Si module, at regional storage
Multi-Si Module	1m^2 Multi-Si module, at regional storage
CdTe Module	1m^2 CdTe module, at regional storage
String Inverter	String inverter with 2.5kW capacity, at regional storage
Mounting System	Mounting system, normalized to 1m^2 of module, at regional storage
Cabling (AC+DC)	Cabling, normalized to 1m^2 of module, at regional storage

Table 3.1: System elements and their functional units

Flowchart of Building-Specific LCA

The functional unit at PV system scale is defined as: ‘operation of a PV system on building X from year Y to Z’, where X indicates the particular residential building, Y indicates the installation year and Z indicates the year of disposal. Z-Y thus indicates the operational lifetime, for which different scenarios will be assessed. An additional scenario is added where the disposed but still usable panels are reused (from year Z to year W). A visualization of the processes, economic flows and system boundaries per PV system is shown in **Figure 3.4**.

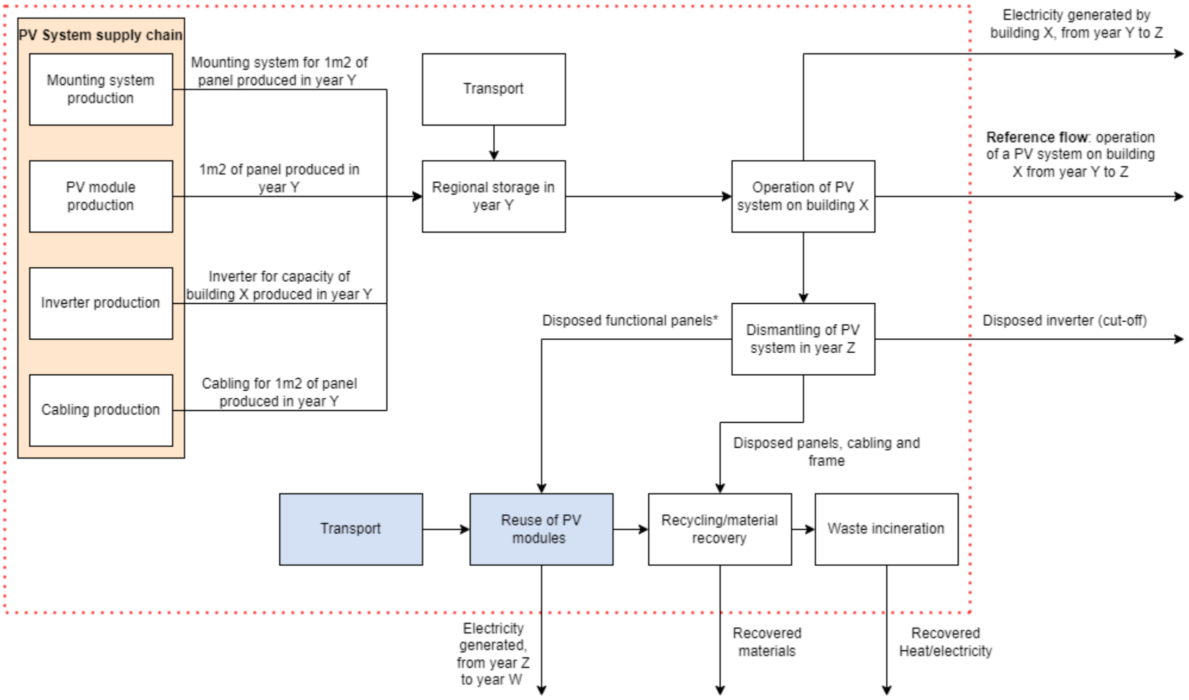
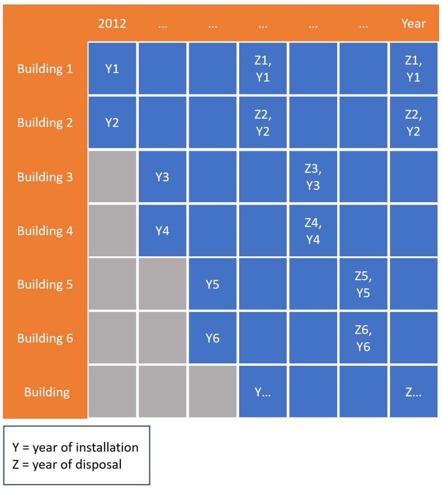


Figure 3.4: Flowchart of processes and flow included for one PV system

* A simplified reuse scenario is also considered, where disposed functional panels are directly reused. In this scenario a new inverter and cabling are installed at the new location. The mounting system is reused as well.

City-Wide System Installations

Since the net environmental impact is considered at city-wide scale and between 2012 and 2050, the reference flow given in **Figure 3.4** is distributed like building blocks over time and space, as visualized in **Figure 3.5**. A certain number of installations take place in year Y, depending on the upscaling rate. Similarly a certain number of systems are disposed. Because of technological development and socio-technical changes, the LCA of each normalized system component will be different, affecting the impact induced in year Y. Similarly, the electricity yield will also be different because of technological development. Furthermore, between year Y and Z, the electricity yield will also decrease because of cell degradation. As soon as a system is disposed, a new system will be installed. This novel method allows for accurate system sizing and scaling at a city-wide scale.



	2012	...	...	...	...	...	Year
Building 1	Y1			Z1, Y1			Z1, Y1
Building 2	Y2			Z2, Y2			Z2, Y2
Building 3		Y3			Z3, Y3		
Building 4		Y4			Z4, Y4		
Building 5			Y5			Z5, Y5	
Building 6			Y6			Z6, Y6	
Building				Y...			Z...

Y = year of installation
Z = year of disposal

Figure 3.5: Visualization of city-wide LCA approach

Temporal Scope

The temporal scope in this LCA consists of PV systems manufactured and installed between 2012 and 2050. A life cycle inventory (LCI) for each system element until regional storage is provided by IEA PVPS (Frischknecht et al., 2020). This LCI is used as a baseline and transformed for each installation year based on technological development, and global socio-technical changes. The LCA is defined as a scenario-based prospective LCA because the life cycle inventory and corresponding impact changes over time based on future scenarios. However, it should be noted that the baseline LCI is mostly based on data collected by Frischknecht et al. in 2020. Therefore transformations are also made of the LCI for earlier years (since 2012). More information on the transformations and scenarios considered can be found in **Section 3.6**.

Regional Scope

Stage A (production) is distributed globally based on the current market and future projections. China is currently the most dominant producer of poly Silicon (79%, 2021), c-Si wafers (97%, 2021), c-Si cells (81%, 2021) and c-Si modules (75%, 2021) and this relative production capacity is only expected to increase (IEA PVPS Trend Report, 2022). As a response the European Commission and the EU member states have put urgency on increasing the production capacity within Europe (European Commission, 2020; Ministerie van Economische Zaken en Klimaat, 2023). First Solar is the most dominant CdTe thin-film module producer and 87% of the modules are produced in Malaysia (Frischknecht, et al., 2020). According to the IEA LCI, the CdTe semi-conductors are produced in the US, which is also taken as an assumption for this study. **Table 3.2** provides an overview of the production region for each system element and the foreground process of a c-Si module, colored in grey. All system elements from China and Malaysia follow the international trade of freight ships along the route to the port of Rotterdam, as visualized in **Figure 3.6**. Furthermore, this figure provides an overview of the production region and electricity mix chosen for each system element. For the transportation of technologies produced in Europe, trucks are used with an average travelling distance of 650 km (Berlin to Amsterdam). This distance is taken since currently most European PV system elements are produced near Berlin (Fraunhofer, 2023). Stage B and C both occur in Amsterdam. Although currently most PV modules are recycled in Belgium (WEEE NL, personal communications), recycling facilities may likely open in the Netherlands in the future.

System element	**Production region foreground process**
Metallurgical grade Silicon	China (CN) or Europe (RER)
Solar grade Silicon	China (CN) or Europe (RER)
Single crystalline Silicon	China (CN) or Europe (RER)
Multi-crystalline Silicon	China (CN) or Europe (RER)
Mono-Si wafer	China (CN) or Europe (RER)
Multi-Si wafer	China (CN) or Europe (RER)
Mono-Si cell	China (CN) or Europe (RER)
Multi-Si cell	China (CN) or Europe (RER)
CdTe semi-conductor	The United States (US)
Mono-Si module	China (CN) or Europe (RER)
Multi-Si module	China (CN) or Europe (RER)
CdTe module	Malaysia (MY)
String inverter	Europe (RER)
Mounting system	Europe (RER)
Cabling (AC+DC)	Europe (RER)

Table 3.2: Production Regions of All Foreground Processes

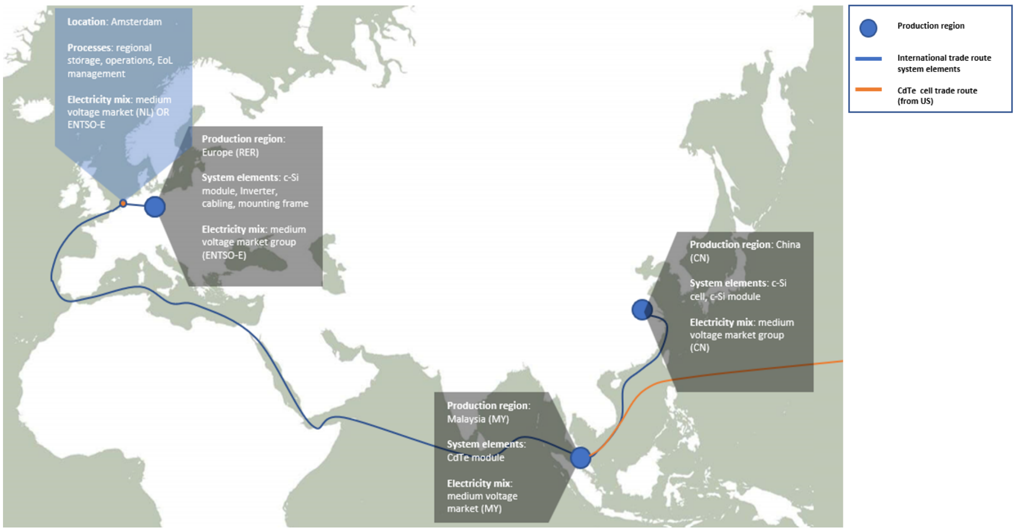


Figure 3.6: Visualization of production regions, transport routes and electrixity mixes

Impact Categories Selected

Various impact categories can be considered to determine the environmental impact of PV systems. This study adopts the ReCiPe midpoint 1.13 family of impact categories. This method is chosen since it allows for translations into shadow costs, as CE Delft has recently published a report with the environmental impact of various ReCiPe impact categories expressed in shadow costs. More information on the use of shadow costs can be found in **Section 3.8**. Three cultural perspectives can be incorporated in the ReCiPe method: individualist, hierarchist, and egalitarian, representing short-term to long-term impacts, respectively. For this LCA, the hierarchist perspective will be used, since it is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms (ReCiPe, 2017). The ReCiPe midpoint 1.13 method consists of 18 impact categories that cover a wide range of environmental concerns. **Table 3.3** shows all impact categories considered in this study and their accompanying indicators and units. The ReCiPe impact categories are readily available within the activity browser, making them easily accessible for immediate use in the LCA analysis.

Impact Category	Indicator*	Unit
Agricultural Land Occupation	ALOP	Square meter-year
Climate Change	GWP100	kg CO2-Eq
Fossil Depletion	FDP	kg Oil-Eq
Freshwater Ecotoxicity	FETPinf	kg 1,4-DCB-Eq
Freshwater Eutrophication	MEP	kg N-Eq
Human Toxicity	HTPinf	kg 1,4-DCB-Eq
Ionising Radiation	IRP	kg U235-Eq
Marine Ecotoxicity	METPinf	kg 1,4-DB-Eq
Marine Eutrophication	MEP	kg N-Eq
Metal Depletion	MDP	kg Fe-Eq
Natural Land Transformation	NLTP	Square-meter
Ozone Depletion	ODPinf	kg CFC-11-Eq
Particulate Matter Formation	PMFP	kg PM10-Eq
Photochemical Oxidant Formation	POFP	kg NMVOC-Eq
Terrestrial Acidification	TAP100	kg 1,4-DCB-Eq
Terrestrial Ecotoxicity	TETPinf	kg 1,4-DCB-Eq
Urban Land Occupation	ULOP	Square meter-year
Water Depletion	WDP	Water-Eq

Table 3.3: Impact categories of the ReCiPe v1.13 method

* **Note:** in the preceding chapters, the impact categories are abbriated by their indicator for easy identification and readability in the tables and figures. However, it should be noted that the impact categories are not the same as the indicators. For example, the indicator for Climate Change is GWP100, which is short for Global Warming Potential within a 100 year time-frame.

Life Cycle Inventory Methods and Data

The life cycle inventory (LCI) data of each system element is adopted from the IEA PVPS Life Cycle Inventory report for the baseline LCA (Frischknecht et al., 2020), and modified to fit the purpose of this study. The EcoInvent database (v3.8) is used for all background processes and the normalized baseline LCA is performed within the software Brightway 2.0 using the GUI of Activity Browser, an open source software for LCA (Steubing et al., 2020). All general assumptions and modifications can be found in **Appendix D**. Technological as well as socio-technical scenarios are documented in excel and translated into scenario difference files. These files are then combined into a superstructure, including background process changes and integrated back into Activity Browser to create different LCAs for each particular production year. More information on this procedure can be found in **Section 3.7**.

Life Cycle Impact Assessment Methods

The life cycle impact assessment results of each normalized system element, until regional storage for each production year, are retrieved using the GUI of Activity Browser. These results are then integrated into a Python model, which determines the PV system and city-wide environmental impact, including the avoided impact due to the electricity yield from solar PV. More information of the integration of this data into the Python model, and the functionality behind this model can be found in **Section 3.7**.

Interpretation and treatment of uncertainty

The results of the LCA will be further checked by means of contribution, sensitivity and consistency analyses. Through an iterative process, any inconsistencies and issues based on the results will be evaluated and the model will be redesigned. A scenario-based approach is conducted to account for several potential uncertainties, further clarified in **Section 3.6**. The key assumptions of the LCA can be found in the next paragraph.

Key assumptions normalized baseline LCA and prospective LCA

This section summarizes the key assumptions used for the normalized baseline LCA and the prospective LCA. **Table 3.4** provides an overview of the key assumptions. Clarification of these assumptions and process-specific assumptions are given in **Appendix D**. Limitations are discussed in **Section 5.3**.

A. Key Assumptions Normalized Baseline LCA
A1. No closed-loop recycling takes places. Only open-loop recycling according to current practice in Europe
A2. The average string inverter has a technical lifetime of 12 years
A3. The Balance Of System, including inverter, cabling and mounting system does have tech. Development
A4. European background processes used for processes which lack data for China
A5. National medium voltage electricity group used for electricity consumption Chinese processes
A6. ENTSO-E medium voltage electricity mix used for electricity consumption European processes
A7. Impact during maintenance and construction/deconstruction can be neglected
A8. End-of-Life management of the inverter is cut off/disregarded in this study
B. Key Assumptions Prospective LCA
B1. Linear upscaling rate assumed from 2012 to 2030 (50% capacity) and from 2030 to 2050 (100% capacity)
B2. End-of-Life (EoL) management remains similar to current process
B3. Only contemporary technologies with corresponding technological development installed
B4. BOS (inverter, mounting system and cabling) tech. development can be neglected
B5. Immediate re-installation takes place after disposal
B6. The dynamic european ENTSO-E grid is displaced

Table 3.4: Key assumptions of the normalized baseline LCA and prospective LCA

3.2. Overview Research Phases

After establishing the overarching LCA methodology in accordance with ISO 14040/14044 standards, the subsequent sections delve into the precise methods and data employed to conduct the prospective LCA within various relevant scenarios. To ensure clarity, the research approach visualization is reiterated in **Figure 3.7**.

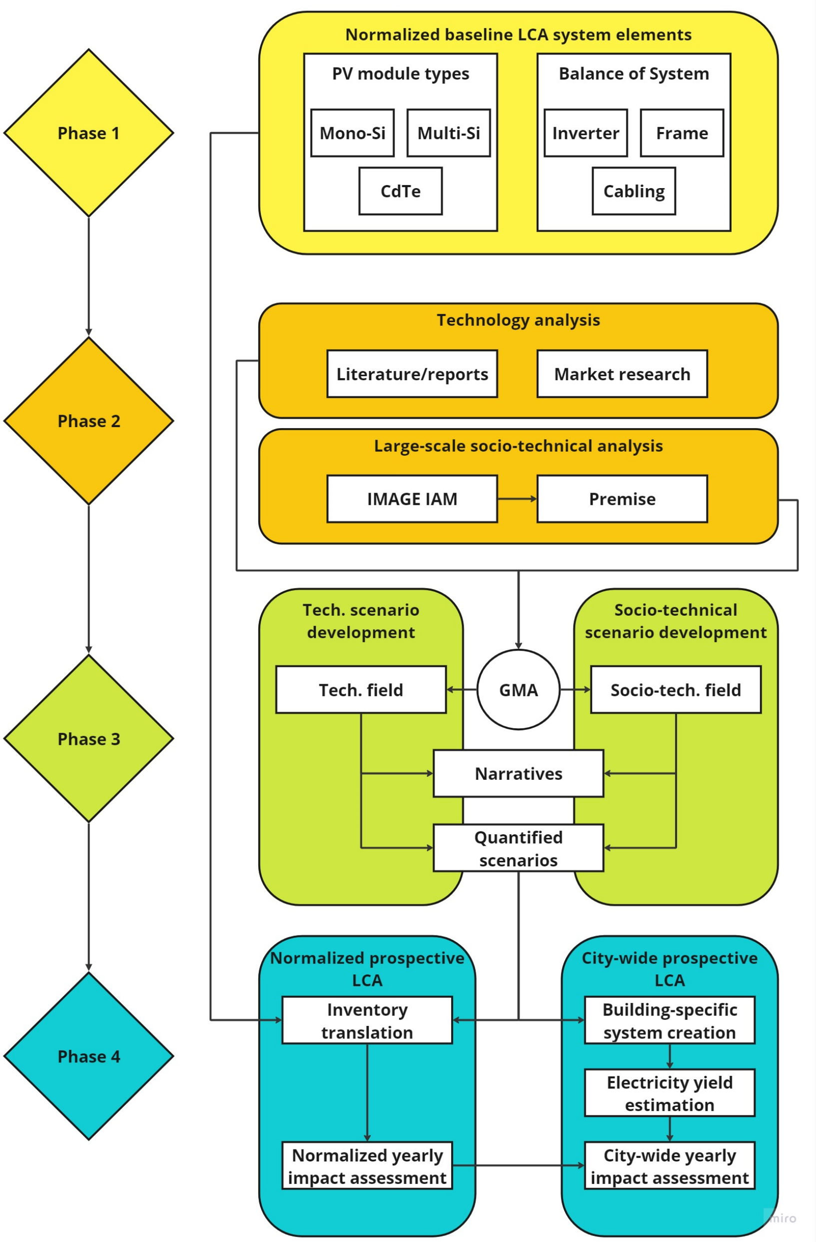


Figure 3.7: Visualization of the four research phases

3.3. Phase 1: Normalized baseline LCA system elements

In the first phase, a static LCA is conducted of each system element separately from raw material extraction to regional storage, as summarized in **Table 3.5**. Regional storage refers to the system elements being stored in the Netherlands, after production and transport. This study takes the static LCA as baseline for the prospective LCA. The static LCA is referred to as the 'Normalized Baseline LCA', because the LCIs of all system components have been normalized to one m^2 of module, with the exception of the inverter which is modified based on each system's peak power. The calculation for the normalization of the inverter is provided in **Section A.2.1** of **Appendix A**. The results of the normalized baseline LCA, including a contribution analysis of production processes, can also be found in **Appendix A**.

Key Information Methods and Data

The temporal scope in this case is still confined to production in 2020, as the most recent data from the IEA PVPS life cycle inventory report, conducted in 2020, is used for each foreground process (Frischknecht et al., 2020). All background processes are taken from the EcoInvent 3.8 database. The mounting system is subdivided into a flat roof mounting system and slanted roof mounting system and used on each building depending on the roof type. All relevant information regarding the scope of the LCA, impact categories chosen and assumptions and limitations have been described in the LCA methodology in **Section 3.1**. The LCA is performed with the software Brightway 2.0, using the GUI of Activity Browser.

Use of Results

The LCA results of each system component will be used as building blocks in phase 4. In phase 2 and 3 scenarios will be developed, based on a technology analysis and socio-technical analysis, to transform the life cycle inventory of this baseline LCA into LCAs for each production year between 2012 and 2050. The scaling process is further described in **Section 3.1.1**.

System Element	Functional Unit
Mono-Si Module	1m^2 Mono-Si module, at regional storage
Multi-Si Module	1m^2 Multi-Si module, at regional storage
CdTe Module	1m^2 CdTe module, at regional storage
String Inverter	String inverter with 2.5kW capacity, at regional storage
Mounting System	Mounting system, normalized to 1m^2 of module, at regional storage
Cabling (AC+DC)	Cabling, normalized to 1m^2 of module, at regional storage

Table 3.5: System elements and their functional units

3.4. Phase 2A: Technology analysis

This section covers all technological variables considered in the prospective LCA of contemporary design PV modules. As mentioned and justified in the LCA methodology, the technological changes of the balance of system (BOS) are not considered in this study. Furthermore, only first generation crystalline Silicon modules and second generation thin-film Cadmium Telluride modules are considered. This study calculates the technological development for each parameter based on historic data until 2022, predicts the development until 2032 and explores different development pathways from 2032 until 2050. An overview of the input parameter values for each scenario, chosen through the General Morphological Analysis (GMA), is provided in **Appendix C**.

3.4.1. Crystalline Silicon PV modules

First generation contemporary design crystalline Silicon PV modules are subcategorized into modules with Mono-Si and Multi-Si cells. As reported in the yearly International Technology Roadmap for Photovoltaic (ITRPV) reports and highlighted in literature (Baliff et al., 2022), the well-established production line, structural characteristics and performance of c-Si modules are optimised to decrease the Levelized Cost Of Energy (LCOE). Based on historic trends and future projections, the life cycle assessment of the products can be updated accordingly. In the theoretical framework, several technological parameters which have been modified by earlier studies are highlighted. This study will also integrate these parameters into the historic trends and multi-scenario projections of technological development. Besides these parameters, several other factors have been considered in the technology analysis of crystalline Silicon modules. All parameters and their main assumptions have been listed in **Table 3.6**. The market share of Multi-Si cells after 2021 is assumed negligible. The market share of each cell type is based on global historic data provided by Fraunhofer Institute (Fraunhofer Institute, 2023).

Parameter	**Assumptions**
Module efficiency	Simplified module efficiency estimates in line with market shares and other factors of cell technologies used in other calculations.
Form factors & corresponding module area	Only 60-cell G1, 120-half-cell M6, 108 half-cell M10, and 120 half-cell M10 considered. Average module area does not exceed 2.00 m^2.
Aluminium consumption	Only Aluminium frame considered. Aluminium in cell neglected. No Aluminium in frameless panels. Aluminium lost during production neglected.
Glass consumption	All frameless panels have a glass backsheet. All framed panels have a plastic back sheet. Glass lost during production neglected.
Module weight	Aluminium and glass weight vary, wafer and other material weights fixed.
Silver consumption	BSF and PERC cells have similar Silver consumption. SHJ, back contact, and TopCon have a similar Silver consumption.
Silicon consumption	Same Silicon per cell assumed between 2012 and 2017.
Electricity demand solar grade Silicon production	Electricity demand only affected by Siemens & FBR process market shares

Table 3.6: Parameters considered in technology analysis c-Si modules and main assumptions

Module efficiency

The module efficiency represents the ability of the PV module to convert sunlight into electricity. It is lower than the cell efficiency, because of various reasons, amongst which the spacing between the cells, the shading of bus bars and additional electrical losses. The module efficiency of c-Si modules is derived from historic trends and projections of ITRPV until 2032. Exploratory scenarios are based on literature.

Form factors c-Si panels

The potential electricity produced by one PV module is directly related to the module efficiency, the number of cells and the cell size. Over the last 5 years, the c-Si industry has seen a big increase in cell size, moving from cells of 252 mm2 (G1) to cells of 331 mm2 (M10) and even 441 mm2 (M12) for utility scale modules (ITRPV reports). However, the number of cells per module nowadays is usually 108 or 120 half cells, which is roughly similar to the original 60 cell module structure. The number of cells and cell area combined can be defined as the form factor, which mostly determines the module size. In this study, four different form factors are considered: 60-cell G1 modules, 120 half-cell M6 modules, 108 half-cell M10 modules and 120 half-cell M10 modules. M12 cells are not considered since they are generally only adopted in utility scale plants (ITRPV, 2022). The ITRPV has provided yearly market shares for each form factor and additionally provides projections on the future market share of each form factor until 2032.

Average area c-Si panels

This study assumes that the area of the panel is directly related to the form factor. **Table 3.7** provides an overview of the module dimensions for each form factor. The thickness is correlated to the glass thickness which changes over time, and is therefore not determined based on the form factor. The panel dimensions are based on several best-sold panels that have been produced in the last 5 years, when the shift from G1 to M10 wafers occurred.

Form factor	Cell area	Panel dimensions	Area
60 G1/M2/M4 cells	252 mm2	1.00m x 1.69m	1.69 m2
120 M6 half-cells	276 mm2	1.05m x 1.78m	1.87 m2
108 M10 half-cells	331 mm2	1.13m x 1.72m	1.95 m2
120 M10 half-cells	331 mm2	1.13m x 1.91m	2.16 m2

Table 3.7: Form factors and corresponding cell area, panel dimensions and panel area

The separate module dimensions are adopted into the PV Works model to determine how many panels can fit on each rooftop in Amsterdam, for each form factor case. More information on this model can be found in **Section 3.7**. The average width, length and area is calculated using **Equation 3.1, 3.2, 3.3** respectively, where MS_i is the market share proportion of form factor i, Wd_{avg} is the average module width, L_{avg} is the average module length and A_{avg} is the average module area.

$$Wd_{\text{avg}} = \sum_i (MS_i * Wd_i) \tag{3.1}$$

$$L_{\text{avg}} = \sum_i (MS_i * L_i) \tag{3.2}$$

$$A_{\text{avg}} = Wd_{avg} * L_{avg} \tag{3.3}$$

In this study, the average module area does not exceed 2.00 m^2. The German trade union has set a constraint on a panel size of 2 m^2 for installation safety measures (PV installer, personal communications). Since the German PV market is one of the biggest markets in Europe, this study assumes that the market share in the Netherlands will also predominantly remain centred around M10-108 half cells. Since these panels have an average module area of 1.95 m^2, it is also assumed that the average panel size will remain roughly 2 m^2 in all technological development scenarios.

Aluminium consumption

In this study, it is assumed that all panels with a frame have an Aluminium frame, since this is currently the most common frame type. The amount of Aluminium per m^2 module is determined based on the following factors: (1) the yearly market share of frameless panels, (2) the average yearly module dimensions and corresponding perimeter, (3) the yearly amount of Aluminium per meter perimeter. The average module perimeter is determined by **Equation 3.4**, where P_{avg} is the average perimeter, Wd_{avg} the average width and L_{avg} the average length based on the market shares of different form factors with different dimensions.

$$P_{avg} = 2 * (Wd_{avg} + L_{avg}) \tag{3.4}$$

After the ITRPV 2014 report, the ITRPV stopped projecting the average amount of Aluminium per meter perimeter. The final projection of 0.4 kg per meter perimeter by 2020 is assumed to remain constant until 2050 for all technological development scenarios since maintaining the structural integrity of PV modules to avoid early failure has a higher priority. It should be noted that other frames with a lower material intensity and a similar or higher structural integrity may take over the market in the future. However, the projected market share of frameless panels is considered in this study and differs per technological development scenario. This yearly market share is incorporated in the average aluminium consumption per m^2 c-Si module. The average Aluminium consumption per m^2 panel is calculated using **Equation 3.5**, where AC_{avg} is the average Aluminium consumption per m^2 panel, MC_f is the market share proportion of framed panels, APP is the Aluminium consumption per meter perimeter and P_{avg} is the average perimeter.

$$AC_{avg} = MC_f * APP * P_{avg} \tag{3.5}$$

The aluminium consumption in c-Si cells is neglected due to its relatively marginal share of 0.046 kg per m^2 panel based on the IEA-PVPS LCI, compared to 1.23 kg of aluminium frame per m^2 panel in 2020, based on own calculations. The Aluminium lost during production is neglected, as the recycling rate of Aluminium is relatively high and material losses during smelting, casting and forming are generally low (International Aluminium Institute, 2020).

Glass consumption

The glass thickness decreases over time based on literature and ITRPV projections. The average glass consumption in kg per m_2 panel is determined using **Equation 3.6**, where GC_{avg} is the average glass consumption, FGT_{avg} is the average front glass thickness, MS_{FL} is the market share proportion of frameless panels, BGT_{avg} is the average back glass thickness, A_{avg} is the average module area and ρ_g is the glass density.

$$GC_{avg} = (FGT_{avg} + MS_{FL} * BGT_{avg}) * A_{avg} * \rho_g \tag{3.6}$$

The glass density is 2500 kg/m^3 and it is assumed that all frameless panels have a glass back sheet, since the ITRPV projects a steep and steady increase in market share of glass back sheets the coming (ITRPV, 2022). It is also assumed that all framed panels have a plastic back sheet. In reality some framed panels have a glass back sheet and some frameless panels have a plastic back sheet. Furthermore, it is assumed that no glass is lost during manufacturing. In reality, some glass may get damaged and is lost in the production process. However, When comparing the calculations to the IEA-PVPS LCI, there is only a slight difference of roughly 10% (7.88 kg compared to 8.8 kg). This is not incorporated in the calculations because of the highly dynamic nature of future manufacturing developments and variations in manufacturer's data, on which the IEA PVPS LCI is based.

Module weight

Several parameters have been integrated into the module weight calculation. First of all, the frame weight and glass weight variables are included. These account for the highest proportion of the module weight, as given in the Bill of Materials (BoM) in the IEA PVPS LCI. Based on this BoM, the weight of the wafers, internal metals and plastics is roughly 2.3 kg per m2 panels, which is roughly 17% of the total weight in 2020. The 2.3 kg is assumed to remain constant over time with the Aluminium and glass weight varying based on the earlier described calculations. **Equation 3.7** shows the calculation for the average module weight, where W_{avg} is the average module weight per m^2 panel, GC_{avg} the glass consumption and AC_{avg} the Aluminium consumption. For both the glass consumption and Aluminium consumption it is assumed that no material is lost during production, making it compatible with the module weight.

$$W_{avg} = GC_{avg} + AC_{avg} + 2.3 \tag{3.7}$$

The module weight is used to determine the environmental impact of transport from China, Malaysia and Germany to Amsterdam, as explained in the LCA methodology. The module weight is expressed in ton-kilometer (tkm), and since the reference flow is normalized to one m^2 of panel, the module weight per m^2 of panel also affects the required transport. Furthermore, the module weight is also used to determine the environmental impact and avoided impact due to End-of-Life (EoL) management and material recovery. The IEA-PVPS LCI provides data on the end-of-life management of c-Si modules per kilogram of module. This data is used in this study, where the EoL and material recovery processes are assumed to remain constant, as explained in the LCA methodology.

Silver consumption

The IEA PVPS LCI includes Silver in the front metallization paste of the Silicon cells. The ITRPV provides historic data and projections until 2032 on the average Silver consumption per cell technology. In this study, the historic and projected market share of BSF/PERC cells and SHJ/Back contact/TopCon cells provided by ITRPV, and the average Silver consumption per cell technology are used to derive the Silver consumption per m2 panel. It is assumed that BSF and PERC have the same Silver consumption, as well as SHJ, back contact and TopCon cells. In reality, there are small variations. The market share of bifacial cells until 2032, which have 0.005 grams more Silver per cell according to the ITRPV, has also been incorporated in the calculations. The yearly average Silver per m^2 panel until 2032, is calculated using **Equation 3.8**, with MS_i being the market share proportion of form factor i, NC_i the number of cells of form factor i, MS_j the market share proportion of cell technology j, SC_{ij} the Silver consumption of cell technology j with a wafer size of form factor i and MS_k the market share proportion of bifacial cells.

$$SC_{avg} = \sum_i \sum_j (MS_i * NC_i * MS_j * SC_{ij} + NC_i * MS_k * 0.000005) \tag{3.8}$$

The front side metallization paste in EcoInvent 3.8 contains 84% Silver, 5% lead and 11% organic chemical. Until 2022 the same proportions of materials are assumed, thus linearly correlating the front side metallization paste consumption with the Silver consumption. However, several research institutes, amongst which Fraunhofer Institute, have recently progressed in the replacement of Silver by Copper in the metallization paste (Fraunhofer Institute, 2022). Since there is a limit in metallization paste reduction, this study assumes that the reduction of silver consumption is compensated by an increase of copper consumption after 2022. To avoid over-complication in the scenario translation file, described in **Section 3.7**, the organic chemical is replaced by Copper.

Silicon consumption

The ITRPV provides historic data and projections until 2032 of the Silicon consumption for each wafer area (G1, M6, M10). The Silicon consumption is directly correlated with the wafer thickness, which is estimated to decrease considerably over the next decades, and the kerf losses and additional losses during wafer production. The average Silicon consumption is calculated using **Equation 3.9**, where SIC_avg is the average Silicon consumption per m^2 panel, MS_i is the market share proportion of form factor i, NC_i is the number of cells of form factor i and SIC_i is the Silicon consumption for the wafer size of form factor i. The Silicon consumption is assumed to be constant between 2012 and 2017, since the wafer thickness and kerf losses have also been constant in this time period according to the ITRPV reports.

$$SIC_{avg} = \sum_i (MS_i * NC_i * SIC_i) \tag{3.9}$$

Electricity consumption Solar Grade Silicon production

There are two main production processes that can be used to produce high value Solar grade Silicon: (1) the Siemens process and (2) the Fluidized Bed Reactor (FBR) process. The Siemens process is the most common process whereas the FBR process is gaining traction and expected to increase with a market share from 5% in 2021 to 20% by 2031 (ITRPV, 2022). Frischknecht et al. (2015) predict a 30 kWh/kg electricity demand for Solar Grade Silicon production by FBR, based on expert discussions, compared to 49 kWh/kg by the Siemens process according to the most recent LCI (Frischknecht et al., 2020). This study takes these electricity demand for both processes and assumes that the rest of the solar grade Silicon production process remains unchanged. The electricity demand of the processes itself remain unchanged over time. The average electricity demand can thus be calculated by using **Equation 3.10**, Where MS_S is the market share proportion of the Siemens process, MS_{FBR} the market share proportion of the FBR process and ED denotes the electricity demand.

$$ED_{avg} = MS_S * ED_S + MS_{FBR} * ED_S \tag{3.10}$$

3.4.2. Cadmium Telluride PV modules

Second generation contemporary design Cadmium Telluride (CdTe) PV modules are also included in the technology analysis and incorporated in future scenario explorations. Currently CdTe panels make less than 5% of the global market share, but they are the biggest competitors to contemporary design c-Si modules. This study takes the static LCA of First Solar's Series 4 module. This module is much smaller than contemporary design c-Si modules (0.6m x 1.2m). First Solar also produces bigger modules such as the Series 6 module (2.0 x 1.2m), but this module has a weight of more than 33 kg. The module size and weight is not fit for residential deployment due to structural and installation constraints. Due to the uncertainty of future CdTe module size, the area of the panels is assumed constant. The parameters which are modified, based on historic data and projections provided by literature, are shown in **Table 3.8**. Less parameters are modified than for c-Si modules because of a lack of data. However, as shown in the static LCA results in **Appendix A**, the environmental impact during production is already much lower than the environmental impact of c-Si module production. The most important tech. development parameter is therefore the module efficiency, which is currently lower for CdTe modules. Optimistic, exploratory scenarios for the module efficiency based on projections by tech. developers may therefore provide insightful results, despite having less structural or production modifications.

Parameter	**Assumptions**
Module efficiency	Only scenario-specific assumptions
Glass consumption	Same thickness decrease as c-Si modules assumed after 2018
Module weight	Only varies based on glass consumption, since the panel is frameless and the panel area remains constant. Other structural components such as the cells are also assumed to have a constant weight
Cadmium Telluride consumption	Linearly decreases with wafer thickness projections
Electricity demand panel production	Constant electricity demand before 2020

Table 3.8: Parameters considered in technology analysis CdTe modules and main assumptions

Module Efficiency

The module efficiency of CdTe modules is based on literature, product reports provided by First Solar and projections based on literature, extrapolations and technology developers, depending on the technological development scenario.

Glass Consumption

The glass thickness before 2018 is based on literature and assumed constant. After 2018, the glass thickness is assumed to decrease at a similar rate as the c-Si module glass thickness. The glass consumption is calculated with the same equation as for c-Si modules.

Module Weight

The module weight decreases based on the glass consumption. Since the panel is frameless and the module size is assumed constant, the weight is not modified based on any other parameters. Other structural components are also assumed to have a constant weight. Therefore, the weight of the product report of First Solar Series 4 is taken and modified based on the glass thickness.

Cadmium Telluride Consumption

The Cadmium Telluride consumption is assumed to linearly decrease with the projected wafer thickness decrease for various scenarios, derived from literature. The kerf losses which have been taken into account for the c-Si cells are assumed to be negligible for the CdTe cells.

Electricity Demand Module Production

The electricity demand is based on projections provided by literature and linearly interpolated for any unknown years. The electricity demand is assumed to remain constant before 2020.

3.5. Phase 2B: Socio-technical analysis

Besides the technological system considered in this study, the overarching socio-technical system at society level is also considered. Socio-technical systems thinking takes into account the dynamic nature and interrelatedness of social and technical systems (Vespignani, 2012). The socio-technical system itself, which is stabilized by lock-in mechanisms such as institutional commitments can have a profound impact on the environmental impact of technologies along their lifecycle (Geels et al., 2017). In the context of the environmental impact of contemporary PV system deployment, this mainly concerns the international ambition of fighting environmental pollution and its effects on the performance, supply chain and management of PV systems.

3.5.1. Background Information Socio-Technical Scenarios

This section provides all the relevant background information on the socio-technical scenarios that have been chosen for the General Morphological Analysis (GMA). **Section 3.5.2** describes the method for the analysis of these scenarios.

International commitment to fight global warming

In 2015, 196 parties at the UN Climate Change Conference (COP21) pledged to a legally binding international treaty on climate change called the Paris Agreement. The overarching goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." (United Nations, 2015). Since then, countries have created climate action plans and set GHG emission reduction targets to align with the international ambitions document in the Paris agreement. Since 2020, countries have submitted their national climate action plans, known as nationally determined contributions (NCDs). The societal effects of national action plans have been and still are crucial to increase momentum of renewable energy generation. For instance, the price and performance improvements of wind, PV and biogas technologies which helped unfolding the German energy transition, involved support from industrial coalitions, positive cultural framing and generous policy support, through the Renewable Energy Act (Geels et al., 2017).

Shared Socioeconomic Pathways

Shared socioeconomic pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100, which have been central to the work of the UN climate reports produced by the Intergovernmental Panel on Climate Change (IPCC) (Allan et al., 2021). Each SSP is based on a different future narratives (Allan et al., 2021) as visualized in Figure 3.8.

Figure 3.8: Shared Socioeconomic Pathways

This study adopts the middle of the road pathway with intermediate challenges, but in different Representative Concentration Pathways (RCPs), as described in the next paragraph. In SSP2, population growth is moderate, reaching around 9 billion by 2100. Income levels are average, and technological progress continues without significant changes in production and consumption patterns. Inequality reduces gradually. SSP2 poses moderate challenges for both mitigation and adaptation, indicating a medium adaptive capacity. (Allan et al., 2021)

Representative Concentration Pathways

In the 2014 Fifth Assessment Report (AR5) the IPCC introduced the Representative Concentration Pathways (RCPs). The RCPs define different trajectories for greenhouse gas concentrations and serve as inputs for climate simulations, enabling the evaluation of potential warming by the end of the century (IPCC, 2014). Various RCPs have been developed and evaluated by the IPCC amongst which:

- **RCP 1.9:** A pathway that limits global warming to below 1.5 °C, which is aligned with the aspirational goal of the Paris Agreement, as mentioned earlier.
- **RCP2.6:** The scenario where global temperature rise is kept below 2 °C by 2100, which can be linked to the overarching goal of the Paris Agreement.
- **RCP 6.5:** This is considered as the baseline scenario where no stringent climate policies are implemented.

The Shared Socioeconomic Pathways (SSPs) establish the socioeconomic context within which emission reductions can be achieved. Each SSP can be compatible with some RCPs, as long as it aligns with the underlying narrative and is plausible within that context. By combining the RCPs and SSPs, the potential climate outcomes based on different socioeconomic and emission reduction scenarios can be assessed. RCP 1.9, 2.6 and 6.5 are all compatible with SSP2 and therefore these scenarios have been chosen as options in the general morphological analysis.

IMAGE Integrated Assessment Model

By means of integrated assessment models (IAMs), environmental consequences can be linked to human activities in various scenarios, integrating land, energy, climate and policy models in one framework (PBL, n.d.). One such a computer model is the IMAGE model, which has been developed by PBL Netherlands Environmental Assessment Agency. It has been designed to analyse large-scale and long-term interactions between human development and the natural environment. The global deployment of renewables, amongst which distributed solar power, linked to the SSPs is also integrated in the model, making it compatible with the socio-technical analysis of this study (van Vuuren et al., 2021). Premise, a tool further described in **Section 3.7**, allows for the integration of IAM scenarios into a prospective LCA. It also provides useful update reports with data of the electricity mix developments for all regions included in IMAGE.

3.5.2. Analysis of Socio-Technical Scenarios

Three different socio-technical scenarios have been chosen for the General Morphological Analysis (GMA): **(1) SSP2-RCP1.9**, **(2) SSP2-RCP2.6** and (3) **SSP2-RCP6.5**. As will be further explained in **Section 3.6**, the GMA is meant to find likely and relevant combinations of variables. To determine the likelihood and relevance of combinations with the socio-technical scenarios, a socio-technical analysis is conducted. The most important aspect to be analyzed is the compatibility of technological development and regional electricity mix developments. For this analysis, the latest scenario report provided by Premise is used (Premise, 2023). Two aspects will be analyzed:

1. The PV market development in each socio-technical scenario and its compatibility with the exploratory technological development scenarios
2. The likelihood of electricity mix scenarios, based on current developments

3.6. Phase 3: Scenario building

Several dimensions in the context of technological, market and socio-technical developments have been introduced that could have an influence on the environmental impact of PV systems in the coming decades. As mentioned in the theoretical framework, various studies manipulate technological parameters such as wafer thickness, and cell efficiency to derive the possible impact of a single system at a certain point in time in the future. However, the technological development is inherently dependent on the socio-technical system it is part of. Global developments may increase or delay the speed of industrial learning. Furthermore, other technologies such as CdTe may have unexpected rapid improvements in performance or receive advantages through subsidization from governmental institutions. Within the scope of a city, different pathways could be stimulated by interventions of the municipality.

Objective General Morphological Analysis

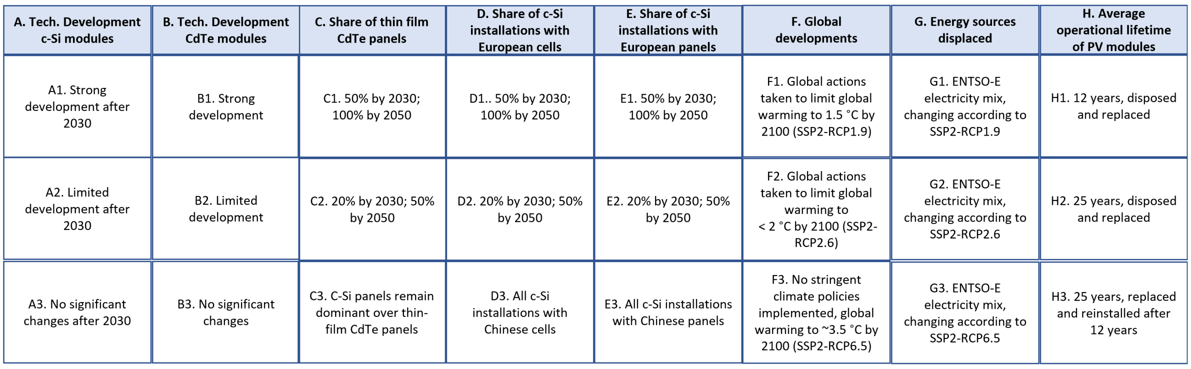
In this study, different operational lifetimes are considered, since the municipality could be an important stakeholder for lifetime extension strategies such as reuse projects of disposed but functional PV modules. Different socio-technical, technological and market developments are incorporated to account for uncertainty of these developments and to increase the robustness of any final conclusions on the effect of lifetime extension strategies. To determine what scenarios have a decent likelihood or are important to include in the assessment, a General Morphological Analysis (GMA) is conducted.

What is a General Morphological Analysis?

GMA can be defined as “a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes” (Ritchey, 2011). It involves identifying and defining the important dimensions of the problem and assigning relevant values or conditions to each dimension. These dimensions and their values form the variables or parameters of the problem. By setting these parameters in parallel columns, an n-dimensional configuration space, called a morphological field, is constructed. To explore the problem space, specific configurations are selected by choosing one value from each variable. These configurations represent formal solutions within the problem complex. The goal is to examine specific configurations in the field to determine which ones are feasible, practical, and/or interesting. GMA is a common method in ex-ante LCA to construct a range of exploratory scenarios for ex-ante or prospective LCAs and other modelling approaches for future scenarios (Delpierre et al., 2021; Ritchey, 2011).

3.6.1. The General Morphological Field

Based on the theoretical framework, technology analysis and socio-technical analysis, 8 variables have been selected for the scenario-building process. Each of these variables can have 3 different values. 3.9 shows the morphological field from which several scenarios will be derived, based on the general morphological analysis.



A. Tech. Development c-Si modules	B. Tech. Development CdTe modules	C. Share of thin film CdTe panels	D. Share of c-Si installations with European cells	E. Share of c-Si installations with European panels	F. Global developments	G. Energy sources displaced	H. Average operational lifetime of PV modules
A1. Strong development after 2030	B1. Strong development	C1. 50% by 2030; 100% by 2050	D1.. 50% by 2030; 100% by 2050	E1. 50% by 2030; 100% by 2050	F1. Global actions taken to limit global warming to 1.5 °C by 2100 (SSP2-RCP1.9)	G1. ENTSO-E electricity mix, changing according to SSP2-RCP1.9	H1. 12 years, disposed and replaced
A2. Limited development after 2030	B2. Limited development	C2. 20% by 2030; 50% by 2050	D2. 20% by 2030; 50% by 2050	E2. 20% by 2030; 50% by 2050	F2. Global actions taken to limit global warming to < 2 °C by 2100 (SSP2-RCP2.6)	G2. ENTSO-E electricity mix, changing according to SSP2-RCP2.6	H2. 25 years, disposed and replaced
A3. No significant changes after 2030	B3. No significant changes	C3. C-Si panels remain dominant over thin-film CdTe panels	D3. All c-Si installations with Chinese cells	E3. All c-Si installations with Chinese panels	F3. No stringent climate policies implemented, global warming to ~3.5 °C by 2100 (SSP2-RCP6.5)	G3. ENTSO-E electricity mix, changing according to SSP2-RCP6.5	H3. 25 years, replaced and reinstalled after 12 years

Figure 3.9: Morphological field for prospective LCA of PV system deployment in Amsterdam

Technological development Mono-Si modules

The ITRPV has predicted technological developments of the c-Si PV industry since 2010, with reasonable accuracy (Baliozian et al., 2020). The most recent ITRPV report has made future projections of this industry until 2032. This study will incorporate these projections for each scenario until 2030. The tech. development scenarios for c-Si can therefore be regarded as predictive until 2030 and exploratory after 2030. Based on literature, three exploratory scenarios are defined: strong development, limited development and no significant changes after 2030.

Technological development and market share of CdTe modules

The environmental impact of CdTe panels during production and disposal has been demonstrated to be lower than c-Si modules but their performance is still trailing behind. Although the number of thin-film installations in Amsterdam is currently negligible, strong developments of the technology could lead to a sudden market shift. Therefore these scenarios are also taken into account in this study. A 50% installation share by 2030 is extreme but under institutional interventions could be possible. This is regarded as an extreme case while a more realistic case would be 20% by 2030. Technological development projections for CdTe modules are based on personal communications by Frischknecht et al. (2015) with industry leaders, historic trend and possible projections based on the First Solar website (First Solar, n.d.).

Share of c-Si installations with European panels

The Chinese PV module manufacturers currently dominate the PV industry. However, the European PV industry is also growing and could overtake the European market in the future. Additionally, local interventions could incentivize households to install European panels.

Share of c-Si installations with European cells

Currently, only a small share of PV modules that are produced in Europe also have the cells or wafers produced in Europe. Most of the Silicon cells come from China. However, with global tensions rising, the European Commission and the European member states have set the ambition of securing its supply of Silicon and semiconductor production (Solar Alliance, n.d.).

Global developments

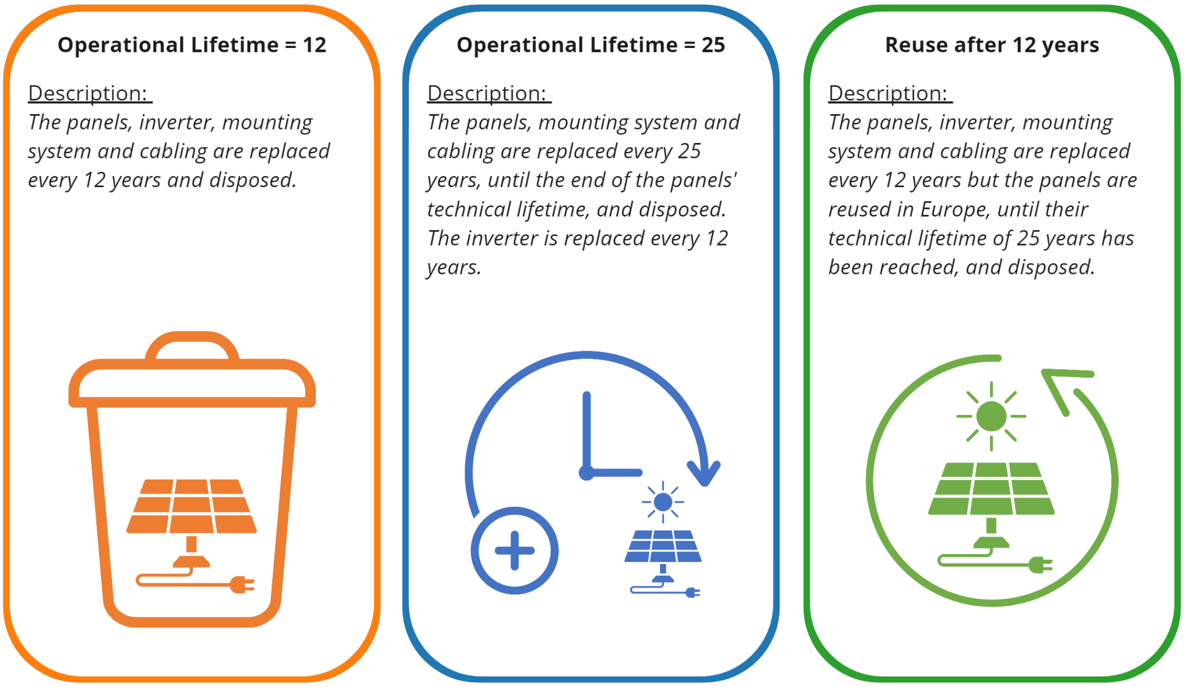
As described in the socio-technical analysis, societal developments including international policies affect the decarbonization pathway which determines the long-term global climate scenarios. In this study three scenarios are included: highly optimistic (1.5 °C by 2100), realistic (< 2 °C by 2100) and conservative (3.5 °C by 2100).

Energy sources displaced

The potential electricity yield displaces the use of a local electricity grid, which is the Dutch grid. However, the IMAGE model only makes future projections for the European average electricity grid (ENTSO-E). Therefore, the dynamic ENTSO-E grid has been chosen for electricity displacement. However, a sensitivity analysis is conducted for the use of a dynamic grid or a static grid in **Appendix B**. The sensitivity of using a European static grid or the Dutch grid on the results is also covered in the Appendix.

3.6.2. Operational Lifetime Scenarios

The objective of this study is to find the environmental impact of PV deployment in Amsterdam under different operational lifetime scenarios and the potential of reusing functional disposed panels. Three operational lifetime scenarios have been included, as shown in **Figure 3.10**. Although each of these scenarios are included in the morphological field for completeness, they are all covered in the prospective LCA because they are part of the research objective.



Operational Lifetime = 12

Description:
The panels, inverter, mounting system and cabling are replaced every 12 years and disposed.

Operational Lifetime = 25

Description:
The panels, mounting system and cabling are replaced every 25 years, until the end of the panels' technical lifetime, and disposed. The inverter is replaced every 12 years.

Reuse after 12 years

Description:
The panels, inverter, mounting system and cabling are replaced every 12 years but the panels are reused in Europe, until their technical lifetime of 25 years has been reached, and disposed.

Figure 3.10: Operational lifetime scenarios

Explanation Operational Lifetime Scenarios

- **Op. LT = 12:** The first exploratory operational lifetime scenario is based on the problem of early disposa. An operational lifetime of 12 years is chosen since this is the average technical lifetime of the inverter. Installers will likely advice households to replace their set of panels when their inverter has broken (personal communications, PV installer), for various economic reasons, as described in **Section 1.0.4**. This is adopted as the baseline scenario, for when no interventions take place. In this scenario each system component is disposed and recycled under current recycling practices.

- **Op. LT = 25:** This study assumes an average technical lifetime of 25 years. Therefore, the second scenario represents the case where each panel is left on the roof until its technical lifetime has been reached. Since the inverter has a technical lifetime of 12 years, the inverter is replaced every 12 years.

- **Reuse:** An additional scenario is assessed where the panels are replaced every 12 years, but the disposed functional panels are re-installed somewhere else. For simplicity, the re-installed panels also displace the European dynamic ENTSO-E grid. It is therefore assumed they are re-installed somewhere in Europe. Furthermore, the mounting system is also reused but a new inverter is required at the re-installation site.

Assumptions Reuse Scenario

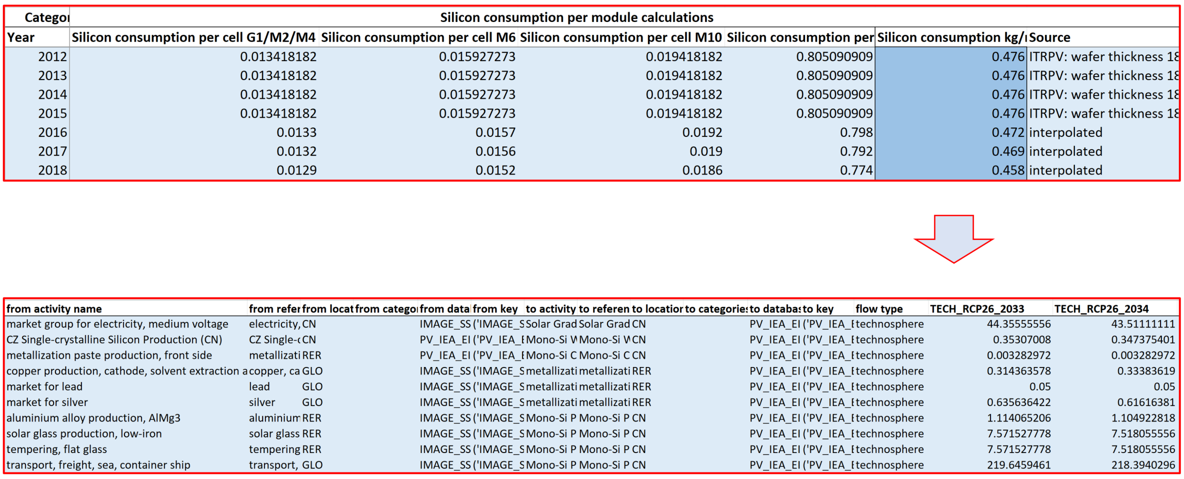
The reuse scenario is used to assess the impact of re-installation. Although the impact of the required extra system elements are taken into account, the impact of testing, certification and possible extra transport has not been considered. This is a simplified scenario and the extra impact induced along the complete secondary supply chain should be assessed in future research.

3.7. Phase 4: Prospective LCA

Now that the baseline normalized LCA for all system components has been done and the scenarios have been set, the prospective LCA at system component level can be performed. The first paragpraph explains how the quantified scenarios are integrated into the life cycle inventory of the baseline LCA, to create a normalized yearly impact assessment. The second paragraph describes the procedure of how the building-specific system is created, how the electricity yield is estimated and how all these aspects are integrated into a final model to determine the city-wide impact.

3.7.1. Quantified scenario integration

Various parameters have been set for the technological and socio-technical development to derive quantified scenarios. In the phase 3 section the tech. development values are given for 2030 and 2050. However, in the appendix a complete overview is given of each parameter modification from 2012 to 2050. These values are manipulated based on literature, ITRPV reports and interpolations. All modifications per parameter are stored in an excel sheet. The Activity Browser GUI has the function of creating different scenarios for the LCI. This requires manipulation of the so-called 'scenario difference file', which is done in excel, as shown in **Figure 3.11**, and imported back into Activity Browser. The scenario difference file is also transformed for the background processes, based on the global developments of electricity generation, as further explained in the next paragraph.



Catego	Silicon consumption per module calculations					
Year	Silicon consumption per cell G1/M2/M4	Silicon consumption per cell M6	Silicon consumption per cell M10	Silicon consumption per	Silicon consumption kg/	Source
2012	0.013418182	0.015927273	0.019418182	0.805090909	0.476	ITRPV: wafer thickness 18
2013	0.013418182	0.015927273	0.019418182	0.805090909	0.476	ITRPV: wafer thickness 18
2014	0.013418182	0.015927273	0.019418182	0.805090909	0.476	ITRPV: wafer thickness 18
2015	0.013418182	0.015927273	0.019418182	0.805090909	0.476	ITRPV: wafer thickness 18
2016	0.0133	0.0157	0.0192	0.798	0.472	interpolated
2017	0.0132	0.0156	0.019	0.792	0.469	interpolated
2018	0.0129	0.0152	0.0186	0.774	0.458	interpolated

from activity name	from refer	from locat	from catego	from data	from key	to activity	to referen	to locatior	to categorie	to databa	to key	flow type	TECH_RCP26_2033	TECH_RCP26_2034
market group for electricity, medium voltage	electricity,	CN		IMAGE_SS	('IMAGE_S	Solar Grad	Solar Grad	CN		PV_IEA_EI	('PV_IEA_E	technosphere	44.35555556	43.51111111
CZ Single-crystalline Silicon Production (CN)	CZ Single-	CN		PV_IEA_EI	('PV_IEA_E	Mono-Si W	Mono-Si W	CN		PV_IEA_EI	('PV_IEA_E	technosphere	0.35307008	0.347375401
metallization paste production, front side	metallizati	RER		PV_IEA_EI	('PV_IEA_E	Mono-Si C	Mono-Si C	CN		PV_IEA_EI	('PV_IEA_E	technosphere	0.003282972	0.003282972
copper production, cathode, solvent extraction a	copper, ca	GLO		IMAGE_SS	('IMAGE_S	metallizati	metallizati	RER		PV_IEA_EI	('PV_IEA_E	technosphere	0.314363578	0.33383619
market for lead	lead	GLO		IMAGE_SS	('IMAGE_S	metallizati	metallizati	RER		PV_IEA_EI	('PV_IEA_E	technosphere	0.05	0.05
market for silver	silver	GLO		IMAGE_SS	('IMAGE_S	metallizati	metallizati	RER		PV_IEA_EI	('PV_IEA_E	technosphere	0.635636422	0.61616381
aluminium alloy production, AlMg3	aluminium	RER		IMAGE_SS	('IMAGE_S	Mono-Si P	Mono-Si P	CN		PV_IEA_EI	('PV_IEA_E	technosphere	1.114065206	1.104922818
solar glass production, low-iron	solar glass	RER		IMAGE_SS	('IMAGE_S	Mono-Si P	Mono-Si P	CN		PV_IEA_EI	('PV_IEA_E	technosphere	7.571527778	7.518055556
tempering, flat glass	tempering	RER		IMAGE_SS	('IMAGE_S	Mono-Si P	Mono-Si P	CN		PV_IEA_EI	('PV_IEA_E	technosphere	7.571527778	7.518055556
transport, freight, sea, container ship	transport,	GLO		IMAGE_SS	('IMAGE_S	Mono-Si P	Mono-Si P	CN		PV_IEA_EI	('PV_IEA_E	technosphere	219.6459461	218.3940296

Figure 3.11: Overview of the tech. development and scenario difference file in Excel

3.7.2. Background process transformations

Premise is a tool that facilitates the alignment of life cycle inventories within the ecoinvent 3.6-3.9 database. This tool can employ either a "cut-off" or "consequential" system model to match the output results of Integrated Assessment Models (IAMs) like IMAGE. The Activity Browser only supports the cut-off system model, so this model is used in this study. By utilizing this tool, it becomes possible to create life cycle inventory databases under future policy scenarios for any year between 2005 and 2100. Premise is used in this study to create LCI inventory databases from 2012 until 2050 of the background processes extracted from EcoInvent v.3.8, based on the IMAGE IAM. The workflow of Premise is illustrated in **Figure 3.12**. The background processes can be transformed for power generation, cement production, steel production, transport and fuels. However, this study only considers power generation. Efficiency, market and Carbon Capture and Storage developments are included in the transformations for power generation. More information can be found on the Read the Docs website of Premise (Premise, n.d.). The superstructure file for each scenario derived from Premise is combined with the technological development scenario difference file and integrated into Activity Browser. No double counting can occur, since only foreground processes have been transformed for technological development, whereas only background processes have been transformed by Premise.

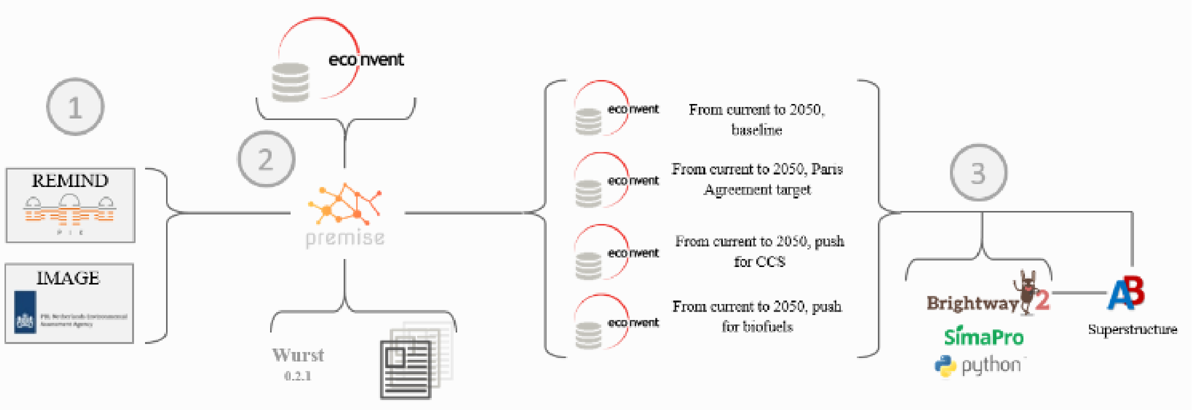


Figure 3.12: Premise workflow to create superstructure for the LCI based on the IAM (Premise, n.d.

3.7.3. City wide prospective LCA

Now that a normalized prospective LCA has been performed for all system components, they can be combined to create a system for each building in Amsterdam. Since the municipality has set targets based on the maximum rooftop capacity, the available area should be defined for system sizing. This is done by means of a model built by PV WORKS.

System sizing

This model creates a so-called PV Potential Map, derived using GIS data. AHN height data is collected by means of fly-overs to create an accurate estimate of the available surface area, roof angle, scattered roof objects such as terraces, and obstructing objects such as chimneys. Based on this data, the model determines the max. potential set-up of PV panels, given the dimensions of the panel, as visualized in **Figure 3.13**. More information on the functionality of this model can be found on the Open Research Database of Amsterdam (AMS Institute, 2022). Now that the amount of PV panel area and roof angle are defined, the normalized system elements can be integrated like building blocks. However, the inverter is normalized based on peak power and therefore additional calculations should be made for the size of the inverter. The inverter capacity is chosen based on the total peak power of the modules. The peak power is calculated in the final model by assuming a linear relation to module efficiency at the moment of installation.

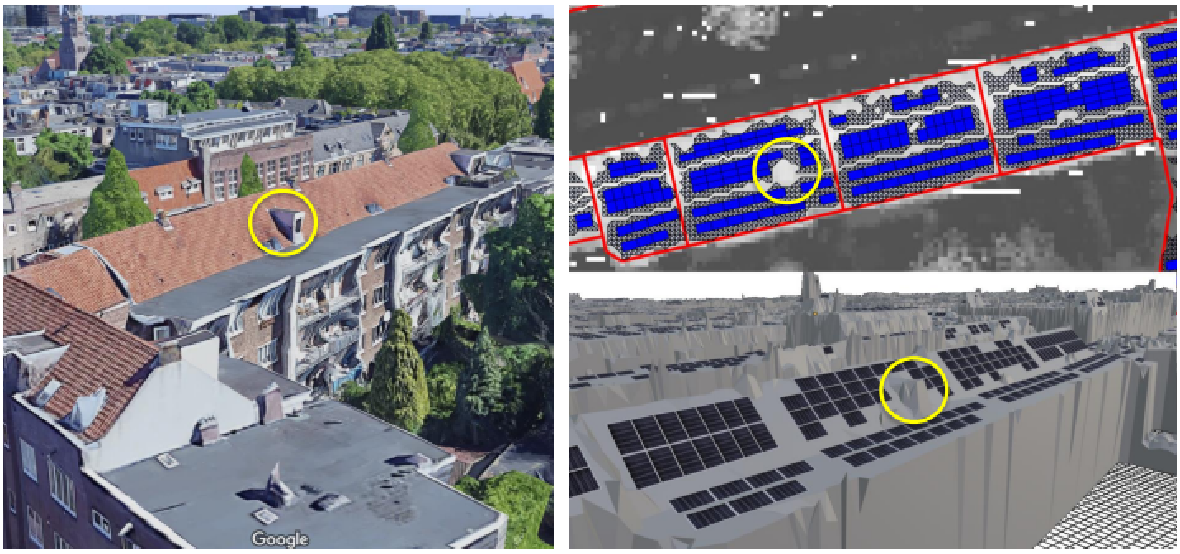


Figure 3.13: Visualization of object identification and panel set-up of PV WORKS model (PV Advent Calendar, 2022

Electricity yield estimation

The model provided by PV Works also determines the potential yearly electricity yield of each building. After the size and specifications of the particular panel, the model determines the potential DC yield by means of a skyline-based approach (Isabella et al., 2019). Different module technologies (c-Si and CdTe) with different sizes, efficiencies and module specifications based on the technological analysis are given as input for the PV WORKS model. A summary of the functionality of the model is given in the next paragraph.

Functionality PV WORKS electricity yield model

The annual irradiation on a PV module depends on the local meteorological conditions. To simulate weather conditions and estimate the average annual irradiation on a PV system in Amsterdam, local climate data is used. In addition to meteorological conditions, the surrounding landscape also plays a significant role in influencing the availability of sunlight. This is due to the potential obstruction of sunlight by nearby or distant objects. The PV WORKS model creates a 3D model of the surrounding environment with a skyline profile for each module and determines the daily irradiation based on the sun's path. Besides the irradiation, the operative efficiency of the PV modules, based on the local module temperature and irradiance level, are calculated to estimate the total annual DC yield. Isabella et al. (2019) provide more exact information on the potential DC yield estimations used in the PV WORKS model.The PV WORKS model does not include the degradation rate, which will be included in the final model.

Deployment Rate

For simplicity, it is assumed that the number of residential PV system installations increases linearly, in accordance with the municipality targets. These targets are as follows:

- 50% of the rooftop capacity suitable for solar generation is filled with solar panels by 2030.
- 100% of the rooftop capacity suitable for solar generation is filled with solar panels by 2050.

It is assumed that the max. potential set-up of PV panels on each rooftop is used. Furthermore, it is assumed that 0 PV systems have been installed before 2012, as this number can be regarded as negligible (Alliander, 2022). New panels are installed on the already used buildings, once the operational lifetime has been reached. Three operational lifetime scenarios are assessed, as described in **Section 3.6.2**. However, to create more realistic scenarios, the operational lifetime is taken as an average rather than an exact value for each PV system. A normal distribution is adopted, where the average operational lifetime is the mean. A standard deviation of 1.67 is taken, which corresponds to 99.7% of the values to be within a range of approximately 5 years around the mean. In the case of an average operational lifetime of 12 years, this would correspond to a minimum lifetime of 7 years and a maximum lifetime of 17 years. In the case of an operational lifetime of 25 years, this would correspond to a minimum lifetime of 20 years and a maximum lifetime of 30 years.

Limitation PV WORKS model

Building-specific electricity yield data was obtained for a neighbourhood with 1774 buildings. However, due to the required run-time, the building-specific electricity yield data could not be obtained for every specific building in Amsterdam. Therefore, the data for the neighbourhood has been extrapolated to the amount of residential buildings in Amsterdam with a suitable rooftop. Based on the PV WORKS model, Amsterdam has 115494 buildings with suitable rooftop for PV installations. To verify that the extrapolation is a sound assumption, the average suitable area per rooftop is checked with the average suitable rooftop area for the neighbourhood. This amounts to a 4% difference which is considered sufficiently close for the extrapolation.

Python model

Figure 3.14 visualizes how all predefined parameters are integrated into a final model, to determine the net environmental impact in each year between 2012 and 2050. A linear deployment rate is assumed and the buildings are randomly selected for installations. It should be noted that normally installations are not randomly distributed but rather occur per street or neighbourhood. However, for the final environmental impact estimations at city-wide scale this does not make a difference. The normalized system components are integrated in the selected buildings at year X, depending on the suitable rooftop area of each building. Furthermore, the PV module types and sizes are selected based on the projected market share in that year for the particular scenario. The operational lifetime is included in the model, to determine when the models are disposed and a new set is reinstalled. It is assumed that after disposal, a new set of panels is reinstalled, in line with the municipality target of utilizing 100% of the suitable rooftop capacity by 2050. As mentioned in the **Section 3.1**, it is assumed that the current disposal practice occurs throughout the time-frame which is a limitation of this study, since it is likely that different disposal practices will be adopted once more systems are disposed. Based on the performance of the installed systems, the potential DC yield is calculated and the yearly degradation is subtracted from this value. The electricity generated in year X is than compared to the environmental impact for the same amount of electricity from the displaced energy mix, to determine the avoided environmental impact for each year. Finally the induced environmental impact until installation and after disposal are combined with the avoided environmental impact to determine the net environmental impact for each year.

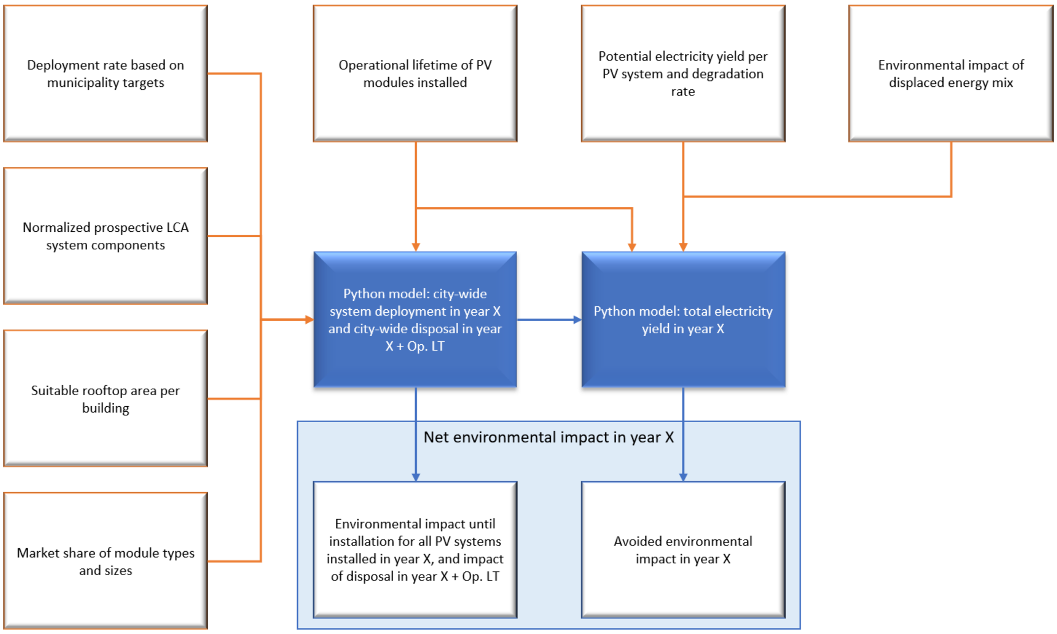


Figure 3.14: Workflow diagram of final Python model

3.8. Data Analysis Methods

As described in the previous section, the final model incorporates the environmental impact encompassing material extraction through installation, as well as the benefits derived from electricity grid displacement and existing recycling practices. This integration yields the annual net environmental impact. To derive meaningful conclusions, the yearly net environmental impact is summed up to find the accumulated or total net environmental impact by 2050 at city-wide scale for each scenario. In this way, the environmental impact can be interpreted as a dynamic stock that should be optimized by the end of the time-frame, which is 2050 in this case. The net accumulated environmental impact of the most interesting impact categories are then further analyzed, to create a better understanding of their behaviour and verify their robustness. This is done by means of a contribution analysis, a sensitivity analysis and a final consistency check. Furthermore, the impact of several impact categories are compared by linking the impact to shadow costs.

3.8.1. Contribution Analysis

The final results are further dissected to perform a contribution analysis of the following components where noteworthy observations are found:

- The contribution of induced impact and avoided impact to the net environmental impact: the dynamic nature of the accumulated environmental impact could be mainly attributed to the changes in avoided impact or induced impact

- The contribution of each system element on the induced environmental impact: technological development of the panels can have a big effect on the accumulated impact. Furthermore, the impact of other system elements, which are only affected by electricity mix changes in the manufacturing country, could also have a high contribution on the final results. The extra inverter and cabling could also create interesting results in the reuse case.

- The contribution of different production processes of c-Si panels can be found in **Appendix A**.

Sensitivity Analysis

The biggest sensitivity analysis is already done by analyzing the effect of different variable combinations, chosen through the general morphological analysis, on the final results. For example, when no stringent climate policies are initiated globally, the electricity mix displaced is much less environmentally friendly. However, the electricity mix used to produce the PV system elements is also less environmentally friendly. The sensitivity of changing this model variable is taken into account by analyzing different scenarios. The sensitivity of each model variable on the final results will not be analyzed separately, due to time constraints and considerable computing time. However, the sensitivity of several important assumptions are checked, as listed below:

- The sensitivity of a complete regional market shift are checked by running the model at a 100% market shift (100% of panels or cells produced in China and 100% of panels or cells produced in Europe).

- The sensitivity of a complete technology shift to 100% CdTe is checked to ensure the robustness of the model and results.

- The local electricity grid, which is displaced by the installed PV systems, also dynamically changes based on global development. When a PV system is used in year X, the electricity generated and used by that system logically displaces the electricity generated by the grid that would otherwise be used. However, the dynamic nature of the local grid is also influenced by the increase in renewable energy generation. In reality there is therefore an inter-dependency between the local grid and the PV systems installed in Amsterdam. It could therefore be argued that the PV systems installed actually displace the electricity generated by the grid before installation. The sensitivity of adopting a dynamic or static grid on the final results is explored.

- The use of the European (ENTSO-E) dynamic grid for electricity displacement: the premise tool only allows for yearly modifications of the grid at European level. In reality, for the case in

Amsterdam, the electricity generated by the Dutch grid is displaced. The sensitivity of adopting the ENTSO-E grid or the Dutch grid on the final results is explored.

Consistency Check

To check for robustness of the results and consistency with existing literature, the LCA results are compared with existing environmental impact estimates.

Shadow costs

The full ReCiPe midpoint v1.13 impact family is considered in this study, consisting of all impact categories as listed in **Table 3.3**. It is difficult to interpret the impact of each impact category without having some overarching reference. That is why the net accumulated environmental impact is also expressed in terms of shadow costs (in euros, €), for each impact category for which shadow cost data is available. Shadow costs represent the monetary value or cost associated with a specific non-monetary factor, such as an environmental impact or a resource constraint. They are used to provide a way to quantify and compare the value of these non-monetary factors in economic terms (De Bruyn et al., 2023). CE Delft has recently published a handbook for shadow costs (De Bruyn et al., 2023). This study adopts the average European shadow cost for each impact category that is included in the handbook and matches in unit with the ReCiPe midpoint v1.13 impact family. The unavailable data for other impact categories is regarded as a limitation in this study. Furthermore, it is assumed that the European shadow costs also apply to production in China and other production regions involved in this LCA. In reality, the impact expressed in economic terms may vary in other regions, which is also a limitation in this study.

Impact category indicator	Unit	Shadow cost (€) /unit
GWP100	kg CO2-Eq	0.13
FDP	kg oil-Eq	0.028
FETP	kg 1,4-DCB-Eq	0.0209
FEP	kg P-Eq	3.74
HTP	kg 1,4-DCB-Eq	0.071
METP	kg 1,4-DCB-Eq	0.0032
MEP	kg N-Eq	14.25
ODP	kg CFC-11-Eq	29.1
TAP100	kg SO2-Eq	5.27
TETP	kg 1,4-DCB-Eq	0.00064
WDP	m3 Water-Eq	0.407
ALOP	Square meter-year	Unknown
IRP	kg U235-Eq	Unknown
MDP	kg Fe-eq	Unknown
NLTP	Square-meter	Unknown
PMFP	kg PM10-Eq	Unknown
POFP	kg NMVOC-Eq	Unknown
ULOP	Square meter-year	Unknown

Table 3.9: Impact categories and corresponding shadow costs expressed in Euros per unit

4

Results

In this chapter, the results of the general morphological analysis and prospective LCA are presented. In addition, key observations are provided in this chapter and further analyzed and interpreted in **Section 5.1** of the discussion.

Recap of Research Objective
As discussed in the theoretical framework, multiple studies have been conducted on the environmental impact of residential PV systems in the future. However, none of these studies take into account the consumer incentive of re-installation before the technical lifetime of the panels has been reached. Multiple reasons for early disposal have been given in **Section 1.0.4**. Lifetime extension strategies could be initiated at city scale to prevent early disposal or to give the functional disposed panels a second life. The aim of this study is to find the effects of lifetime extension strategies on the net environmental impact of residential rooftop PV systems, installed in Amsterdam between 2012 and 2050. Three operational lifetime scenarios have been chosen: (1) an operational lifetime of 12 years, (2) an operational lifetime of 25 years, (3) re-installation after 12 years, but reuse of the functional panels until the assumed technical lifetime of 25 years has been reached.

Recap of Research Questions and Methods
By means of a unique prospective LCA approach, the induced impact along the supply chain and the avoided impact due to the electricity yield can be integrated to make city-wide estimates. To account for the high uncertainty in future projections, four exploratory scenarios have been selected using a general morphological analysis. The results of this analysis are used to answer the first sub-research question and are given in **Section 4.1**. By quantifying these scenarios and adopting these in the prospective LCA, a range of answers can be given to the second sub-research question. The results of the prospective LCA for scenario 1, 2, 3 and 4 are provided in **Section 4.2, 4.3, 4.4 and 4.5**, respectively.

SQ1: What are relevant socio-technical and technological development scenarios to account for uncertainty in long-term projections of the net environmental impact of rooftop PV systems?

SQ2: What is the total net environmental impact of residential rooftop PV systems installed on the roofs of Amsterdam between 2012 to 2050, considering each relevant socio-technical, technological development and operational lifetime scenario?

4.1. Scenario Selection

This section covers the results of the General Morphological Analysis (GMA). It is subdivided into an overview of the technology analysis results, the socio-technical analysis results and finally the GMA scenarios are chosen based on the analyses results.

4.1.1. Technology Analysis

Table 4.1 provides the year-specific results of the technical parameters chosen for the technology analysis. It should be noted that these are the specific values for today, 2030 and 2050, while projections have also been made for each year in between. Visualizations for the results of the complete time-frame are given in **Appendix C**.

Type	Parameter	TODAY	2030	2050 (A1)	2050 (A2)	2050 (A3)	Unit
Mono-Si	Module efficiency	21	23	27	25.5	24	%
Mono-Si	Module size	1.98	1.99	2.00	2.00	2.00	m2
Mono-Si	Aluminium consumption	1.21	1.12	0.96	1.04	1.12	kg/m2 module
Mono-Si	Glass consumption	8.00	7.88	6.33	6.98	7.63	kg/m2 module
Mono-Si	Silver consumption	0.0024	0.0022	0.0009	0.00155	0.0022	kg/m2 module
Mono-Si	Wafer thickness	160	143	100	120	140	μm
Mono-Si	Kerf losses	52	44	30	36	42	μm
Mono-Si	Silicon consumption	0.44	0.37	0.26	0.31	0.36	kg/m2 module
Mono-Si	Elec. demand SG-Silicon	48	46	30	38	45	kWh/kg
CdTe	Module efficiency	19	21	27	24.5	22	%
CdTe	Glass consumption (Glass-Glass)	13.75	13.25	10.00	11.50	13.00	kg/m2 module
CdTe	Wafer thickness	3.6	2.7	0.1	1.3	2.4	μm
CdTe	Cadmium Telluride consumption	0.021	0.015	0.001	0.008	0.014	kg/m2 module
CdTe	Electricity demand module production	32.5	30.5	24.7	27.3	29.9	kWh/m2 module

Table 4.1: PV Technological development scenarios

As explained in the methodology, this study takes a predictive scenario approach until 2030 and an exploratory scenario approach for the years after 2030. A1 represents strong technological development, A2 limited technological development and A3 conservative technological development. The calculations conducted for each technology parameter can be found in **Section 3.4**.

Compatibility with Deployment Rate

In the theoretical framework, it is explained that industrial scale technological development is largely dependent on the acceleration of global deployment. In the last decade the worldwide deployment of PV has accelerated exponentially and as a consequence technologies have seen great technological development. However, if the exponential acceleration of PV deployment comes to a halt and stabilizes, technologies are less likely to experience great technological development. It therefore makes sense that conservative technological development is linked to the socio-technical scenario where the acceleration of PV deployment has come to a halt. Furthermore, strong technological development should be linked to the scenario where PV deployment is still accelerating. The next section covers the socio-technical analysis, where the expected PV deployment in each global development scenario is analyzed. Furthermore, the electricity mix projections are analyzed and compared to recent developments.

4.1.2. Socio-Technical Analysis

An overview of Western European Union and Chinese electricity generation through residential and centralized solar PV is given in **Table 4.2**, based on data provided by the scenario report of Premise (Premise, 2023). Additionally the complete projected electricity mix for SSP2-RCP 1.9, SSP2-RCP2.6 and SSP2-RCP6.5 are visualized in the graphs.

IAM Scenario	**Region**	**Residential PV Generation (EJ)**			**Centralized PV Generation (EJ)**			**Combined PV Generation (EJ)**		
		Today	2030	2050	Today	2030	2050	Today	2030	2050
SSP2-RCP1.9	Global	1.92	4.98	16.0	1.66	8.71	31.0	3.58	13.69	47.0
	WEU	0.49	0.81	1.11	0.12	0.32	1.88	0.61	1.13	2.99
	China	0.25	3.79	4.34	0.74	1.19	4.43	0.99	4.98	8,77
SSP2-RCP2.6	Global	1.90	2.77	13.0	1.63	5.97	23.0	3.53	8.74	36
	WEU	0.49	0.82	1.06	0.12	0.15	1.69	0.61	0.97	2.75
	China	0.43	1.02	4.16	0.80	2.28	2.37	1.23	3.30	6.53
SSP2-RCP6.5	Global	1.92	3.04	13.0	1.79	4.18	15.0	3.71	7.22	28.0
	WEU	0.49	0.82	0.99	0.13	0.16	1.35	0.62	0.98	2.34
	China	0.44	0.77	4.23	1.15	1.36	3.14	1.59	2.13	7.37

Table 4.2: Deployment of PV in different RCP scenarios at large scale

Key Findings Socio-Technical Analysis

Figure 4.1 shows the historic global electricity yield of residential and centralized PV systems combined (IEA, 2022) and the target yield based on the three RCP scenarios from **Table 4.2**. Based on the historic trends, the deployment of PV would experience an acceleration in both SSP2-RCP1.9 and SSP2-RCP2.6 (To a different degree). Both are reasonable scenarios considering the substantial drop in module prices and increase in non-renewable energy prices.

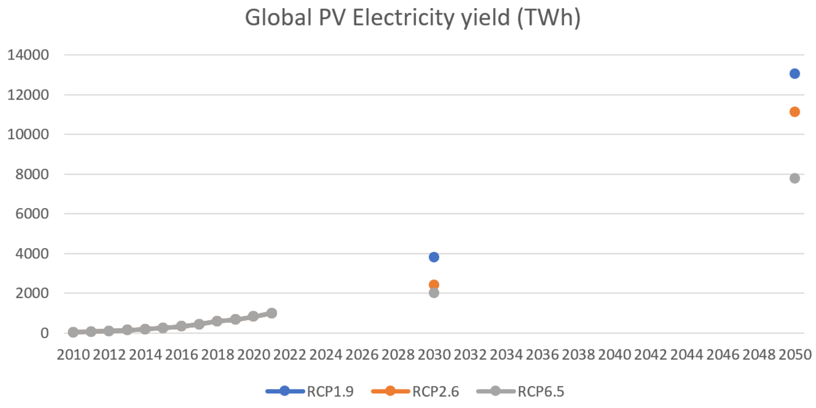
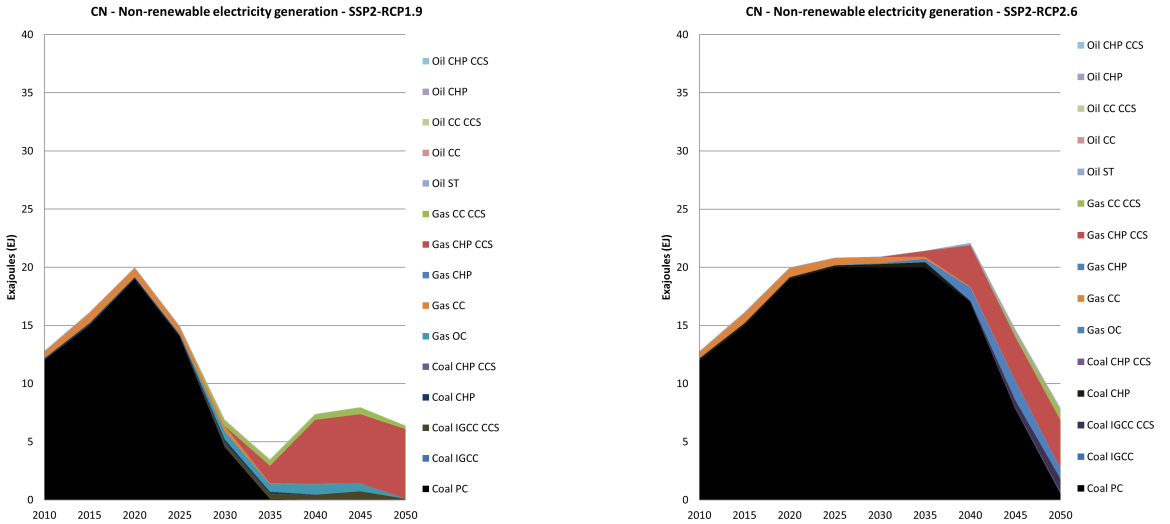


Figure 4.1: Global solar electricity generation trend and RCP projections

However, when considering the amount of electricity generated by Coal in China, the RCP1.9 scenario seems far out of reach. **Figure 4.2** shows the non-renewable electricity generation in China for SSP2-RCP1.9 and SSP2-RCP2.6. SSP2-RCP1.9 contains a drop of coal generated electricity by 2020. Contrarily, China is currently still expanding its coal power and is therefore realistically more in line with SSP2-RCP2.6 and SSP2-RCP6.5. Taking into account the fact that most of the supply chain occurs in China, it would be illogical to use the SSP2-RCP1.9 pathway the assess the environmental impact of PV technologies in the future. However, The PV industry has seen an unprecedented drop in module prices and is expected to only become cheaper than non-renewables (Fraunhofer, 2021). Therefore, global deployment of PV and technological development could potentially follow the pathway of RCP1.9 while the overall Chinese and/or global developments are more in line with RCP2.6 and RCP6.5. This decoupling is taken into account in the scenario building process.



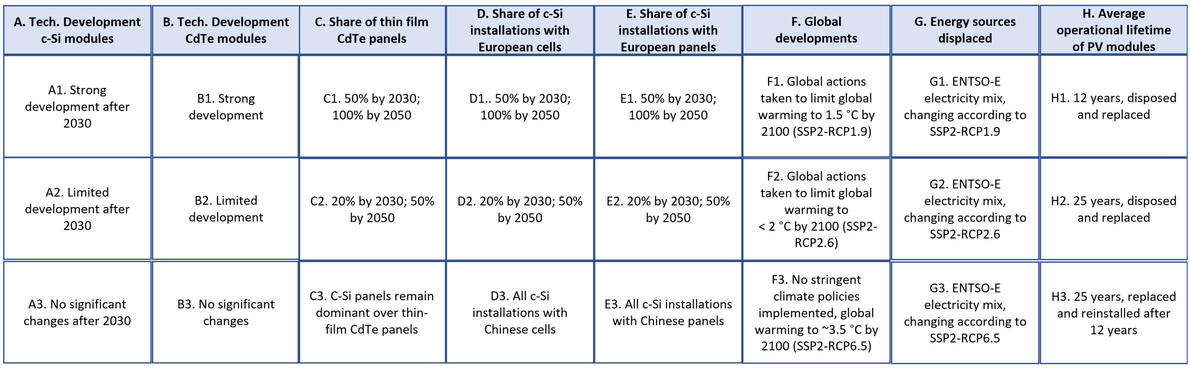
(a) Non-renewable electricity generation in China for SSP2-RCP1.9

(b) Non-renewable electricity generation in China for SSP2-RCP2.6

Figure 4.2: Comparison of non-renewable electricity generation in China (Premise, 2023)

4.1.3. GMA Results

This section covers the results of the general morphological analysis, which integrates the results of the technology analysis and socio-technical analysis to create consistent and relevant scenarios. First a cross-consistency check is conducted to identify unrealistic combinations of variables. Afterwards, several realistic and relevant scenarios are chosen. The morphological field with all possible variables is shown in **Figure 4.3**.



A. Tech. Development c-Si modules	B. Tech. Development CdTe modules	C. Share of thin film CdTe panels	D. Share of c-Si installations with European cells	E. Share of c-Si installations with European panels	F. Global developments	G. Energy sources displaced	H. Average operational lifetime of PV modules
A1. Strong development after 2030	B1. Strong development	C1. 50% by 2030; 100% by 2050	D1.. 50% by 2030; 100% by 2050	E1. 50% by 2030; 100% by 2050	F1. Global actions taken to limit global warming to 1.5 °C by 2100 (SSP2-RCP1.9)	G1. ENTSO-E electricity mix, changing according to SSP2-RCP1.9	H1. 12 years, disposed and replaced
A2. Limited development after 2030	B2. Limited development	C2. 20% by 2030; 50% by 2050	D2. 20% by 2030; 50% by 2050	E2. 20% by 2030; 50% by 2050	F2. Global actions taken to limit global warming to < 2 °C by 2100 (SSP2-RCP2.6)	G2. ENTSO-E electricity mix, changing according to SSP2-RCP2.6	H2. 25 years, disposed and replaced
A3. No significant changes after 2030	B3. No significant changes	C3. C-Si panels remain dominant over thin-film CdTe panels	D3. All c-Si installations with Chinese cells	E3. All c-Si installations with Chinese panels	F3. No stringent climate policies implemented, global warming to ~3.5 °C by 2100 (SSP2-RCP6.5)	G3. ENTSO-E electricity mix, changing according to SSP2-RCP6.5	H3. 25 years, replaced and reinstalled after 12 years

Figure 4.3: Morphological field for prospective LCA of PV system deployment in Amsterdam

Cross-consistency check

Several variable combinations have been excluded in an initial cross-consistency check, as shown in **Figure 4.4**. This check only looks for combinations which are deemed not possible. For example, with PV being an integral part of the decarbonization pathways of most nations, no technological development after 2030 while following the SSP2-RCP1.9 pathway can be excluded. Furthermore, energy source displacement at European scale is directly related to the RCPs and if the technological development of c-Si is very high after 2030, CdTe panels will not fully dominate c-Si panels by 2050 simply because of the industrial scale of c-Si PV.

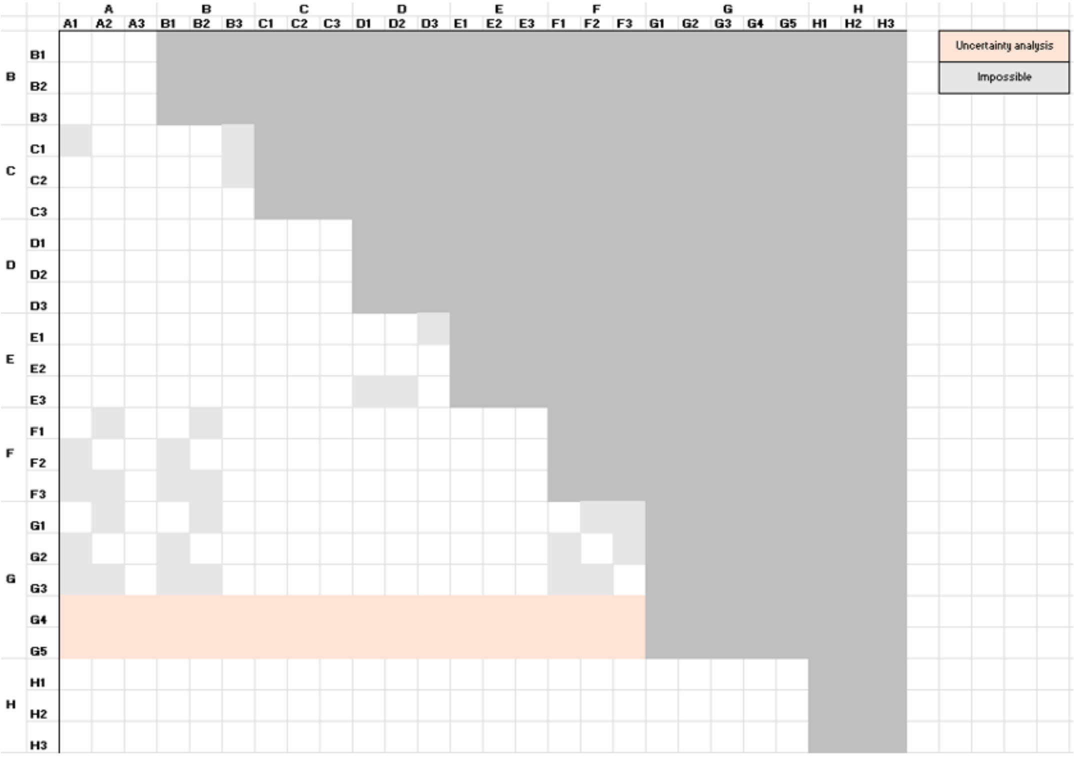


Figure 4.4: Initial cross-consistency analysis of morphological field

Choice of Scenarios

Four scenarios have been chosen for the prospective LCA based on the general morphological analysis with clarifications listed below:

1. **Scenario 1:** This scenario represents strong technological development for c-Si panels, in line with a global deployment rate of SSP2-RCP2.6. The electricity mixes in China and Europe follow SSP2-RCP2.6, which is a realistic global development pathway where global warming is limited to < 2 °C by 2100. In this scenario it is assumed that all panels and cells are produced in China. Although a market shift to Europe in the coming decades is likely, it is uncertain to what degree this will occur. Therefore, considering the relevance of scenarios, the full range of possible market shifts should be covered. Logically the energy sources displaced follow a similar Representative Concentration Pathway, which is RCP2.6. All operational lifetime scenarios are considered.

2. **Scenario 2:** This scenario represents conservative technological development in the pessimistic scenario where global PV deployment will follow SSP2-RCP6.5. Furthermore, electricity mixes will follow SSP2-RCP6.5, which is an extremely pessimistic scenario where global warming reaches 3.5 °C by 2100. It is also assumed that all panels and cells are produced in China. This scenario is chosen, combining a conservative technological development, electricity mix development and market shift, to consider the most pessimistic developments and its effects to the results of this study. Logically the energy sources displaced follow a similar Representative Concentration Pathway, which is RCP6.5. All operational lifetime scenarios are considered.

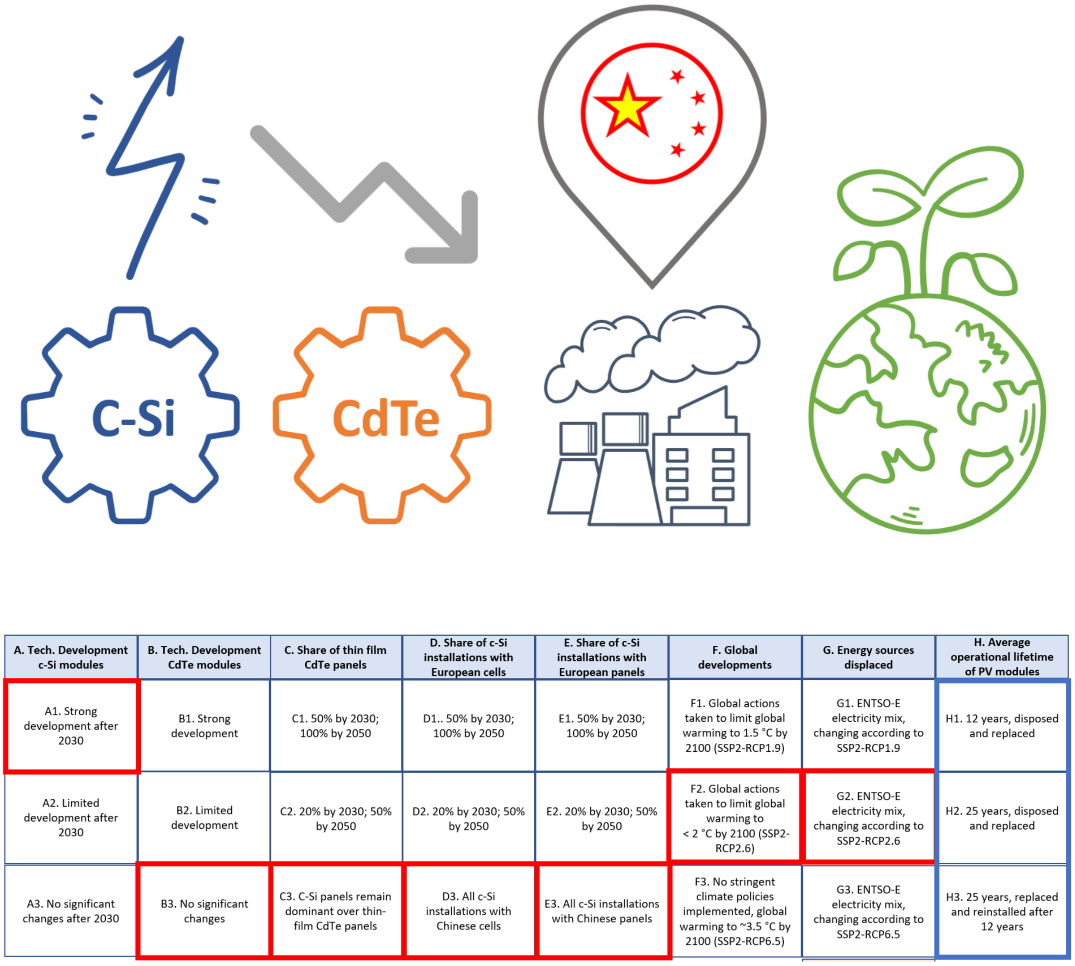
3. **Scenario 3:** This scenario represents a realistic market shift to Europe. This means that 20% of the yearly installed cells in Amsterdam are produced in Europe by 2030 and 50% by 2050. Furthermore, 50% of the yearly installed panels in Amsterdam are produced in Europe by 2030 and 100% by 2050. This is deemed realistic since currently close to zero cells are produced in Europe, and it requires a considerable amount of time to scale up large-scale production. Nonetheless, several initiatives are ongoing and the European Commission is investing a large amount of money in creating European semi-conductors. The European Chip Act has a target of 20% semi-conductors build in Europe by 2030 and this scenario assumes the same trend will occur for Silicon cells. Since

the panel production in Europe is already quickly growing, a 50% share by 2030 is considered as viable. The 100% share in Europe by 2050 is considered as an extreme case, which is chosen to cover the full range of possible market shifts, similar to scenario 1. It is still assumed that c-Si is the dominant panel type. Realistic global development are assumed, which follow SSP2-RCP2.6. Logically the energy sources displaced follow a similar Representative Concentration Pathway. All operational lifetime scenarios are considered.

4. **Scenario 4:** This scenario represents a realistic market shift to CdTe panels, where CdTe panels undergo a very optimistic technological development, similar to c-Si panels. This scenario is relevant since the environmental impact of CdTe panels during production is currently much lower than c-Si panels (see **Appendix A**. In case the performance of CdTe panels catches up with c-Si panels it may experience a realistic market shift. Like scenario 3, it requires serious upscaling of production capacity to manage a swift market shift. Therefore a realistic market shift is considered where 20% of the yearly panels installed in Amsterdam by 2030 and 50% by 2050. Realistic global development are assumed, which follow SSP2-RCP2.6. Logically the energy sources displaced follow a similar Representative Concentration Pathway. All operational lifetime scenarios are considered.

4.2. Prospective LCA Results Scenario 1

This section presents the final results of the prospective LCA for scenario 1 at city-wide scale. Scenario 1 assesses all lifetime extension strategies of c-Si panels, with cells and panels produced in China, with high technological development and under realistic global developments, following SSP2-RCP2.6. This scenario is subdivided into 1-H1, 1-H2 and 1-H3, based on the operational lifetime of the PV modules. 1-H1 assumes average panel replacement after 12 years, at the average inverter lifetime. The old panels are then disposed, following the current End-of-Life management procedure. 1-H2 assumes an operational lifetime of 25 years, where panels are kept on roofs until their technical lifetime of 25 years has been reached. The panels are then disposed, following the current End-of-Life management procedure. 1-H3 assumes the replacement of panels after 12 years, but the functional panels are reused at another location until their technical lifetime of 25 years has been reached.



A. Tech. Development c-Si modules	B. Tech. Development CdTe modules	C. Share of thin film CdTe panels	D. Share of c-Si installations with European cells	E. Share of c-Si installations with European panels	F. Global developments	G. Energy sources displaced	H. Average operational lifetime of PV modules
A1. Strong development after 2030	B1. Strong development	C1. 50% by 2030; 100% by 2050	D1.. 50% by 2030; 100% by 2050	E1. 50% by 2030; 100% by 2050	F1. Global actions taken to limit global warming to 1.5 °C by 2100 (SSP2-RCP1.9)	G1. ENTSO-E electricity mix, changing according to SSP2-RCP1.9	H1. 12 years, disposed and replaced
A2. Limited development after 2030	B2. Limited development	C2. 20% by 2030; 50% by 2050	D2. 20% by 2030; 50% by 2050	E2. 20% by 2030; 50% by 2050	F2. Global actions taken to limit global warming to < 2 °C by 2100 (SSP2-RCP2.6)	G2. ENTSO-E electricity mix, changing according to SSP2-RCP2.6	H2. 25 years, disposed and replaced
A3. No significant changes after 2030	B3. No significant changes	C3. C-Si panels remain dominant over thin-film CdTe panels	D3. All c-Si installations with Chinese cells	E3. All c-Si installations with Chinese panels	F3. No stringent climate policies implemented, global warming to ~3.5 °C by 2100 (SSP2-RCP6.5)	G3. ENTSO-E electricity mix, changing according to SSP2-RCP6.5	H3. 25 years, replaced and reinstalled after 12 years

Figure 4.5: Scenario 1 visualization variable choice

City-wide environmental impact

Table 4.3 provides an overview of the net accumulated impact for each impact category by 2050, expressed in absolute values. To make the data more apprehendable, the net accumulated impact for each impact category, relative to the op. LT = 12 scenario, is visualized in **Figure 4.6**. To assess the significance of different impact categories in a more relatable and understandable manner, the net accumulated impact in 2050 is also expressed in shadow costs (in euros, €) in **Table 4.4** and visualized in **Figure 4.7**. It should be noted that the shadow costs for several impact categories are unknown, which have been left in grey. A negative value indicates more avoided impact than induced impact.

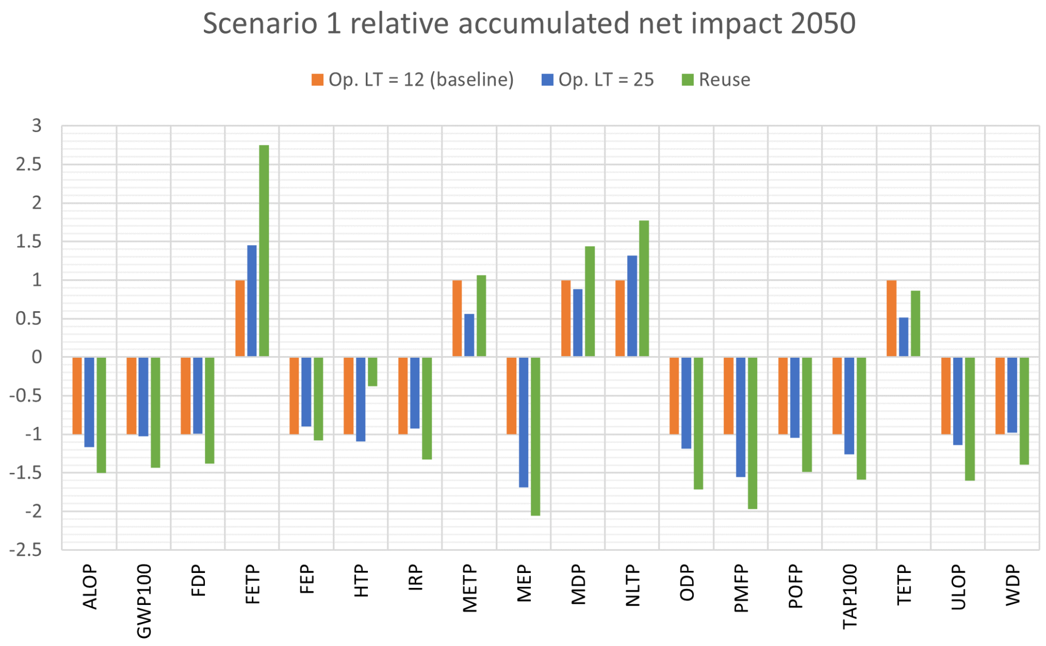


Figure 4.6: Net accumulated impact relative to op. LT = 12 for scenario 1

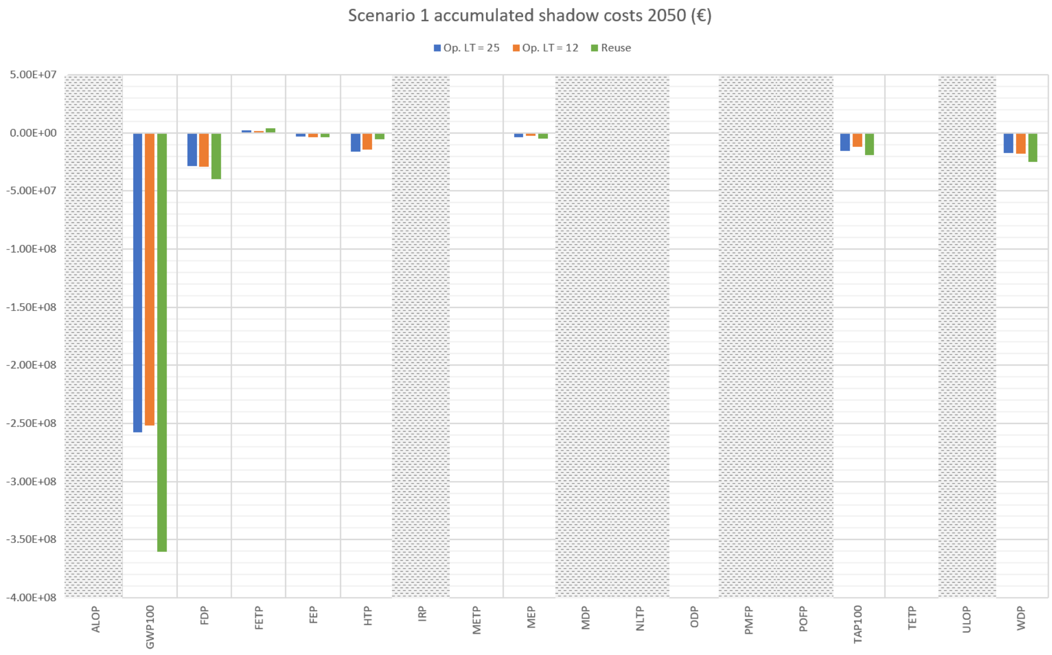


Figure 4.7: Net accumulated impact in 2050, expressed in shadow costs (in Euros, €) for scenario 1 (grey = unknown)

ACCUMULATED NET IMPACT SCENARIO 1

Op. LT	25 years	25 years	12 years	12 years	Reuse	Reuse	
Year	2030	2050	2030	2050	2030	2050	Unit
ALOP	-2.56E+07	-8.52E+07	-2.17E+07	-7.32E+07	-2.41E+07	-1.10E+08	Square meter-year
GWP100	-4.92E+08	-1.98E+09	-4.43E+08	-1.93E+09	-5.02E+08	-2.77E+09	kg CO2-Eq
FDP	-1.91E+08	-1.02E+09	-1.79E+08	-1.03E+09	-1.91E+08	-1.42E+09	kg oil-Eq
FETP	5.14E+07	9.43E+07	4.51E+07	6.50E+07	7.14E+07	1.79E+08	kg 1,4-DCB-Eq
FEP	-3.67E+05	-8.85E+05	-3.82E+05	-9.83E+05	-3.60E+05	-1.06E+06	kg P-Eq
HTP	-5.98E+07	-2.23E+08	-4.42E+07	-2.04E+08	1.25E+07	-7.61E+07	kg 1,4-DCB-Eq
IRP	-6.13E+08	-2.36E+09	-6.36E+08	-2.55E+09	-6.97E+08	-3.39E+09	kg U235-Eq
METP	4.51E+07	8.27E+07	5.45E+07	1.48E+08	6.27E+07	1.57E+08	kg 1,4-DCB-Eq
MEP	-5.23E+04	-2.72E+05	-1.78E+04	-1.61E+05	-2.52E+04	-3.31E+05	kg N-Eq
MDP	1.50E+08	3.74E+08	1.61E+08	4.23E+08	1.98E+08	6.08E+08	kg Fe-eq
NLTP	-5.87E+03	7.69E+04	-1.33E+04	5.84E+04	-1.48E+04	1.04E+05	Square-meter
ODP	-5.01E+00	-1.09E+02	9.48E-01	-9.16E+01	-5.19E-01	-1.57E+02	kg CFC-11-Eq
PMFP	6.74E+04	-8.96E+05	1.98E+05	-5.77E+05	2.11E+05	-1.13E+06	kg PM10-Eq
POFP	-6.41E+05	-5.50E+06	-4.62E+05	-5.26E+06	-5.10E+05	-7.81E+06	kg NMVOC-Eq
TAP100	-3.39E+05	-2.91E+06	-1.06E+05	-2.32E+06	-8.18E+04	-3.67E+06	kg SO2-Eq
TETP	8.05E+04	1.39E+05	1.15E+05	2.68E+05	1.16E+05	2.31E+05	kg 1,4-DCB-Eq
ULOP	-3.85E+05	-1.14E+07	2.74E+05	-9.99E+06	2.71E+05	-1.60E+07	Square meter-year
WDP	-8.03E+06	-4.29E+07	-7.63E+06	-4.39E+07	-8.45E+06	-6.10E+07	m3 Water-Eq

Table 4.3: Results accumulated net impact scenario 1

TOTAL SHADOW COSTS SCENARIO 1

Op. LT	25 years	12 years	Reuse
ALOP	Unknown	Unknown	Unknown
GWP100	-2.58E+08	-2.52E+08	-3.60E+08
FDP	-2.85E+07	-2.89E+07	-3.98E+07
FETP	1.97E+06	1.36E+06	3.74E+06
FEP	-3.31E+06	-3.67E+06	-3.97E+06
HTP	-1.58E+07	-1.45E+07	-5.40E+06
IRP	Unknown	Unknown	Unknown
METP	2.64E+05	4.73E+05	5.02E+05
MEP	-3.87E+06	-2.30E+06	-4.72E+06
MDP	Unknown	Unknown	Unknown
NLTP	Unknown	Unknown	Unknown
ODP	-3.17E+03	-2.67E+03	-4.57E+03
PMFP	Unknown	Unknown	Unknown
POFP	Unknown	Unknown	Unknown
TAP100	-1.54E+07	-1.22E+07	-1.93E+07
TETP	8.88E+01	1.72E+02	1.48E+02
ULOP	Unknown	Unknown	Unknown
WDP	-1.75E+07	-1.79E+07	-2.48E+07
SUM	**-3.40E+08**	**-3.29E+08**	**-4.54E+08**

Table 4.4: Results accumulated net impact by 2050 for scenario 1, expressed in shadow costs (in Euros, €)

Observations
Several observations can be made on the city-wide prospective LCA results. Each of the observations are listed and further clarified below. An in-depth analysis and interpretation of the observations is given in **Section 5.1**.

1. **Slight Environmental Advantage for Operational Lifetime Extension**

   The net accumulated environmental impact on Global Warming in the Op. LT = 25 scenario is -5E+07 kg CO2-Eq emissions, or 2.5 % lower than the Op. LT = 12 scenario. This means that disposing and reinstalling panels after 12 years has a slightly worse effect on Global Warming than keeping the panels on the roof until their assumed technical lifetime of 25 years. The impact on Marine Eutrophication is considerably better for the Op. LT = 25 scenario, as well as Particulate Matter Formation and Marine Eco-Toxicity. When expressed in total shadow costs by 2050, the Op. LT = 25 scenario performs slightly better with 11 million euros more environmental costs saved. In this case, the environmental costs of Ionising Radiation, Metal Depletion, Natural Land Transformation, Particulate Matter Formation, Photochemical Oxidant Formation, and Urban Land Occupation have not been taken into account. However, most of these categories show a better result for the reuse scenario which will likely result in more avoided environmental costs in the op. LT = 25 case.

2. **Substantial Environmental Advantage for Reuse of PV modules**

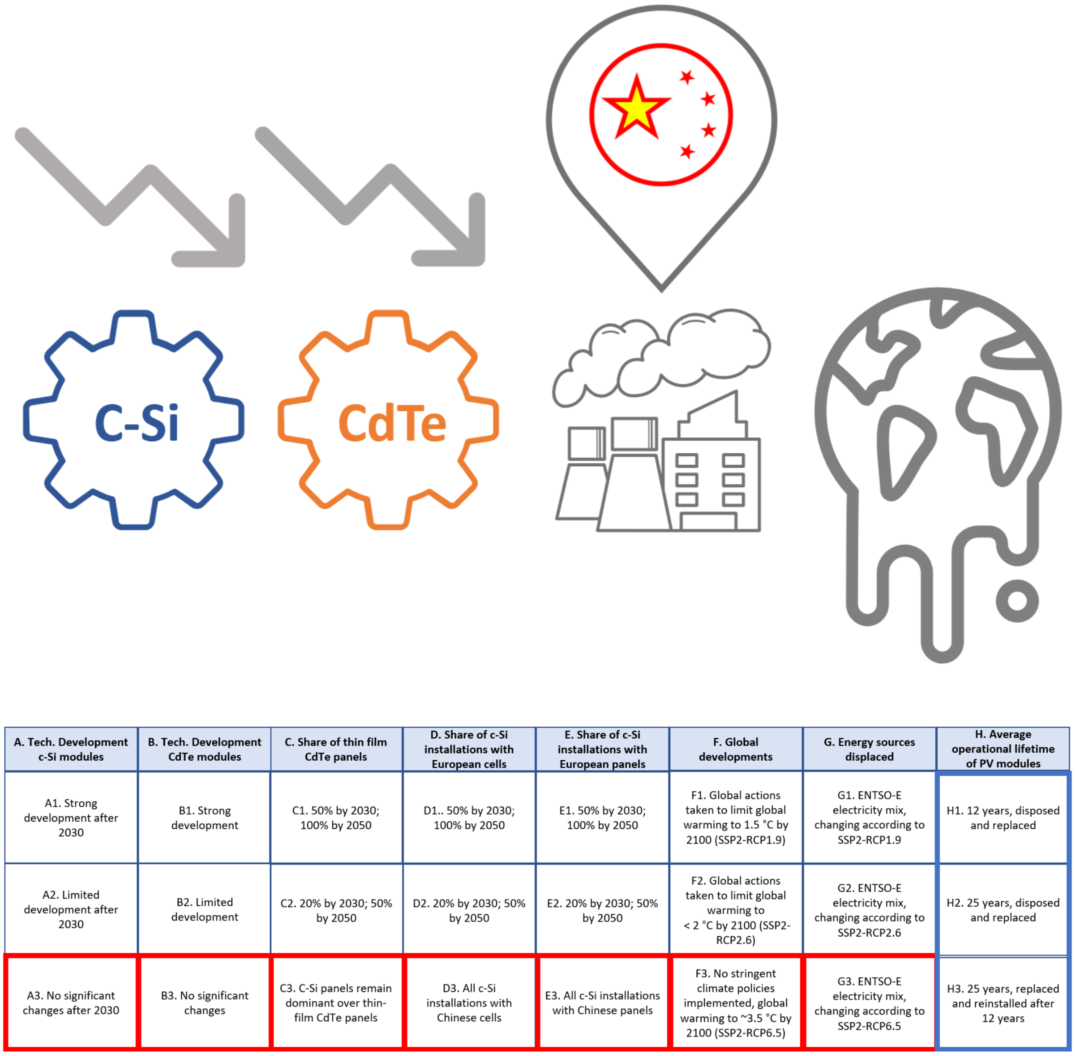
   Based on the accumulated net impact results, it can be concluded that the avoided impact in the reuse case is considerably higher for most impact categories that have a negative net impact. However, the avoided impact is not lower for Human Toxicity. This difference can mainly be attributed to the extra inverters and cabling that has to be produced for re-installation, as demonstrated in the contribution analysis in **Section 5.1.1**. If Amsterdam were to reinstall all the functional panels that are disposed after 12 years, it could further increase its avoided impact by 790 million kilogram CO2-Eq emissions. In other words, the net environmental impact on Global Warming of the reuse scenario is 40% lower than the op. LT = 12 scenario. Although the impact of several impact categories cannot be expressed in monetary terms, **Figure 4.7** shows that in this case the effects of Global Warming on society are by far the greatest, when expressed in societal costs. If all functional panels were reinstalled after 12 years and reused until an operational lifetime of 25 years is reached, an additional 114 million euros of environmental costs could be saved. In this case, the environmental costs of Ionising Radiation, Metal Depletion, Natural Land Transformation, Particulate Matter Formation, Photochemical Oxidant Formation and Urban Land Occupation have not been taken into account. However, most of these categories show a better result for the reuse scenario which will likely result in more avoided environmental costs in the reuse case.

3. **Net Positive Environmental Impact Categories**

   In each operational lifetime scenario, the induced impact is higher than the avoided impact for Freshwater Eco-Toxicity, Marine Eco-Toxicity, Metal Depletion and Terrestial Eco-Toxicity. For Natural Land Transformation a positive value corresponds to better outcome. This is verified by checking the impact of multiple background processes in EcoInvent v3.8, which show a negative value while they are inducing a bad impact on the environment by requiring natural land transformation. For example, 1kWh electricity generation in 2015 by the ENTSO-E electricity mix has an impact of -1.5E-5 square-meter on Natural Land Transformation. The higher induced impact on the earlier mentioned impact categories can mainly be attributed to the extra required inverters and cabling, as further clarified in the contribution analysis in **Section 5.1.1**.

4.3. Prospective LCA Results Scenario 2

This section presents the final results of the prospective LCA for scenario 2 at city-wide scale. Scenario 2 assesses all lifetime extension strategies of c-Si panels, with cells and panels produced in China under pessimistic global developments, following SSP2-RCP6.5. This scenario is subdivided into 2-H1, 2-H2 and 2-H3, based on the operational lifetime of the PV modules. 2-H1 assumes average panel replacement after 12 years, at the average inverter lifetime. The old panels are then disposed, following the current End-of-Life management procedure. 2-H2 assumes an operational lifetime of 25 years, where panels are kept on roofs until their technical lifetime of 25 years has been reached. The panels are then disposed, following the current End-of-Life management procedure. 2-H3 assumes the replacement of panels after 12 years, but the functional panels are reused at another location until their technical lifetime of 25 years has been reached.



A. Tech. Development c-Si modules	B. Tech. Development CdTe modules	C. Share of thin film CdTe panels	D. Share of c-Si installations with European cells	E. Share of c-Si installations with European panels	F. Global developments	G. Energy sources displaced	H. Average operational lifetime of PV modules
A1. Strong development after 2030	B1. Strong development	C1. 50% by 2030; 100% by 2050	D1.. 50% by 2030; 100% by 2050	E1. 50% by 2030; 100% by 2050	F1. Global actions taken to limit global warming to 1.5 °C by 2100 (SSP2-RCP1.9)	G1. ENTSO-E electricity mix, changing according to SSP2-RCP1.9	H1. 12 years, disposed and replaced
A2. Limited development after 2030	B2. Limited development	C2. 20% by 2030; 50% by 2050	D2. 20% by 2030; 50% by 2050	E2. 20% by 2030; 50% by 2050	F2. Global actions taken to limit global warming to < 2 °C by 2100 (SSP2-RCP2.6)	G2. ENTSO-E electricity mix, changing according to SSP2-RCP2.6	H2. 25 years, disposed and replaced
A3. No significant changes after 2030	B3. No significant changes	C3. C-Si panels remain dominant over thin-film CdTe panels	D3. All c-Si installations with Chinese cells	E3. All c-Si installations with Chinese panels	F3. No stringent climate policies implemented, global warming to ~3.5 °C by 2100 (SSP2-RCP6.5)	G3. ENTSO-E electricity mix, changing according to SSP2-RCP6.5	H3. 25 years, replaced and reinstalled after 12 years

Figure 4.8: Scenario 2 visualization variable choice

City-wide environmental impact

Table 4.5 provides an overview of the net accumulated impact for each impact category by 2050, expressed in absolute values. To make the data more apprehendable, the net accumulated impact for each impact category, relative to the op. LT = 12 scenario, is visualized in **Figure 4.9**. To assess the significance of different impact categories in a more relatable and understandable manner, the net accumulated impact in 2050 is also expressed in shadow costs (in euros, €) in **Table 4.6** and visualized in **Figure 4.10**. It should be noted that the shadow costs for several impact categories are unknown, which have been left in grey. A negative value indicates more avoided impact than induced impact.

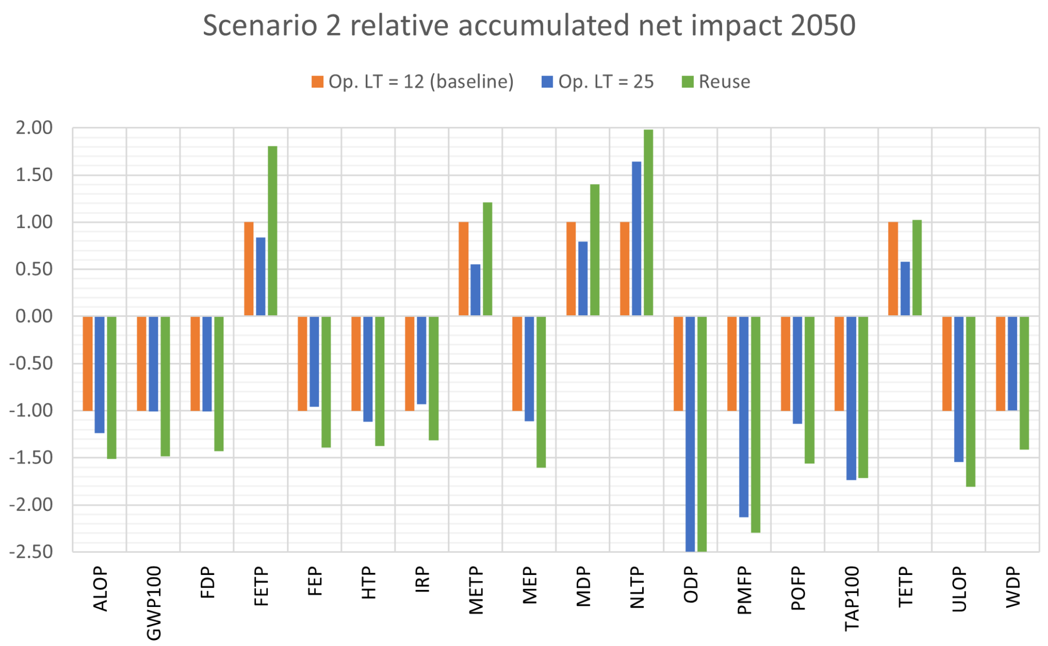


Figure 4.9: Net accumulated impact relative to op. LT = 12 for scenario 2

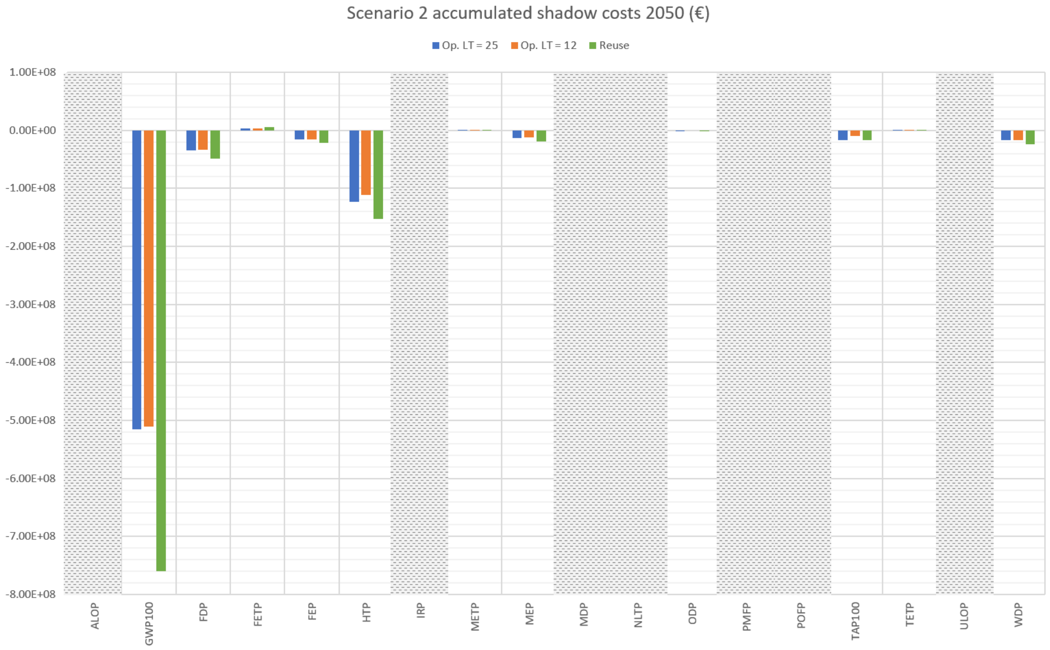


Figure 4.10: Net accumulated impact in 2050, expressed in shadow costs (in Euros, €) for scenario 2 (grey = unknown)

ACCUMULATED NET IMPACT SCENARIO 2

Op. LT Year	25 years 2030	25 years 2050	12 years 2030	12 years 2050	Reuse 2030	Reuse 2050	Unit
ALOP	-2.97E+07	-8.09E+07	-2.54E+07	-6.52E+07	-2.87E+07	-9.86E+07	Square meter-year
GWP100	-5.40E+08	-3.96E+09	-4.83E+08	-3.93E+09	-5.51E+08	-5.84E+09	kg CO2-Eq
FDP	-1.92E+08	-1.22E+09	-1.77E+08	-1.21E+09	-1.90E+08	-1.73E+09	kg oil-Eq
FETP	7.44E+07	1.26E+08	8.08E+07	1.51E+08	1.10E+08	2.72E+08	kg 1,4-DCB-Eq
FEP	-4.77E+05	-4.05E+06	-4.73E+05	-4.23E+06	-4.73E+05	-5.88E+06	kg P-Eq
HTP	-4.76E+06	-1.74E+09	6.81E+07	-1.56E+09	1.45E+08	-2.15E+09	kg 1,4-DCB-Eq
IRP	-6.03E+08	-2.03E+09	-6.24E+08	-2.18E+09	-6.85E+08	-2.87E+09	kg U235-Eq
METP	6.54E+07	1.08E+08	8.19E+07	1.95E+08	9.69E+07	2.36E+08	kg 1,4-DCB-Eq
MEP	-8.11E+04	-9.45E+05	-4.44E+04	-8.51E+05	-5.74E+04	-1.37E+06	kg N-Eq
MDP	1.91E+08	5.00E+08	2.21E+08	6.28E+08	2.66E+08	8.81E+08	kg Fe-eq
NLTP	-1.02E+04	9.18E+04	-2.11E+04	5.59E+04	-2.36E+04	1.11E+05	Square-meter
ODP	-3.76E-01	-2.63E+01	6.18E+00	-3.24E-02	5.15E+00	-2.90E+01	kg CFC-11-Eq
PMFP	1.73E+05	-1.17E+06	3.67E+05	-5.50E+05	4.06E+05	-1.26E+06	kg PM10-Eq
POFP	-5.25E+05	-5.23E+06	-2.79E+05	-4.59E+06	-3.21E+05	-7.17E+06	kg NMVOC-Eq
TAP100	-6.36E+03	-3.25E+06	4.11E+05	-1.87E+06	5.28E+05	-3.22E+06	kg SO2-Eq
TETP	9.89E+04	2.27E+05	1.39E+05	3.92E+05	1.45E+05	4.02E+05	kg 1,4-DCB-Eq
ULOP	2.75E+05	-9.69E+06	1.31E+06	-6.28E+06	1.49E+06	-1.14E+07	Square meter-year
WDP	-7.84E+06	-4.21E+07	-7.39E+06	-4.22E+07	-8.17E+06	-5.96E+07	m3 Water-Eq

Table 4.5: Results accumulated net impact scenario 2

TOTAL SHADOW COSTS SCENARIO 2

Op. LT	25 years	12 years	Reuse
ALOP	Unknown	Unknown	Unknown
GWP100	-5.15E+08	-5.11E+08	-7.59E+08
FDP	-3.42E+07	-3.39E+07	-4.84E+07
FETP	2.64E+06	3.15E+06	5.69E+06
FEP	-1.51E+07	-1.58E+07	-2.20E+07
HTP	-1.24E+08	-1.11E+08	-1.52E+08
IRP	Unknown	Unknown	Unknown
METP	3.47E+05	6.24E+05	7.55E+05
MEP	-1.35E+07	-1.21E+07	-1.95E+07
MDP	Unknown	Unknown	Unknown
NLTP	Unknown	Unknown	Unknown
ODP	-7.65E+02	-9.42E-01	-8.45E+02
PMFP	Unknown	Unknown	Unknown
POFP	Unknown	Unknown	Unknown
TAP100	-1.71E+07	-9.87E+06	-1.69E+07
TETP	1.45E+02	2.51E+02	2.57E+02
ULOP	Unknown	Unknown	Unknown
WDP	-1.71E+07	-1.72E+07	-2.42E+07
SUM	**-7.33E+08**	**-7.07E+08**	**-1.04E+09**

Table 4.6: Results accumulated net impact by 2050 for scenario 2, expressed in shadow costs (in Euros, €)

Observations

Several observations can be made on the city-wide prospective LCA results of scenario 2. These observations are listed and further clarified below. An in-depth analysis and interpretation of the observations is given in **Section 5.1** of the discussion.

1. **Higher Avoided Impact in Scenario 2**

   If Amsterdam were to reinstall all the functional panels that are disposed after 12 years, it could further increase its avoided impact by 1910 million kilogram CO2-Eq emissions, which is 48% more than the direct disposal after 12 years scenario. This is 1120 million kilograms more than in scenario 1. Additionally, 333 million euros of environmental costs could be saved, which is 219 million euros more than in scenario 1. This dramatic increase, despite poor technological development, can be explained by the effect of the SSP2-RCP6.5 pathway. This is further clarified in the contribution analysis in **Section 5.1.2** and verified by means of a sensitivity analysis in **Appendix B**.

2. **Slight Environmental Advantage for Lifetime Extension of PV Modules**

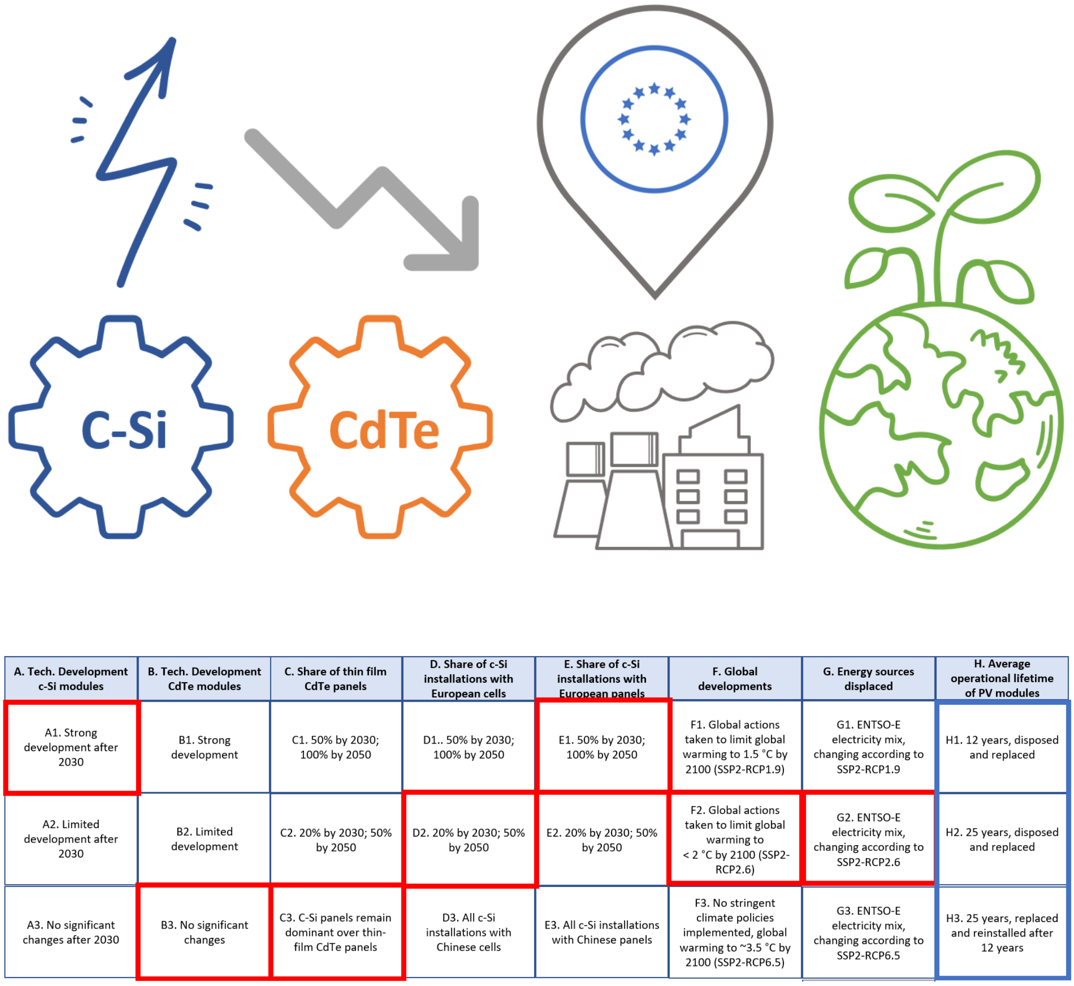
   If all panels were left on the roofs until they have reached their technical lifetime of 25 years, 30 million kg CO2-Eq emissions could be avoided and 26 million euros of environmental costs could be saved. This is more than for scenario 1, but still marginal compared to the reuse scenario. Reasoning for this has been given in **Section 5.1.1**.

3. **Net Positive Environmental Impact Categories**

   Similar to scenario 1, only Freshwater Eco-Toxicity, Marine Eco-Toxicity, Metal Depletion and Terrestrial Eco-Toxicity have a higher induced impact than avoided impact for all operational lifetime scenarios. A positive Natural Land Transformation value is beneficial for the environment, as explained in **Section 4.2**. However, two peculiarities strike out. The avoided Ozone Depletion impact in the Op. LT = 25 and reuse scenario is dramatically higher than for the Op. LT = 12 scenario. Furthermore, the net accumulated impact of Human Toxicity is much higher than in scenario 1 for all operational lifetime scenarios. Both phenomena are explained in the contribution analysis in **Section 5.1.2**.

4.4. Prospective LCA Results Scenario 3

This section presents the final results of the prospective LCA for scenario 3 at city-wide scale. In this scenario, all lifetime extension strategies of c-Si panels are assessed with a realistic market shift from China to Europe. The market shift occurs under strong technological development of c-Si panels after 2030 and realistic global developments, following SSP2-RCP2.6. 20% of solar cells are produced in Europe by 2030 and 50% by 2050. Furthermore 50% of the solar panels installed in Amsterdam are produced in Europe by 2030 and 100% by 2050. This scenario is subdivided into 3-H1, 3-H2 and 3-H3. 3-H1 assumes average panel replacement after 12 years, at the average inverter lifetime. The old panels are then disposed, following the current End-of-Life management procedure. 3-H2 assumes an operational lifetime of 25 years, where panels are kept on roofs until their technical lifetime of 25 years has been reached. The panels are then disposed, following the current End-of-Life management procedure. 3-H3 assumes the replacement of panels after 12 years, but the functional panels are reused at another location until their technical lifetime of 25 years has been reached.



A. Tech. Development c-Si modules	B. Tech. Development CdTe modules	C. Share of thin film CdTe panels	D. Share of c-Si installations with European cells	E. Share of c-Si installations with European panels	F. Global developments	G. Energy sources displaced	H. Average operational lifetime of PV modules
A1. Strong development after 2030	B1. Strong development	C1. 50% by 2030; 100% by 2050	D1.. 50% by 2030; 100% by 2050	E1. 50% by 2030; 100% by 2050	F1. Global actions taken to limit global warming to 1.5 °C by 2100 (SSP2-RCP1.9)	G1. ENTSO-E electricity mix, changing according to SSP2-RCP1.9	H1. 12 years, disposed and replaced
A2. Limited development after 2030	B2. Limited development	C2. 20% by 2030; 50% by 2050	D2. 20% by 2030; 50% by 2050	E2. 20% by 2030; 50% by 2050	F2. Global actions taken to limit global warming to < 2 °C by 2100 (SSP2-RCP2.6)	G2. ENTSO-E electricity mix, changing according to SSP2-RCP2.6	H2. 25 years, disposed and replaced
A3. No significant changes after 2030	B3. No significant changes	C3. C-Si panels remain dominant over thin-film CdTe panels	D3. All c-Si installations with Chinese cells	E3. All c-Si installations with Chinese panels	F3. No stringent climate policies implemented, global warming to ~3.5 °C by 2100 (SSP2-RCP6.5)	G3. ENTSO-E electricity mix, changing according to SSP2-RCP6.5	H3. 25 years, replaced and reinstalled after 12 years

Figure 4.11: Scenario 3 visualization variable choice

City-wide environmental impact

Table 4.7 provides an overview of the net accumulated impact for each impact category by 2050, expressed in absolute values. To make the data more apprehendable, the net accumulated impact for each impact category, relative to the op. LT = 12 scenario, is visualized in **Figure 4.12**. To assess the significance of different impact categories in a more relatable and understandable manner, the net accumulated impact in 2050 is also expressed in shadow costs (in euros, €) in **Table 4.8** and visualized in **Figure 4.13**. It should be noted that the shadow costs for several impact categories are unknown, which have been left in grey. A negative value indicates more avoided impact than induced impact.

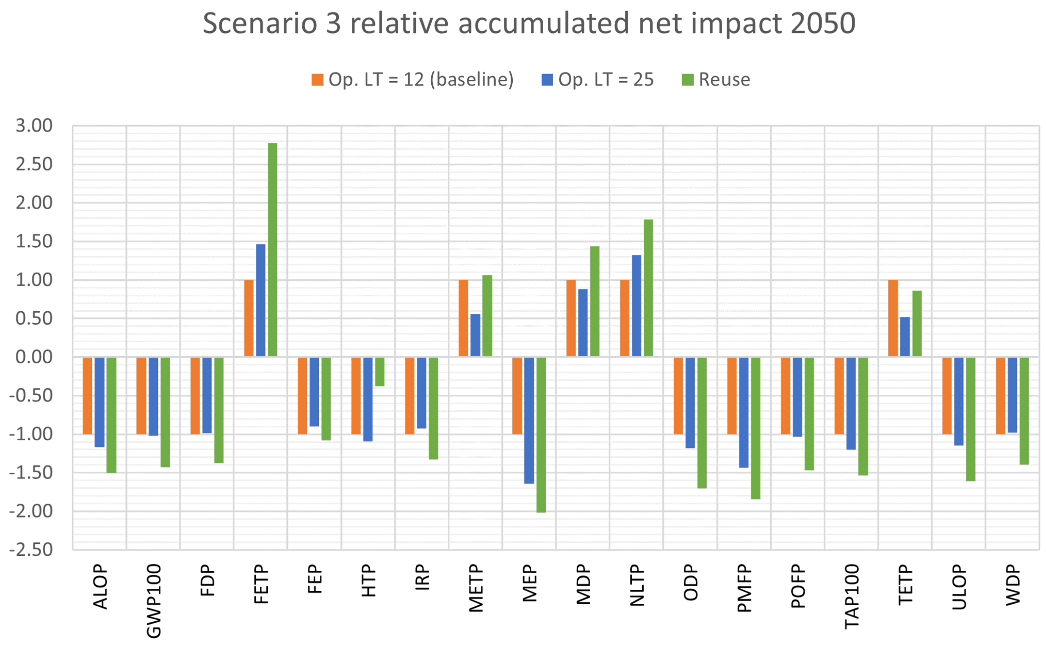


Figure 4.12: Net accumulated impact relative to op. LT = 12 for scenario 3

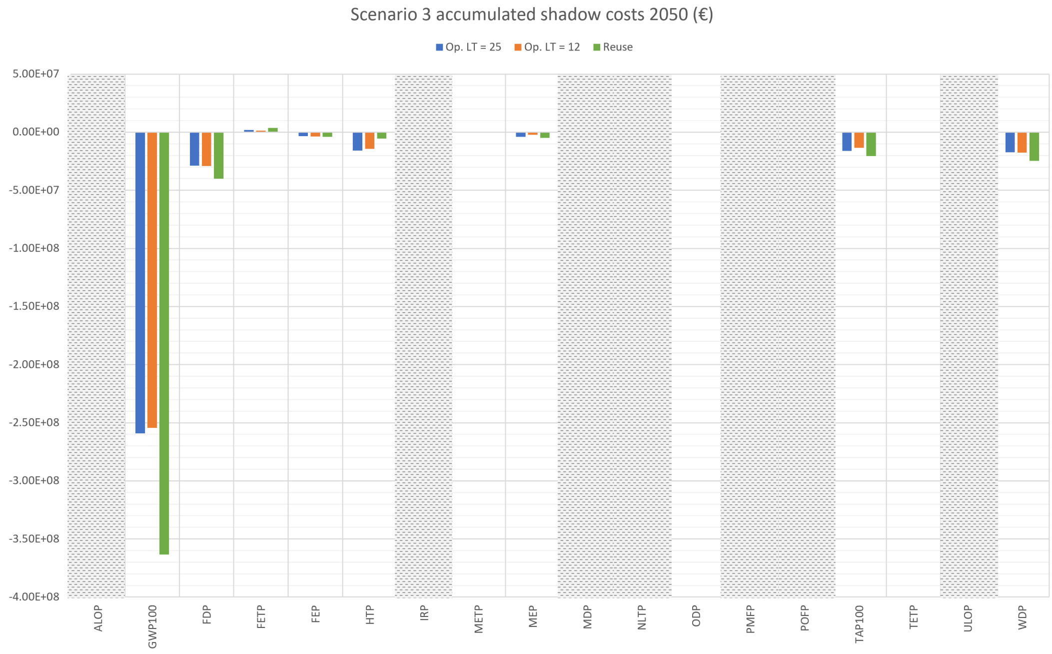


Figure 4.13: Net accumulated impact in 2050, expressed in shadow costs (in Euros, €) for scenario 3 (grey = unknown)

ACCUMULATED NET IMPACT SCENARIO 3							
Op. LT	25 years	25 years	12 years	12 years	Reuse	Reuse	
Year	2030	2050	2030	2050	2030	2050	Unit
ALOP	-2.56E+07	-8.50E+07	-2.17E+07	-7.29E+07	-2.42E+07	-1.09E+08	Square meter-year
GWP100	-4.96E+08	-1.99E+09	-4.50E+08	-1.96E+09	-5.09E+08	-2.80E+09	kg CO2-Eq
FDP	-1.92E+08	-1.02E+09	-1.80E+08	-1.04E+09	-1.93E+08	-1.43E+09	kg oil-Eq
FETP	5.14E+07	9.41E+07	4.50E+07	6.42E+07	7.13E+07	1.78E+08	kg 1,4-DCB-Eq
FEP	-3.67E+05	-8.83E+05	-3.81E+05	-9.80E+05	-3.60E+05	-1.06E+06	kg P-Eq
HTP	-6.00E+07	-2.22E+08	-4.45E+07	-2.04E+08	1.19E+07	-7.67E+07	kg 1,4-DCB-Eq
IRP	-6.12E+08	-2.36E+09	-6.34E+08	-2.54E+09	-6.95E+08	-3.38E+09	kg U235-Eq
METP	4.51E+07	8.25E+07	5.44E+07	1.47E+08	6.26E+07	1.56E+08	kg 1,4-DCB-Eq
MEP	-5.27E+04	-2.75E+05	-1.87E+04	-1.67E+05	-2.61E+04	-3.37E+05	kg N-Eq
MDP	1.50E+08	3.74E+08	1.61E+08	4.22E+08	1.98E+08	6.08E+08	kg Fe-eq
NLTP	-5.68E+03	7.62E+04	-1.29E+04	5.75E+04	-1.44E+04	1.03E+05	Square-meter
ODP	-5.02E+00	-1.09E+02	9.06E-01	-9.28E+01	-5.78E-01	-1.58E+02	kg CFC-11-Eq
PMFP	5.84E+04	-9.43E+05	1.80E+05	-6.59E+05	1.93E+05	-1.22E+06	kg PM10-Eq
POFP	-6.54E+05	-5.61E+06	-4.88E+05	-5.44E+06	-5.37E+05	-7.99E+06	kg NMVOC-Eq
TAP100	-3.55E+05	-3.04E+06	-1.37E+05	-2.53E+06	-1.14E+05	-3.89E+06	kg SO2-Eq
TETP	8.05E+04	1.39E+05	1.14E+05	2.68E+05	1.16E+05	2.31E+05	kg 1,4-DCB-Eq
ULOP	-4.02E+05	-1.13E+07	2.40E+05	-9.87E+06	2.35E+05	-1.59E+07	Square meter-year
WDP	-8.01E+06	-4.27E+07	-7.61E+06	-4.35E+07	-8.43E+06	-6.07E+07	m3 Water-Eq

Table 4.7: Results accumulated net impact scenario 3

TOTAL SHADOW COSTS SCENARIO 3			
Op. LT	25 years	12 years	Reuse
ALOP	Unknown	Unknown	Unknown
GWP100	-2.59E+08	-2.54E+08	-3.63E+08
FDP	-2.87E+07	-2.91E+07	-4.01E+07
FETP	1.97E+06	1.34E+06	3.72E+06
FEP	-3.30E+06	-3.66E+06	-3.96E+06
HTP	-1.58E+07	-1.45E+07	-5.44E+06
IRP	Unknown	Unknown	Unknown
METP	2.64E+05	4.72E+05	5.00E+05
MEP	-3.92E+06	-2.38E+06	-4.81E+06
MDP	Unknown	Unknown	Unknown
NLTP	Unknown	Unknown	Unknown
ODP	-3.18E+03	-2.70E+03	-4.60E+03
PMFP	Unknown	Unknown	Unknown
POFP	Unknown	Unknown	Unknown
TAP100	-1.60E+07	-1.34E+07	-2.05E+07
TETP	8.89E+01	1.72E+02	1.48E+02
ULOP	Unknown	Unknown	Unknown
WDP	-1.74E+07	-1.77E+07	-2.47E+07
SUM	**-3.42E+08**	**-3.33E+08**	**-4.59E+08**

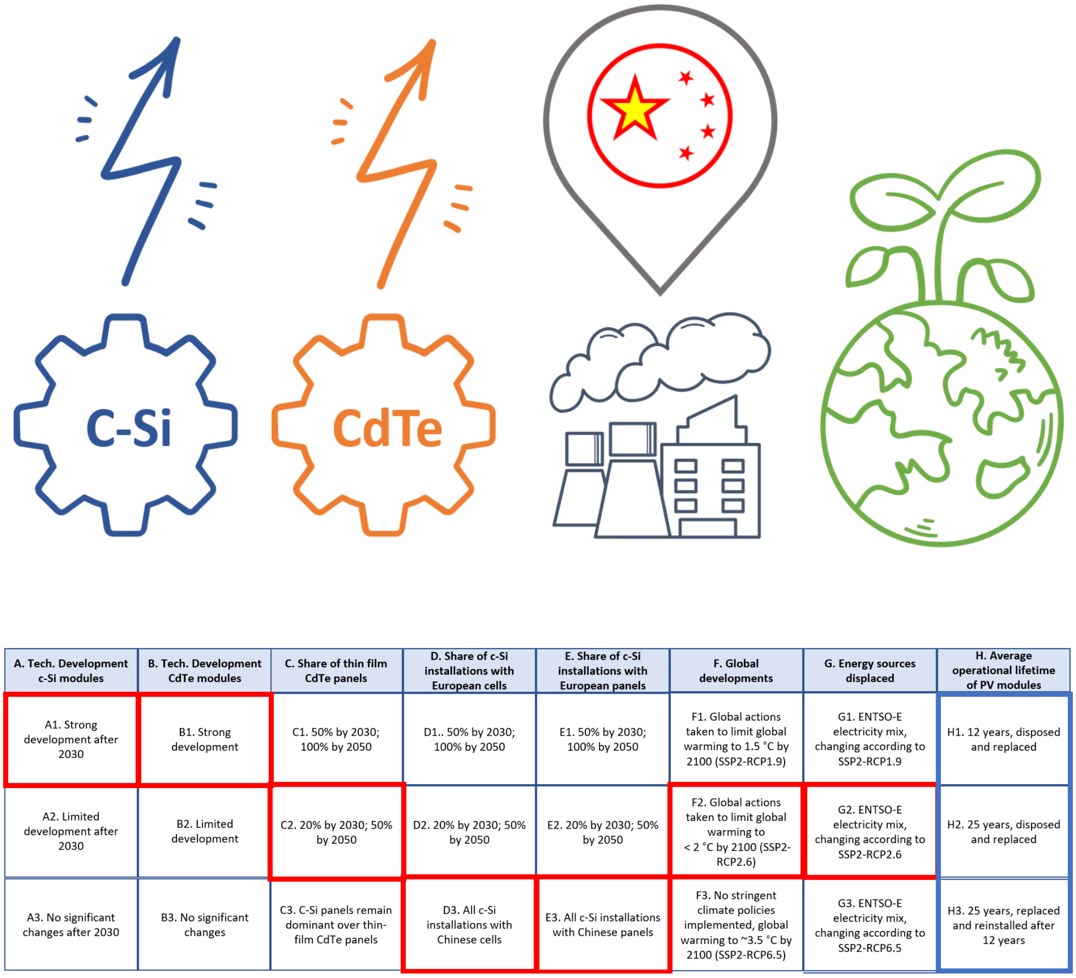
Table 4.8: Results accumulated net impact by 2050 for scenario 3, expressed in shadow costs (in Euros, €)

Observations

The results seem identical to the results of scenario 1. However, slight changes can be observed in the absolute values. In the Op. LT = 12 year and reuse case, a realistic market shift to Europe would mean 30 million kg less CO2-Eq emissions and 5 million euros of shadow costs saved, based on the assumptions of this study. These gains are only marginal compared to interventions such as the reuse of functional disposed panels. Reasoning for this phenomena is given in **Section 5.1.3** of the discussion.

4.5. Prospective LCA Results Scenario 4

This section presents the final results of the prospective LCA for scenario 4 at city-wide scale. This scenario assesses all lifetime extension strategies, where the tech. development of CdTe panels is substantial and becomes competitive with c-Si panels in the coming decades. In this scenario, 20% of the yearly installations consist of CdTe panels by 2030 and 50% by 2050. Global developments follow the realistic SSP2-RCP2.6 scenario. This scenario is subdivided into 4-H1, 4-H2 and 4-H3. 4-H1 assumes average panel replacement after 12 years, at the average inverter lifetime. The old panels are then disposed, following the current End-of-Life management procedure. 4-H2 assumes an operational lifetime of 25 years, where panels are kept on roofs until their technical lifetime of 25 years has been reached. The panels are then disposed, following the current End-of-Life management procedure. 4-H3 assumes the replacement of panels after 12 years, but the functional panels are reused at another location until their technical lifetime of 25 years has been reached.



A. Tech. Development c-Si modules	B. Tech. Development CdTe modules	C. Share of thin film CdTe panels	D. Share of c-Si installations with European cells	E. Share of c-Si installations with European panels	F. Global developments	G. Energy sources displaced	H. Average operational lifetime of PV modules
A1. Strong development after 2030	B1. Strong development	C1. 50% by 2030; 100% by 2050	D1.. 50% by 2030; 100% by 2050	E1. 50% by 2030; 100% by 2050	F1. Global actions taken to limit global warming to 1.5 °C by 2100 (SSP2-RCP1.9)	G1. ENTSO-E electricity mix, changing according to SSP2-RCP1.9	H1. 12 years, disposed and replaced
A2. Limited development after 2030	B2. Limited development	C2. 20% by 2030; 50% by 2050	D2. 20% by 2030; 50% by 2050	E2. 20% by 2030; 50% by 2050	F2. Global actions taken to limit global warming to < 2 °C by 2100 (SSP2-RCP2.6)	G2. ENTSO-E electricity mix, changing according to SSP2-RCP2.6	H2. 25 years, disposed and replaced
A3. No significant changes after 2030	B3. No significant changes	C3. C-Si panels remain dominant over thin-film CdTe panels	D3. All c-Si installations with Chinese cells	E3. All c-Si installations with Chinese panels	F3. No stringent climate policies implemented, global warming to ~3.5 °C by 2100 (SSP2-RCP6.5)	G3. ENTSO-E electricity mix, changing according to SSP2-RCP6.5	H3. 25 years, replaced and reinstalled after 12 years

Figure 4.14: Scenario 4 visualization variable choice

City-wide environmental impact

Table 4.9 provides an overview of the net accumulated impact for each impact category by 2050, expressed in absolute values. To make the data more apprehendable, the net accumulated impact for each impact category, relative to the op. LT = 12 scenario, is visualized in **Figure 4.15**. To assess the significance of different impact categories in a more relatable and understandable manner, the net accumulated impact in 2050 is also expressed in shadow costs (in euros, €) in **Table 4.10** and visualized in **Figure 4.16**. It should be noted that the shadow costs for several impact categories are unknown, which have been left in grey. A negative value indicates more avoided impact than induced impact.

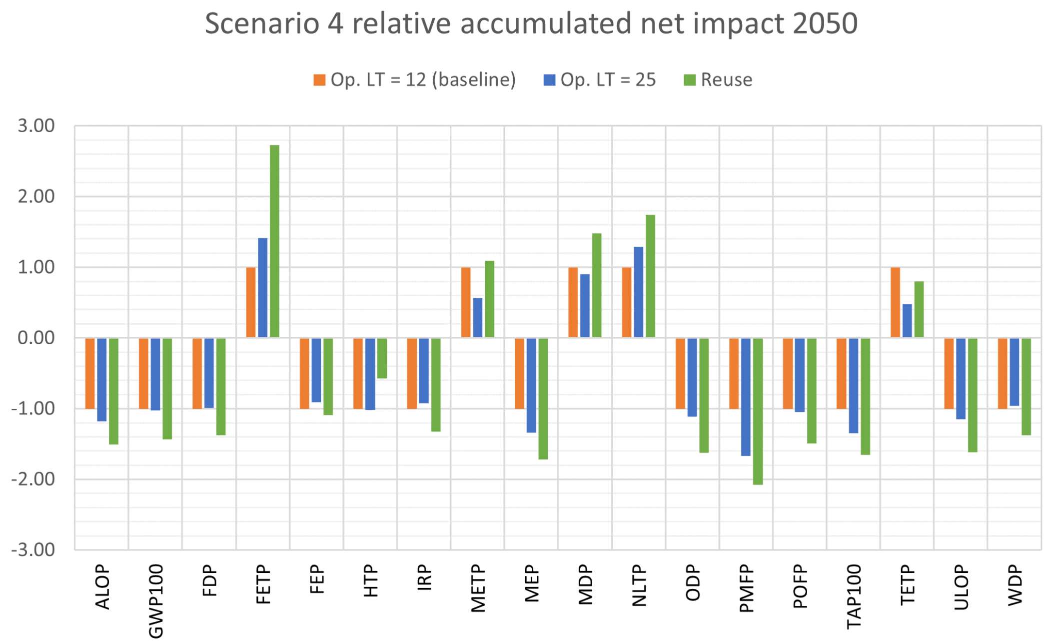


Figure 4.15: Net accumulated impact relative to op. LT = 12 for scenario 4

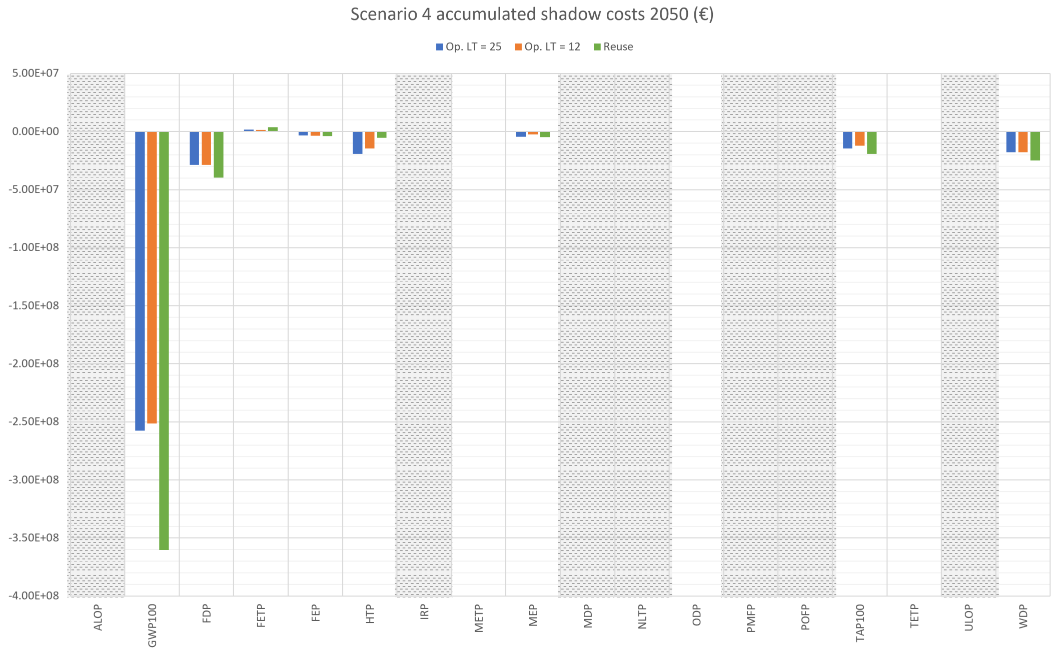


Figure 4.16: Net accumulated impact in 2050, expressed in shadow costs (in Euros, €) for scenario 4 (grey = unknown)

ACCUMULATED NET IMPACT SCENARIO 4

Op. LT	25 years	25 years	12 years	12 years	Reuse	Reuse	
Year	2030	2050	2030	2050	2030	2050	Unit
ALOP	-2.57E+07	-8.34E+07	-2.18E+07	-7.09E+07	-2.42E+07	-1.07E+08	Square meter-year
GWP100	-4.94E+08	-1.98E+09	-4.46E+08	-1.94E+09	-5.04E+08	-2.77E+09	kg CO2-Eq
FDP	-1.91E+08	-1.02E+09	-1.79E+08	-1.04E+09	-1.91E+08	-1.43E+09	kg oil-Eq
FETP	5.10E+07	8.66E+07	4.38E+07	6.11E+07	7.04E+07	1.67E+08	kg 1,4-DCB-Eq
FEP	-3.69E+05	-9.04E+05	-3.85E+05	-9.99E+05	-3.62E+05	-1.09E+06	kg P-Eq
HTP	-6.34E+07	-2.71E+08	-5.24E+07	-2.67E+08	5.71E+06	-1.53E+08	kg 1,4-DCB-Eq
IRP	-6.14E+08	-2.37E+09	-6.37E+08	-2.56E+09	-6.97E+08	-3.40E+09	kg U235-Eq
METP	4.47E+07	7.58E+07	5.34E+07	1.34E+08	6.18E+07	1.46E+08	kg 1,4-DCB-Eq
MEP	-5.54E+04	-3.14E+05	-2.41E+04	-2.34E+05	-3.11E+04	-4.02E+05	kg N-Eq
MDP	1.48E+08	3.41E+08	1.57E+08	3.77E+08	1.95E+08	5.56E+08	kg Fe-eq
NLTP	-5.67E+03	7.80E+04	-1.28E+04	6.04E+04	-1.45E+04	1.05E+05	Square-meter
ODP	-5.46E+00	-1.17E+02	2.00E-02	-1.05E+02	-1.38E+00	-1.71E+02	kg CFC-11-Eq
PMFP	6.81E+04	-8.54E+05	1.98E+05	-5.13E+05	2.13E+05	-1.06E+06	kg PM10-Eq
POFP	-6.41E+05	-5.48E+06	-4.64E+05	-5.22E+06	-5.08E+05	-7.77E+06	kg NMVOC-Eq
TAP100	-3.29E+05	-2.74E+06	-8.74E+04	-2.04E+06	-5.90E+04	-3.37E+06	kg SO2-Eq
TETP	7.73E+04	9.27E+04	1.08E+05	1.93E+05	1.09E+05	1.55E+05	kg 1,4-DCB-Eq
ULOP	-4.07E+05	-1.15E+07	2.25E+05	-9.98E+06	2.32E+05	-1.61E+07	Square meter-year
WDP	-8.11E+06	-4.40E+07	-7.79E+06	-4.57E+07	-8.59E+06	-6.27E+07	m3 Water-Eq

Table 4.9: Results accumulated net impact scenario 4

TOTAL SHADOW COSTS SCENARIO 4

Op. LT	25 years	12 years	Reuse
ALOP	Unknown	Unknown	Unknown
GWP100	-2.57E+08	-2.52E+08	-3.60E+08
FDP	-2.87E+07	-2.91E+07	-3.99E+07
FETP	1.81E+06	1.28E+06	3.48E+06
FEP	-3.38E+06	-3.74E+06	-4.09E+06
HTP	-1.93E+07	-1.90E+07	-1.08E+07
IRP	Unknown	Unknown	Unknown
METP	2.43E+05	4.28E+05	4.67E+05
MEP	-4.48E+06	-3.34E+06	-5.73E+06
MDP	Unknown	Unknown	Unknown
NLTP	Unknown	Unknown	Unknown
ODP	-3.41E+03	-3.07E+03	-4.97E+03
PMFP	Unknown	Unknown	Unknown
POFP	Unknown	Unknown	Unknown
TAP100	-1.44E+07	-1.08E+07	-1.78E+07
TETP	5.93E+01	1.23E+02	9.92E+01
ULOP	Unknown	Unknown	Unknown
WDP	-1.79E+07	-1.86E+07	-2.55E+07
SUM	**-3.44E+08**	**-3.35E+08**	**-4.60E+08**

Table 4.10: Results accumulated net impact by 2050 for scenario 4, expressed in shadow costs (in Euros, €)

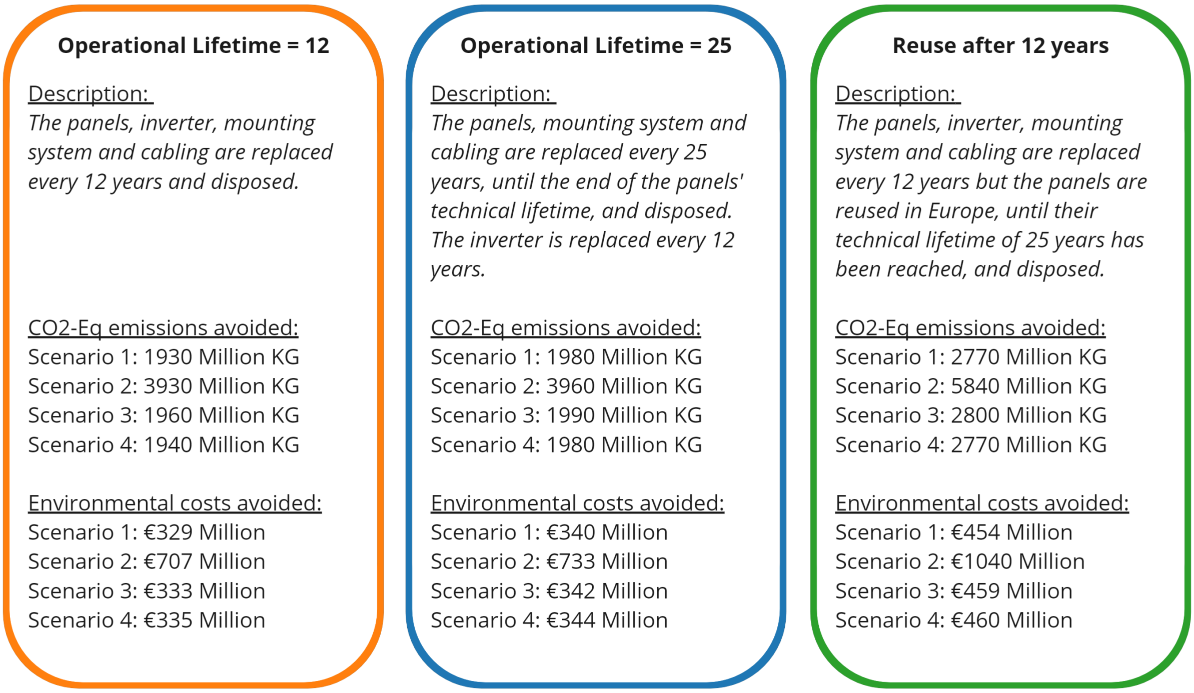
Observations

Similar to scenario 3, this scenario shows only marginal differences compared to scenario 1, when analyzing the different operational lifetime cases. The only input difference to scenario 1 is that CdTe modules gain competitiveness with c-Si panels due to the strong technological development, creating similar performance levels within a few decades. In this scenario, the difference in net accumulated impact for Global Warming can be regarded negligible. However, several absolute values show notable differences. These differences are further analyzed in **Section 5.1.5**. Furthermore, the robustness of the differences in results are analyzed by means of a sensitivity check on the impact of a complete and sudden market shift to CdTe panels (100% c-Si panels and 100% CdTe panels), in **Section 5.1.5** of the discussion.

5

Discussion

In this chapter, the research findings and the research approach are discussed in a wider scope. First the scenario-dependent results are critically analyzed in combination with their contribution analysis and sensitivity analysis. Hereafter the results are compared with literature and limitations to the research are discussed. Based on these limitations, future research opportunities are addressed and finally a reflection of the methodology is provided to link the implications of this study to theoretical knowledge and practice. **Figure 5.1** gives a summary of the main results for each operational lifetime scenario.



Operational Lifetime = 12

Description:
The panels, inverter, mounting system and cabling are replaced every 12 years and disposed.

CO2-Eq emissions avoided:
Scenario 1: 1930 Million KG
Scenario 2: 3930 Million KG
Scenario 3: 1960 Million KG
Scenario 4: 1940 Million KG

Environmental costs avoided:
Scenario 1: €329 Million
Scenario 2: €707 Million
Scenario 3: €333 Million
Scenario 4: €335 Million

Operational Lifetime = 25

Description:
The panels, mounting system and cabling are replaced every 25 years, until the end of the panels' technical lifetime, and disposed. The inverter is replaced every 12 years.

CO2-Eq emissions avoided:
Scenario 1: 1980 Million KG
Scenario 2: 3960 Million KG
Scenario 3: 1990 Million KG
Scenario 4: 1980 Million KG

Environmental costs avoided:
Scenario 1: €340 Million
Scenario 2: €733 Million
Scenario 3: €342 Million
Scenario 4: €344 Million

Reuse after 12 years

Description:
The panels, inverter, mounting system and cabling are replaced every 12 years but the panels are reused in Europe, until their technical lifetime of 25 years has been reached, and disposed.

CO2-Eq emissions avoided:
Scenario 1: 2770 Million KG
Scenario 2: 5840 Million KG
Scenario 3: 2800 Million KG
Scenario 4: 2770 Million KG

Environmental costs avoided:
Scenario 1: €454 Million
Scenario 2: €1040 Million
Scenario 3: €459 Million
Scenario 4: €460 Million

Figure 5.1: Overview of key results city-wide prospective LCA for each scenario

5.1. Interpretation of Results

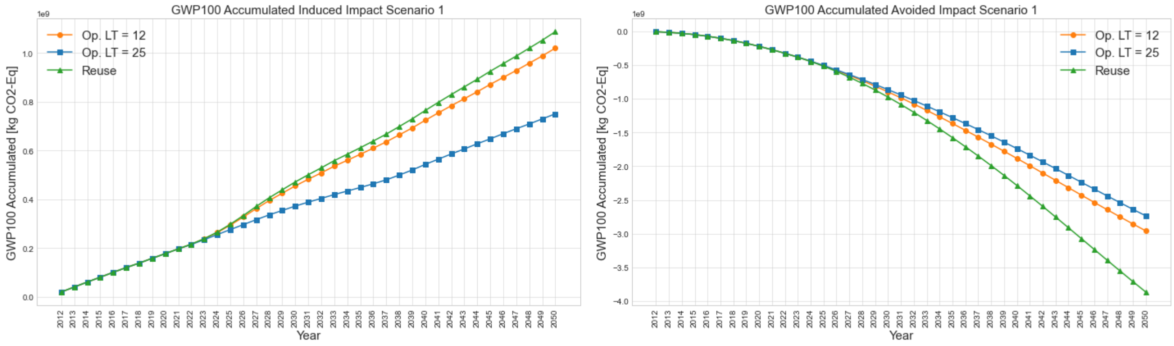
Chapter 4 has provided a complete overview of the overarching city-wide prospective LCA results for each scenario, derived through the general morphological analysis (GMA). Each scenario shows a great environmental advantage for the reuse case, which is what could be expected based on the circular processing ladder presented in the introduction.

5.1.1. Contribution Analysis Scenario 1

The overarching accumulated net environmental impact results of scenario 1, provided in **Section 4.2**, have led to several noteworthy observations. By conducting a systematic contribution analysis, the underlying factors behind the observed phenomena can be uncovered and validated.

Marginal Gains for Disposal Postponement

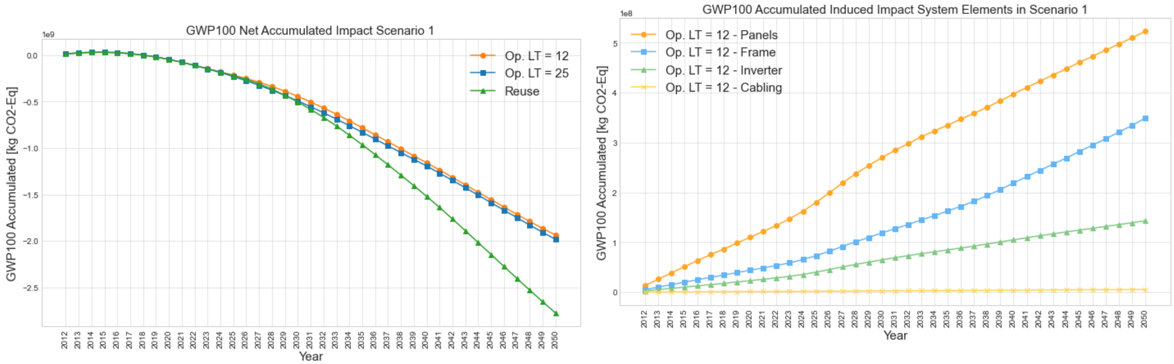
As pointed out in observation 1, the op. LT = 25 scenario only performs slightly better than the op. LT = 12 scenario for Global Warming (2.5% better) and for total shadow costs (3.3% better). The explanation of this phenomenon is three-fold. Global Warming is taken as example for simplicity. First of all, in the op. LT = 12 scenario, newer panels with a higher performance are replaced at a faster rate. This causes a higher electricity yield which in turn avoids more CO2-Eq emissions, as shown in **Figure 5.2b**. However, a higher replacement rate also implies more panels, frames and cabling to be produced. This causes a higher induced Global Warming impact, as shown in **Figure 5.2a**. When integrating both induced impact and avoided impact, the net accumulated impact can be obtained, as visualized in **Figure 5.3a**. The fact that the avoided impact exceeds the induced impact can also partially be explained by other technological development factors, besides the performance. As shown in **Figure 5.3b**, the PV panel production is the biggest contributor to the induced impact. However, the accumulated impact increase of PV modules remains linear while the installation rate increases, as more panels are replaced. **Figure 5.4** shows that due to technological development and the electricity mix change in China, which follows the SSP2-RCP2.6 pathway, the impact of production decreases substantially for almost all impact categories. When taking into account all these factors, an operational lifetime of 25 years shows marginal benefits compared to an operational lifetime of 12 years.



(a) Accumulated induced impact Global Warming in scenario 1

(b) Accumulated avoided impact Global Warming in scenario 1

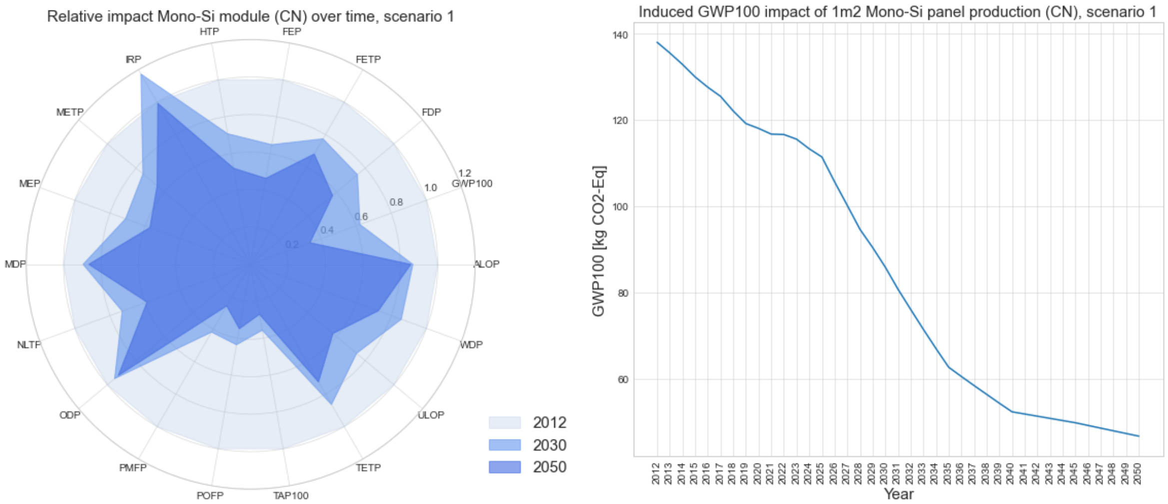
Figure 5.2: Comparison of Accumulated Induced and Avoided Impact for Global Warming



(a) Net accumulated impact Global Warming in scenario 1

(b) Contribution system elements Global Warming for Op. LT = 12 in scenario 1

Figure 5.3: Net accumulated impact Global Warming and contribution system elements accumulated induced impact



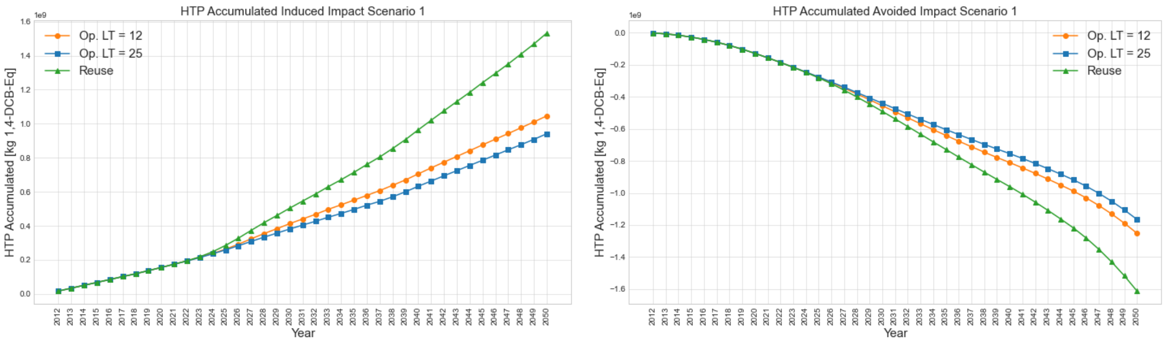
(a) Spider plot of induced impact Mono-Si panel (CN) production in scenario 1, relative to 2012

(b) Global Warming induced impact 1m2 Mono-Si panel (CN) production in scenario 1

Figure 5.4: Visualization of induced impact over time for 1m2 of Mono-Si panel, produced in China in scenario 1

Counter-Intuitive Effects for Reuse of PV Modules

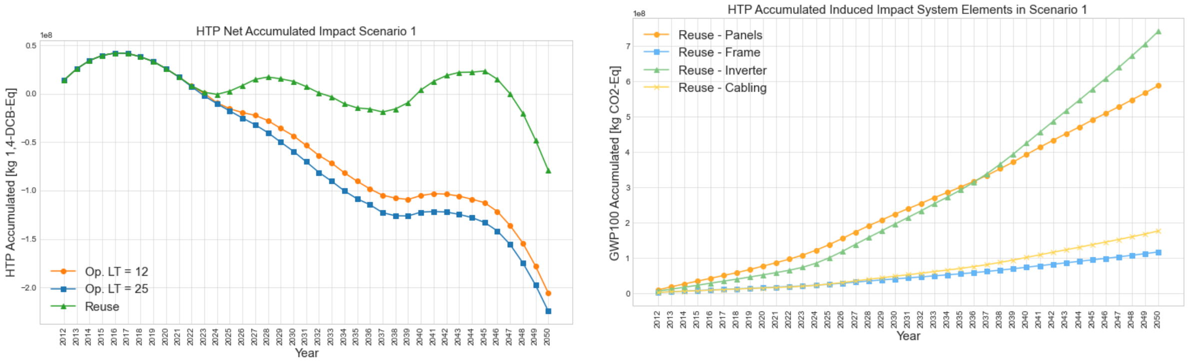
Although the re-installation of disposed functional solar panels creates a positive environmental effect for most impact categories, some counter-intuitive observations can be made. For example, the net accumulated impact on Human Toxicity is worse in the reuse case. To determine why, the final results for human toxicity are dissected into the accumulated induced impact and avoided impact in **Figure 5.5a** and **Figure 5.5b**, respectively. The reuse case starts increasing in accumulated induced impact as soon as new panels are installed and the old panels are reinstalled. Similarly, the avoided impact starts increasing because more electricity generated by the grid is displaced. **Figure 5.6a** combines both the accumulated avoided impact and the accumulated induced impact to visualize the net impact. It is important to note that the y-axis has decreased in scale (from E+09 to E+08) for better visualization. It now becomes clear that as soon as new installations start to occur after 12 years of the first installation period, the net accumulated impact starts increasing again. As shown in **Figure 5.6b**, the biggest contributor to this phenomena is the inverter, which even exceeds the accumulated impact of the panels by 2037. The substantial amount of extra inverters, combined with the extra cabling required in the reuse case therefore has a negative effect on Human Toxicity. Despite this negative effect, the net accumulated impact is still lower than zero by 2050 due to the avoided impact, as shown in **Figure 5.6a**. Similar effects occur for Marine Eco-Toxicity, Freshwater Eco-Toxicity and Metal Depletion, where the net accumulated impact is actually above zero. It is unclear whether technological development will lead to a lower induced impact for inverters in the future, as this is outside of the scope of this study.



(a) Accumulated induced impact HTP in scenario 1

(b) Accumulated avoided impact HTP in scenario 1

Figure 5.5: Comparison of accumulated induced and avoided impact for Human Toxicity in scenario 1



(a) Net Accumulated impact HTP in scenario 1

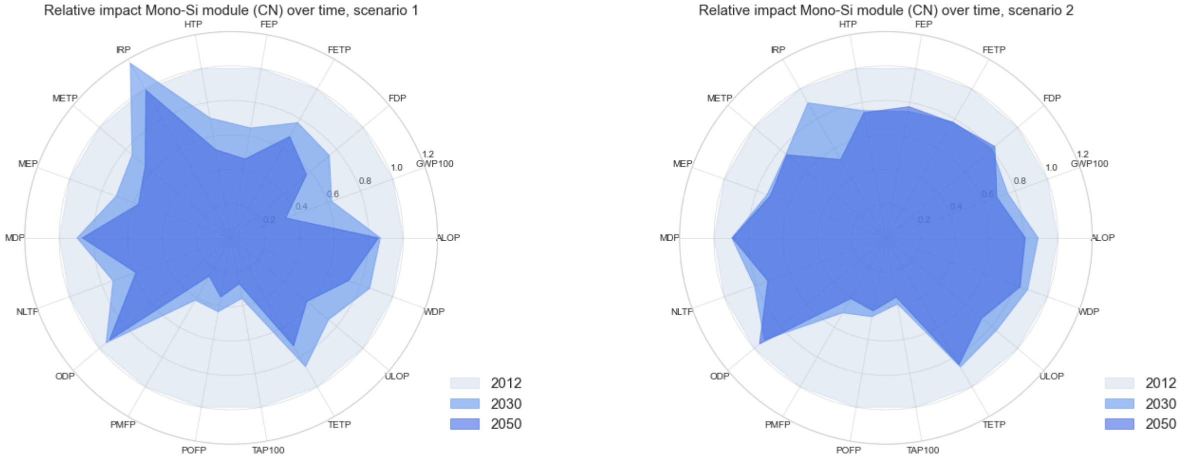
(b) Accumulated induced impact HTP for each PV system element for the reuse case in scenario 1

5.1.2. Contribution Analysis Scenario 2

Several interesting distinctions can be made between the results of scenario 1 and scenario 2, provided in **Section 4.2**. By conducting a systematic contribution analysis, the underlying factors behind the observed phenomena can be uncovered and validated.

Higher Avoided Impact in Scenario 2

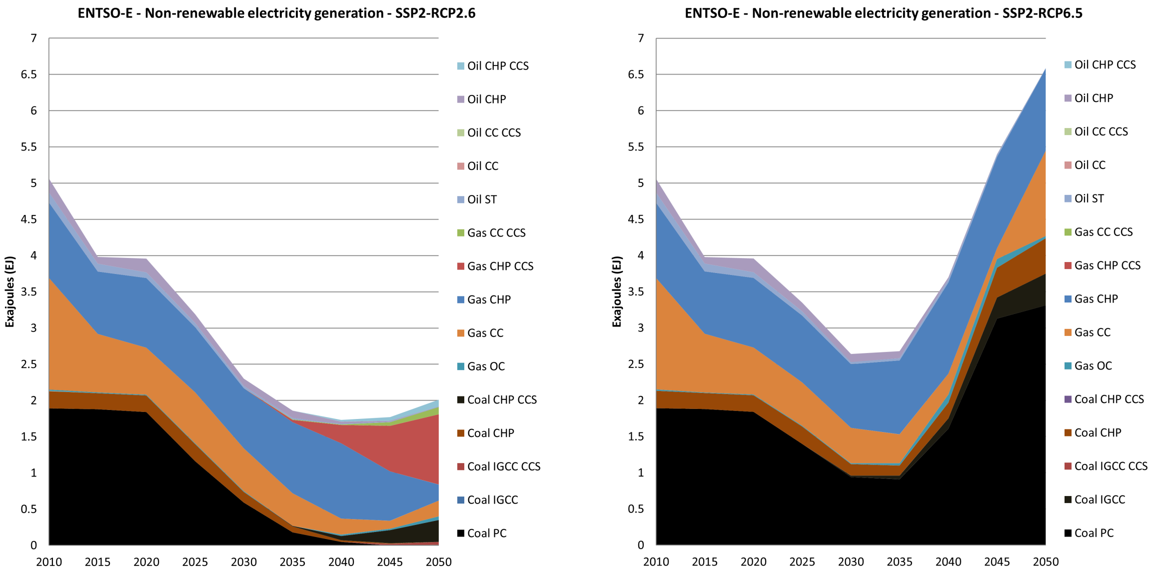
As mentioned in observation 1, the avoided impact is much higher in scenario 2 than in scenario 1, despite a lower technological development of PV modules after 2030. This can be explained by comparing the dynamic ENTSO-E grids that are displaced in both scenarios. **Figure 5.8** shows the dynamic non-renewable and renewable electricity generation mix for ENTSO-E in both scenarios. It becomes apparent that the electricity mix displaced in scenario 1 contains much less non-renewables after 2030 which are the main contributors for most environmental impact categories. Therefore, in the scenario of no stringent climate policies in Europe, the avoided impact of the municipality's PV installation targets becomes much higher. **Figure 5.7** shows the difference in impact of PV production in China for both scenarios. Because of lower technological development and worse electricity mix development in China, the environmental impact for panel production remains relatively high in 2050 for scenario 2. However, despite the higher induced impact during production, the net accumulated impact is more sensitive to changes in avoided impact than induced impact, as shown in the sensitivity analysis in **Appendix B**, which is why the net accumulated impact in scenario 2 generally scores better. **Appendix B** provides additional analysis on the sensitivity of electricity mix developments and technological developments on the results, as well as the relative effect on different operational lifetime scenarios.



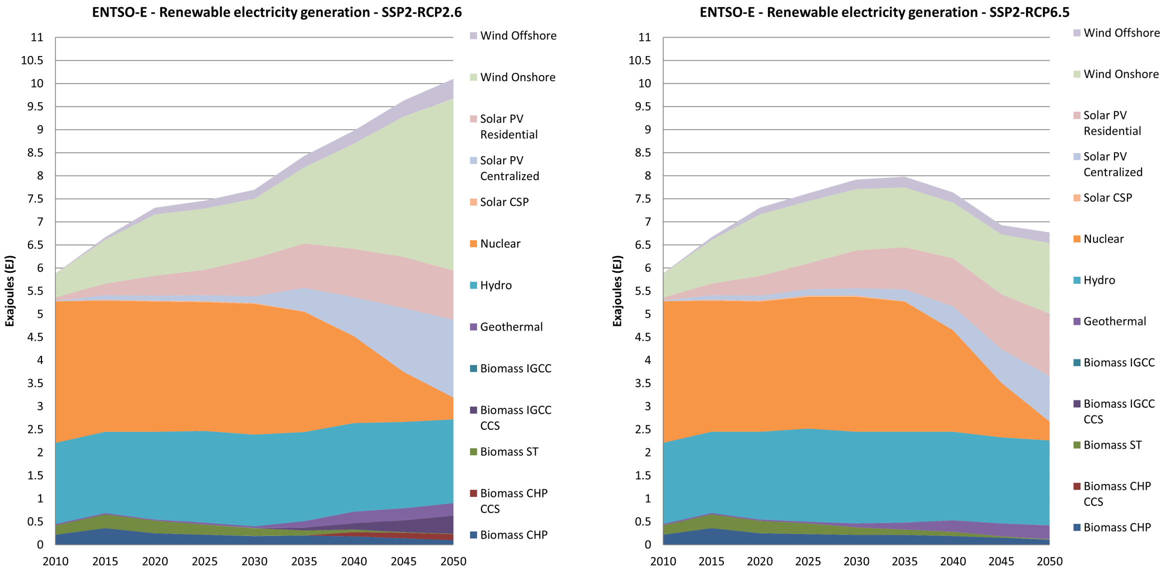
(a) Spider plot of induced impact Mono-Si panel (CN) production in scenario 1, relative to 2012

(b) Spider plot of induced impact Mono-Si panel (CN) production in scenario 2, relative to 2012

Figure 5.7: Relative impact Mono-Si module, produced in China for both scenarios



(a) ENTSO-E Electricity generation mix of non-renewables in scenario 1 **(b)** ENTSO-E Electricity generation mix of non-renewables in scenario 2

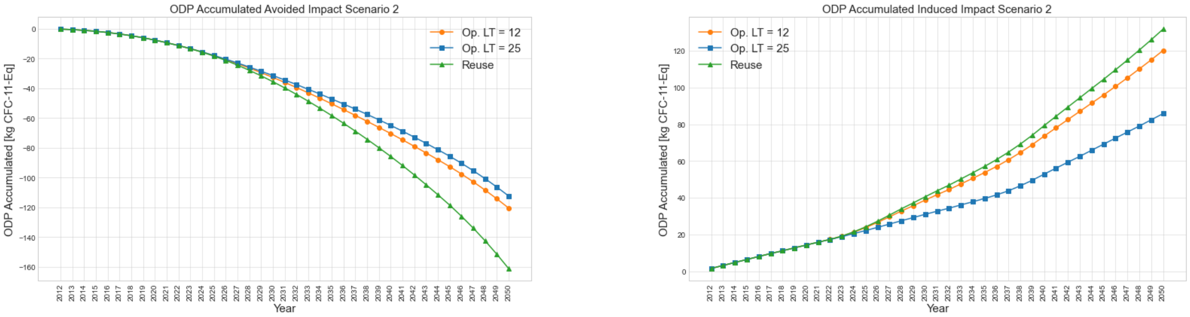


(c) ENTSO-E Electricity generation mix of renewables in scenario 1 **(d)** ENTSO-E Electricity generation mix of renewables in scenario 2

Figure 5.8: Comparison of electricity generation mixes in scenarios 1 and 2 (data obtained from Premise (2023)

Ozone Depletion Differences

The net accumulated Ozone Depletion impact for the Op. LT = 25 case and Reuse case is much lower than for the Op. LT = 12 case. The bars on **Figure 4.3** are unrepresentative since they fall outside the graph borders and are actually more than a factor 800 lower. This seems unrealistic but for the net accumulated impact this could very well be the case, since it is the accumulated induced impact - the accumulated avoided impact. In the Op. LT = 12 case these two variables cancel each other out to a value close to zero, which explains the relative difference in net accumulated impact, as visualized in **Figure 5.9** and **Figure 5.10**.



(a) Ozone Depletion accumulated avoided impact in scenario 2

(b) Ozone Depletion accumulated induced impact in scenario 2

Figure 5.9: Avoided and induced accumulated impact for Ozone Depletion in scenario 2

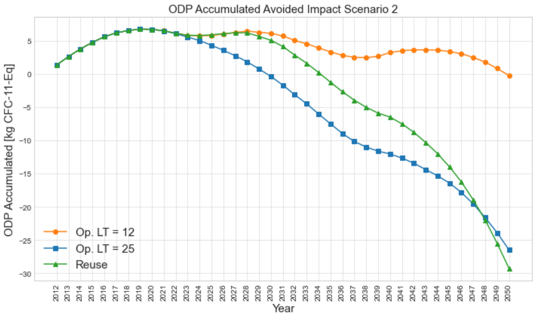


Figure 5.10: Ozone Depletion net accumulated impact in scenario 2

Avoided Impact Human Toxicity

In scenario 2, the avoided shadow costs for Human Toxicity are much more than in scenario 1, in all operational lifetime cases. When taking the Op. LT = 25 case as example, 108 million euros more Human Toxicity costs can be avoided. The reason for this is the enormous share of electricity generated by coal in Europe in scenario 2, as shown in **Figure 5.8**. Although even a higher share of coal is used in China, which also induces a higher impact on Human Toxicity during production, the amount of grid electricity displaced is much higher than the amount of electricity consumed during production.

5.1.3. Marginal Gains for Regional Market Shift to Europe in Scenario 3

Only marginal differences can be found between scenario 1 and scenario 3, which represents a realistic market shift to Europe. One might initially expect substantial differences, as China currently mostly runs on coal power. However, these marginal gains in the model can be explained by three reasons. First of all, a realistic market shift to Europe is considered which is assumed to be the following:

- 20% of cells and 50% of panels are produced in Europe by 2030
- 50% of cells and 100% of panels are produced in Europe by 2050

When considering the electricity mix developments in China and Europe in the SSP2-RCP2.6 scenario, this shift occurs too slow to have substantial effects. As shown in **Figure 5.11**, by 2040 each panel induces roughly the same amount of CO2-Eq emissions. Furthermore, as already shown in **Figure 5.3b**, the Balance Of System (BOS) accounts for roughly 50% of the induced impact, which is produced in Europe in both scenarios. Finally, as shown earlier in **Figure 5.2**, the avoided accumulated impact for most impact categories is substantially lower than the accumulated induced impact. The regional market shift only affects the induced impact. These three factors contribute to the marginal environmental advantage for a realistic market shift to Europe.

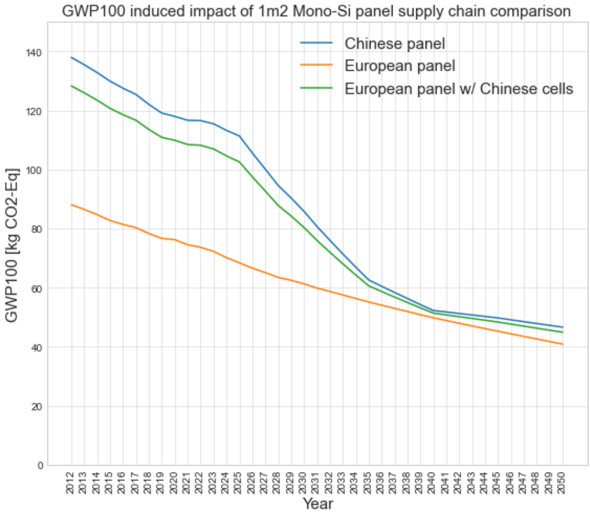


Figure 5.11: difference in impact production regions Mono-Si supply chain

Limitations and assumptions regional market shift

However, as mentioned in **Section 3.1**, several assumptions and limitations of this study may cause unrepresentative regional differences. First of all, equivalent technological development is assumed in both regions and only contemporary design PV technologies are considered. As mentioned in **Section 1.0.3**, novel PV technologies with a focus on reuse and recycling are currently being developed in the Netherlands, which may reshape the local PV market in the long run. While these technologies are promising, it may take decades before these technologies become competitive with contemporary design panels which have been optimised for mass production. Secondly, the SSP2-RCP2.6 pathway projects a rapid increase of renewables and a divergence from coal in China. However, currently China is still increasing its coal-generated power capacity. Whether China will actually follow RCP2.6 is therefore very uncertain. Although the results have been validated in this section, the sensitivity of the market shift is further checked in **Appendix 5.1.4**, to make sure that the merely identical results to scenario 1 are not caused by any model errors. Thirdly and perhaps most importantly, the baseline LCA lacks a lot of data for Chinese production and uses European data instead. This may have substantial effects on the model results. However, the most impactful background process is electricity generation, which has been incorporated in the LCA.

5.1.4. Sensitivity Check: Regional Market Shift to Europe

As shown in **Section 4.4**, the prospective LCA model only estimates marginal gains of roughly 30 million kg more CO2-Eq emissions avoided and 5 million euros of shadow costs saved. Several reasons have been given for this observation in **Section 5.1.3**. However, to verify the results and check the functionality of the model an immediate 100% market shift for c-Si panels to Europe is modelled. The Op. LT = 12 case is chosen for comparison, as the same amount of panels are produced in both cases. Three scenarios are chosen to check the sensitivity of a regional market shift: (1) 100% panel production in China, which is the scenario mentioned in **Section 4.2**, (2) a realistic market shift to Europe, which is the scenario mentioned in **Section 4.3**, (3) 100% panel production in Europe, which is an additional scenario. **Figure 5.12** shows the results of the net accumulated impact for all three regional market scenarios in 2030 and 2050.

Advantage of European Production

As expected, the net accumulated impact is now substantially lower/better in 2030 for the Europe scenario. For example, the net Global Warming impact for complete production in Europe is 17% lower than for China. This confirms that the module responds to regional market shifts, but still has a relatively low effect compared to other factors, such as the reuse of PV modules. Furthermore, the accumulated net impact difference decreases towards 2050, since the Chinese electricity mix also follows the realistic SSP2-RCP2.6 projection.

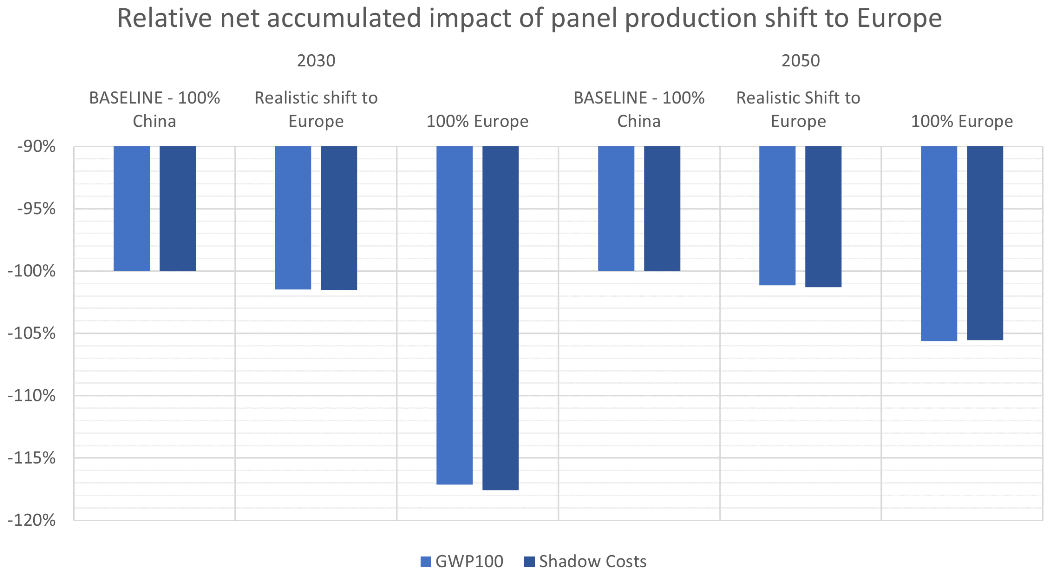


Figure 5.12: Relative net accumulated impact for Global Warming and Shadow Costs in three regional scenarios

5.1.5. Marginal Gains for CdTe Market Shift in Scenario 4

Scenario 4 covers a realistic market shift to CdTe modules, where 20% of the yearly installed modules are CdTe modules by 2030 and 50% by 2050. The CdTe modules follow an optimistic technological development projection as visualized in **Appendix C**. The marginal gains in scenario 4 only apply under the heavy assumption that the CdTe modules reach a similar module efficiency of 27% by 2050. The CdTe modules are assumed to be produced in Malaysia, which is where the biggest producer First Solar produces most of their modules.

Environmental advantages CdTe modules

Although most impact categories show relatively similar results, Freshwater Eco-Toxicity, Human Toxicity, Marine Eutrophication, Metal Depletion, Particulate Matter Formation and Terrestrial Eco-Toxicity have a better net impact in the CdTe scenario. Since the electricity yield of CdTe installations will never exceed the electricity yield of c-Si installations in this scenario, the results differences can only be attributed to the induced impact. The technology comparison of the baseline LCA provided in **Appendix A**, visualized in **Figure 5.13**, shows that the impact for all these categories is currently substantially lower for the production of one square meter CdTe module than for one square meter c-Si module. However, as scenario 4 shows, this difference becomes only marginal when deployed in the city under a realistic market shift over time. To check the robustness of the results and the sensitivity of a technology market shift, a 100% CdTe scenario is compared to scenario 1 and 4 in the next section.

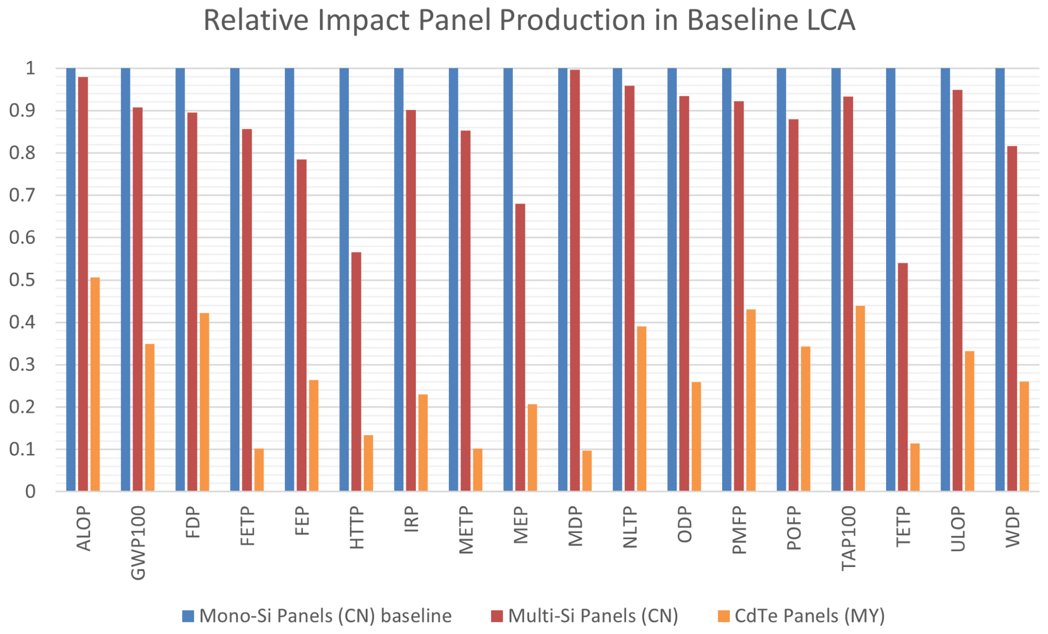


Figure 5.13: Relative environmental impact for production of different module technologies in baseline LCA

5.1.6. Sensitivity Check: Technology Market Shift CdTe Modules

While **Figure 5.13** shows a clear advantage for CdTe in the induced impact during production for all impact categories, when the system is dynamically deployed at city-scale the advantage becomes lower. A sensitivity check on the impact of a market shift to CdTe modules is performed, where three scenarios are compared: (1) 100% c-Si modules, which is the scenario mentioned in **Section 4.2**, (2) a realistic market shift to technologically advanced CdTe modules, which is the scenario mentioned in **Section 4.5** and (3) 100% CdTe modules, which is an additional scenario to check the sensitivity. As shown in **Figure 5.14**, the accumulated induced impact in 2030 would be considerably lower if only CdTe modules were installed. However, the difference in accumulated induced impact is lower in 2050 due to the lower environmental impact of c-Si modules in later decades. The shadow costs are relatively lower than the Global Warming impact, because several other impact categories are included that score substantially better for CdTe, as mentioned in the previous section. When also taking into account the avoided impact, which can only be lower for CdTe modules since their performance is worse until 2050, the difference in impact becomes only marginal. This proofs the robustness of the results in **Section 4.4**.

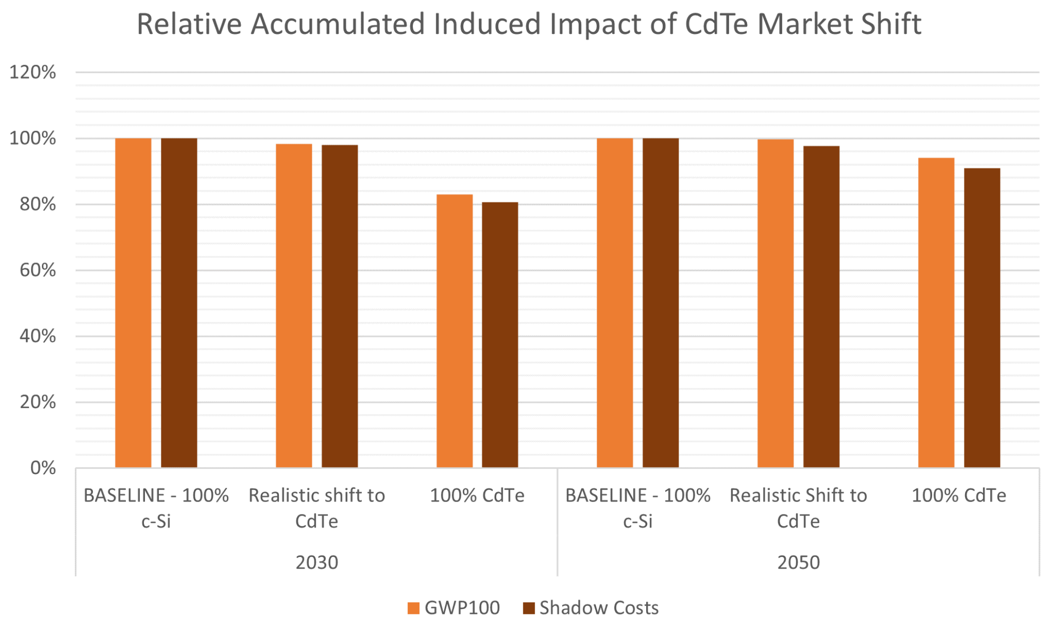


Figure 5.14: Relative accumulated induced impact for Global Warming and Shadow Costs in three technology scenarios

5.2. Consistency Check

Although this study presents a new approach for determining the city-wide environmental impact of PV system deployment, a consistency check is conducted to verify the robustness of several parameters with earlier research. The results of the articles collected for the theoretical framework are compared to the results of the prospective LCA where possible.

Prospective LCA 3kWp Mono-Si residential PV system

Frischknecht et al. (2015) conducted a prospective LCA of residential PV systems. Although there are multiple differences in their study and this thesis, such as the system scope, functional units and operational lifetime scenarios, the induced environmental impact of a residential PV system produced in 2015 and 2050 can be compared. **Figure 5.15** shows the induced Global Warming impact in CO2-Eq emissions for a 3kWp PV system installed on a slanted roof in Europe, using modules with a surface area of $1.7m^2$. A global regional market share projection is used, with most PV modules produced in China.

Peak power to total module area calculation

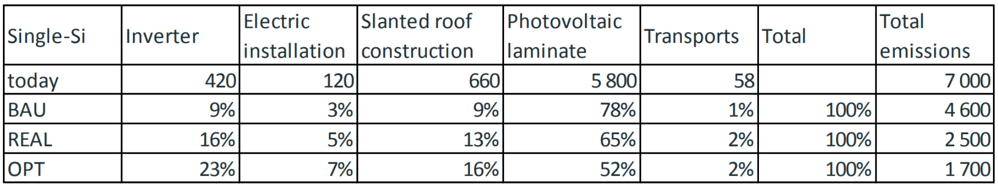
To compare the results of this study to the results provided by Frischknecht et al. (2015), first the environmental impact of all components of a residential PV system with 3kWp capacity must be determined for production in 2015 and 2050. Since this thesis study determines the building specific environmental impact based on square meter rooftop area used for PV panels, a transformation from kWp to square meter panel is conducted manually. Since Frischknecht et al. (2015) do not make any differentiations for module area in the prospective LCA, a similar module area of $1.7m^2$ is used for this calculation. **Table 5.1** shows the calculations conducted to derive the module area used for a 3kWp installation in 2015 and 2050, in both scenarios. This thesis study denotes the 'Business As Usual (BAU)' scenario as 'Conservative (CONS)' and the 'Optimistic (OPT)' scenario as 'Strong'. Standard Test Conditions (STC) are assumed for the module peak power and module area calculations.

Parameter	Abb.	2015	2050 (STRONG)	Unit	Derivation
Module Area	MA	1.7	1.7	m^2	Constant
Total Peak Power (STC)	TPP	3000	3000	Wp	Constant
Module efficiency	ME	17	27	%	Technology analysis
Module Peak Power (STC)	MPP	289	459	Wp	MA * ME * 1000 (STC)
Total module area used		**17.6**	**11.1**	**m^2**	**TPP/MPP (STC) * MA**

Table 5.1: Derivation of total module area for a 3 kWp residential PV system in 2050 in the strong development scenario

Inconsistent results impact panels

The inverter capacity is assumed to be similar to the Total Peak Power (TPP) and the inverter's Global Warming impact is calculated, using the equation described in **Section A.2.1** in **Appendix A**. The other system elements have been normalized to one square meter module and can be calculated directly, using the total module area used. Transport to regional storage has already been integrated in the normalized system element LCA. **Table 5.2** shows the results of the consistency check for the 2015 scenario and the 2050 'Strong' or 'Opt' scenario. The results are compared to the results provided by Frischknecht et al. (2015) in **Figure 5.15**. While the inverter, cabling and mounting system have reasonably similar results, the impact of the panels in 2015 is more than twice as high in the study of Frischknecht et al. (2015).



Single-Si	Inverter	Electric installation	Slanted roof construction	Photovoltaic laminate	Transports	Total	Total emissions
today	420	120	660	5 800	58		7 000
BAU	9%	3%	9%	78%	1%	100%	4 600
REAL	16%	5%	13%	65%	2%	100%	2 500
OPT	23%	7%	16%	52%	2%	100%	1 700

Figure 5.15: Results Global Warming of prospective LCA 3kWp PV System, by Frischknecht et al. (2015)

	Inverter	Cabling	Mounting System	Panels	Total emissions
2015	15%	3%	21%	61%	3772
2050 (STRONG)	18%	3%	37%	42%	1227

Table 5.2: Results consistency check Global Warming 3kWp PV System

Reasons for inconsistency

Multiple reasons can be given for the difference in production impact of Mono-Si panels as listed below.

1. **Different foreground process modifications:** this thesis study uses the updated IEA-PVPS LCI provided in 2020 and modifies the LCI for 2015 backwards based on ITRPV reports and literature for several parameters, as explained in **Section 3.4** and visualized in **Appendix C**. Another study used in the theoretical framework compares the results for a Mono-Si panel from the 2015 and the updated 2020 IEA-PVPS LCI (Fthenakis & Leccisi, 2021). Their results show that the Global Warming impact of a Mono-Si panel has decreased by 50%, between 2015 and 2020. However, this thesis study finds a difference of roughly 10%, between 2015 and 2020. The inconsistency between these results for 2015 likely largely has to do with the different process modifications. In the updated 2020 LCI, many more parameters are updated from the 2015 LCI than the parameters modified in this study.

2. **Different background process modifications:** this thesis study uses background transformations based on the IMAGE Integrated Assessment Model, whereas Frischknecht et al. (2015) conduct manual transformations of various processes such as electricity generation, copper production and glass production. These processes would be defined as background processes in this thesis study.

3. **Different EcoInvent database:** this thesis study uses the much more up-to-date EcoInvent v3.8 database whereas Frischknecht et al. (2015) use the EcoInvent v2.2+ database for background processes.

4. **Different impact assessment method:** this thesis study uses the ReCiPe (H) v1.13 impact assessment method whereas Frischknecht et al. (2015) use the IPCC 2013 method. Both methods use different characterization factors, which determine the translation from an environmental flow to environmental impact.

Implication of inconsistency to final results

To check whether the results of Frischknecht et al. (2015) would affect the final results and to what degree, a backward sensitivity analysis is conducted on the Global Warming impact. The CO2-Eq emissions for each system element given in **Figure 5.15** are used as input values for the model used in this thesis study. First the emissions for 'today' (2015) and 'OPT' (2050) are normalized back to $1m^2$ of PV module and to an inverter with 2.5kW capacity. Then a simplified projection is made for the years between 2015 and 2050 based on interpolation. **Figure 5.16** shows the relative difference in the net accumulated impact for Global Warming, in all operational lifetime scenarios.

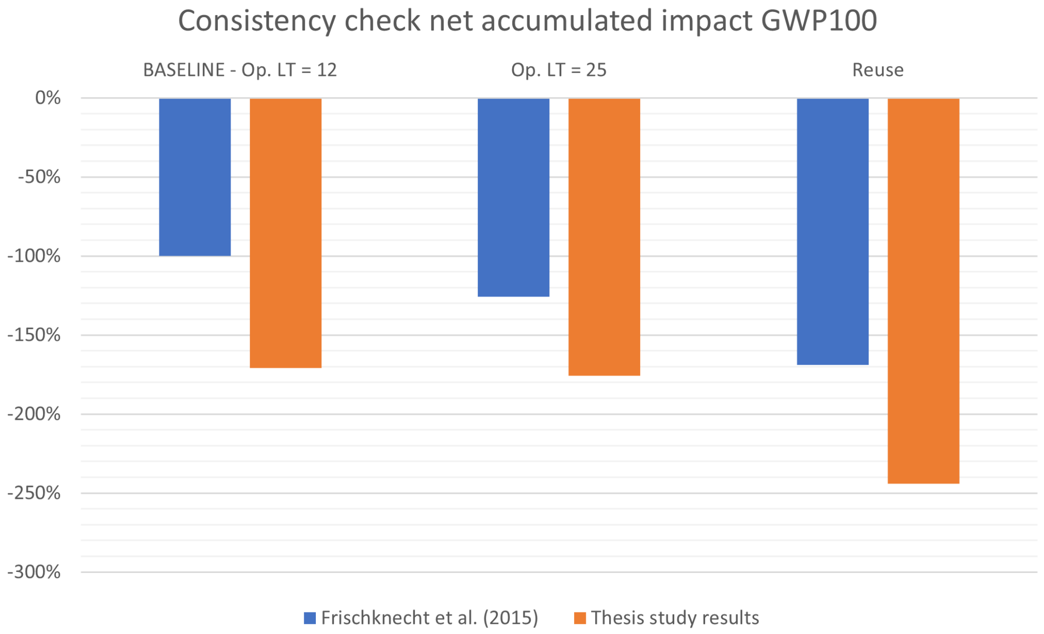


Figure 5.16: Relative net accumulated impact Global Warming compared to input parameters derived from Frischknecht et al (2015)

Conclusion consistency check

The net accumulated impact resulting from the input parameters derived in this thesis study is notably lower compared to the impact calculated using input parameters from Frischknecht et al. (2015). This discrepancy is primarily attributed to the additional induced impact stemming from the production of the system elements. The reasons behind the differences in induced impact are listed in the previous paragraph. However, when focusing on the comparison of operational lifetime scenarios, similar conclusions can be drawn. The scenario with an operational lifetime (Op. LT) of 25 years exhibits a 25% improvement over the scenario with Op. LT = 12 years. Furthermore, the scenario involving panel reuse demonstrates a remarkable 70% improvement. Despite variations in input data and the utilization of distinct impact assessment methods—factors that usually result in substantial differences in life cycle assessment (LCA) results, as described in the theoretical framework—the application of a consistency check enhances the robustness of comparative operational lifetime outcomes.

5.3. Limitations

This section discusses the research limitations and how they may have affected the results. The limitations are subdivided into three domains: (1) data uncertainty, (2) scenario coverage and (3) methodology simplifications.

5.3.1. Data Uncertainty

A prospective LCA always implies a degree of uncertainty as future projections are made. Certainly for future estimates with complex global inter-dependencies. In this thesis study several scenarios have been developed to mitigate the uncertainty behind future projections to the extent possible. However, the uncertainty of the accuracy of the data used in the baseline LCA as well as the prospective LCA still decrease the reliability of the results. This section describes the main data uncertainties and what implications they may have on the final results.

Scarcity Chinese PV Module Production Data

The IEA-PVPS LCI provides data on the production of PV system elements based on literature and reports from European manufacturers. However, production data from Chinese manufacturers is lacking. Although the manufacturing processes can be assumed to be reasonably similar, the production location of different background processes may have a substantial effect on the environmental impact during production. Due to data scarcity, European background processes have been used for the processes where Chinese data is lacking. It is unlikely that Chinese manufacturers use mostly European products or services for the production of their panels. This puts a high uncertainty on the environmental impact of Chinese production, which may be substantially higher than the results of this study. However, as shown in the consistency check, a substantial increase of environmental impact during production would only influence the absolute values of the prospective LCA but not the final conclusions that can be drawn with respective to operational lifetime scenarios. It does however put the only marginal advantage of European production shown in **Section 5.1.3** into question.

Uncertainty Technological Development PV Modules

The ITRPV provides yearly projections of certain technological advancements for c-Si modules in the following 10 years. The different ITRPV reports show that projections made in 2017 may be substantially different than the projections in 2022. As a consequence, some of the projections used in this study may become unrepresentative in 5 years. However, in general reasonable projections can be made within a time-frame of 10 years. Since the model is extended to 2050, exploratory scenarios have been used for after 2030. Furthermore, as explained in **Section 5.6**, the model used in this study can easily be adapted to generate up to date results.

Lack of Data Technological Development BOS

The contribution analysis in **Section 5.1.1**, shows that the contribution of other system components than the panels becomes higher over time. This can partially be attributed to the fact that the LCIs of Balance Of System (BOS) components, such as the inverter, remain unchanged. However, although other studies mentioned in the theoretical framework also assume no technological development of these components, it is likely that their their production processes will become more environmentally friendly over time. Furthermore, the operational lifetime of the inverter may also increase, which affects the likelihood of disposal after 12 years.

5.3.2. Scenario Coverage

Multiple scenarios have been developed to deal with future uncertainties. However, due to time constraints, data scarcity and modelling constraints, several considerably important factors have not been covered in this study.

Implications of Grid Congestion

First of all, one of the big assumptions in this study is that the potential electricity yield is also used to displace the grid electricity. However, as recent developments in the Dutch energy sector have shown, it is unlikely that all of the potential electricity will also actually be utilized. The main reason for this is the overcapacity of the electricity grid. The pace at which grid infrastructure can be build may not be able to keep up with the pace of the extra electricity generated at daytime. As a result, an imbalance between supply and demand may occur, which can only be resolved by storing the excess electricity or by deploying specific supply and demand shift strategies such as demand respond programs. If the excess electricity gets lost, it would have a negative effect on the avoided impact, as less grid supplied electricity can be displaced. This would ultimately lead to a better case for lifetime extension strategies, as the net impact becomes more sensitive to induced impact and less sensitive to avoided impact. However, if grid congestion becomes an unsolvable problem, people may already be economically encouraged to keep their old panels on the roofs. It may also incentivize them to buy residential electricity storage systems, which would cause an extra induced impact on the environment. Possible dynamics of these factors are interesting for future studies.

Only Contemporary Design Technologies

This study focuses on contemporary design PV technologies and neglects possible emerging technologies that may have a profoundly different environmental footprint and performance. Technologies that have not yet become competitive with contemporary technologies must be assessed through an ex-ante LCA, as explained in the theoretical framework. An ex-ante LCA induces many uncertainties and is very sensitive to estimated industrial developments. Making somewhat scientifically sound estimations and aligning them with contemporary design technology projections would be a study on its own. However, history proofs that the likelihood of a technology being replaced by a new technology is high. Whether this shift will occur within the coming decades is unknown. The new technologies could develop considerably in performance and increase in induced impact. However, they may also be designed for high-value recycling, and gain quick traction in the PV market through subsidization schemes. The possible implications of these phenomena should be assessed in future research. The model used in this study can be adapted to integrate these possible future developments.

Constant End-of-Life Management

Another assumption that may affect future projections is the use of the current End-of-Life management procedure in future scenarios. This procedure only involves open-loop low-value bulk recycling of the main components such as the glass and frame but incineration of high-value components such as the cells. Closed-loop recycling and high-value recycling may have a profound effect on the results. Currently, Dutch companies, startups and research institutions such as Solarge, Biosphere Solar and TNO are developing circular PV modules. How the deployment of these panels would affect the results on operational lifetime extension and reuse should be further investigated. The model used in this study can be utilized for this purpose, as it is flexible for the integration of new technologies and End-of-Life management practices.

5.3.3. Methodology Simplifications

Several simplifications have been made in model for the prospective LCA. This section summarizes the key simplifications and their possible impact.

Linear Upscaling Rate

A constant installation rate is adopted from 2012 to 2050, based on Amsterdam's solar panel deployment targets. In reality, the amount of installations since 2012 is more in line with an exponential curve than a linear curve, as shown in **Figure ??** in the introduction. This means that in reality the amount of installations in the first few years was much lower than in the last few years. This would imply that the induced impact in the first decade is actually lower and the avoided impact is higher. It is unlikely that this assumption will dramatically affect the findings. However, unexpected future developments diverging from a linear trend may have more substantial effects. The uncertainty of these developments is regarded as a limitation of this study.

European Grid for Avoided Impact
The Integrated Assessment Model IMAGE only makes future development pathways at European scale and not at national scale. However, the European ENTSO-E grid is different than the Dutch grid which may cause different results. The effect of displacing a Dutch static grid is assessed in **Section B.3** of **Appendix B**. THe static Dutch grid has a slightly higher environmental impact than the static ENTSO-E grid. However, if the Dutch grid would be displaced dynamically, it would not affect any final conclusions that could be drawn for the operational lifetime comparison.

Simplification Reuse Scenario
As described in **Section 3.7**, the reuse scenario is used to assess the impact of re-installation. Although the impact of the required extra system elements are taken into account, the impact of testing, certification and possible extra transport has not been considered. This is a simplified scenario and the extra impact induced along the complete secondary supply chain should be assessed in future research.

5.4. Future Research

This study explored the impact of different operational lifetime scenarios on the environmental impact of upscaling PV systems on residential buildings in Amsterdam. However, the results may be considered as the beginning of a more extensive assessment of the implications for early disposal and opportunities of reusal of system elements. Various factors mentioned in the limitations section are important to assess from an academic perspective. Several key topics are listed below:

- **New EOL strategies:** the effects of new End-of-Life management strategies are relatively unexplored and a thesis study on this topic may open doors to new valuable insights in this domain. The methodology and model of this study can be adopted and adapted to make future projections at a city-wide scale.
- **Emerging technologies:** he effects of deploying emerging technologies can be added to the scenarios assessed in this study. The impact of emerging products such as the circular solar panel of Biosphere Solar may be assessed at a city-wide scale.
- **European influence:** The effects of a regional market shift to Europe have been explored in this study but the outcomes are influenced by several limiting factors given in **Section 5.1.3**. Further research may produce different outcomes which could be valuable for policy makers or buiding owners.
- **Impact raw material use and resource independence:** This thesis study only covers environmental impacts which have direct and indirect societal effects. However, more direct societal effects such as critical raw material scarcity and the dependence on potential global conflict countries are other important topics to be researched. The model used in this thesis can be extended to include a dynamic MFA, which focuses on material flows and stocks.
- **Impact assessment secondary supply chain:** The impact induced by testing, certification and extra transport has not been taken into account in the reuse scenario. Although the impact of these services are likely lower than the environmental impact of production, this should be explored in future research.
- **Heatmap for Environmental impact at city-scale:** Due to time constraints, the environmental impact per building could not be visualized by means of a heatmap. However, this map could provide additional insights for Amsterdam, where the most critical environmental impact can be found.

5.5. Theoretical Implications

From an academic perspective, the methodology and findings of this study contribute to theoretical knowledge in the field of industrial ecology. This section addresses the academic significance of the study.

Methodology: combining building-specific data with normalized prospective LCA
This study integrates the PV WORKS model with a prospective LCAof specific system elements. The PV WORKS model assesses the appropriate rooftop area and optimal panel quantity for installation, leveraging GIS data for individual buildings. Additionally, the model evaluates potential electricity yield, taking building-specific factors like shading into account. Through prospective LCAs for each system element, normalized to one square meter of panel, it becomes feasible to estimate the building- and year-specific environmental impacts. This framework enables city-wide projections aligned with policy goals that emphasize the utilization of suitable rooftop space. This approach marks a departure from conventional prospective LCAs of residential PV systems, which traditionally use power capacity as the functional unit. For instance, in the case of Frischknecht et al. (2015), the focus centers on a 3kWp residential PV system in Europe. The integration of GIS data with normalized prospective LCA data represents a substantial advancement in bridging the gap between theoretical projections and practical implementation.

Findings: operational lifetime is critical for large-scale reuse scenarios
Until now, prospective Life Cycle Assessment (LCA) studies have predominantly equated the technical lifetime with the operational lifetime, disregarding the occurrence of early disposal and its associated environmental drawbacks. However, this study, supported by Sodhi et al. (2022), presents a more pragmatic foundation by considering a baseline operational lifetime scenario of 12 years. This more realistic approach takes into account an array of economic and technical factors, as outlined in **Section 1.0.4**. By acknowledging the possibility of perfectly functional panels being disposed after just 12 years, the potential for PV panel reuse becomes significantly more pronounced. The environmental and natural resource implications of this phenomenon introduce substantial opportunities for future research explorations, in the domain of environmental impact assessments as well as material flow analyses.

5.6. Practical Implications

Both the tooling created and the findings of this study have potential impact on a practical level. This section addresses the practical implications of the study.

Methodology: flexible tooling for periodic updates and policy-dependent refinements
This study makes use of the open-access and user-friendly GUI Activity Browser along with the Brightway2 software to construct normalized baseline LCAs, utilizing the regularly updated IEA PVPS LCI database. Through scenario translation files, adapted in Excel, the LCI can be adapted for future scenarios. Both the LCI database and Excel files are easily modifiable to harmonize with new scenarios of interest. These scenario translation files are modified based on periodically updated ITRPV reports for predictive modelling, and literature for exploratory modelling. The results of the normalized baseline LCAs are integrated into the Python model. This model also has the capability to extend its functionalities to accommodate material flow analyses. The intentionally adaptable tools provide a foundation for possible future research in the domain of large-scale PV impact projection. This can help institutions redirect and optimize interventions such as investments in PV reuse projects.

Findings: enormous environmental impact mitigation opportunity in reuse of PV modules
the results of this research indicate an enormous opportunity for the municipality of Amsterdam to take the city's environmental impact mitigation and circularity strategy to the next level. Recommendations on the first steps of initiating the large scale reuse of disposed functional panels are given in the conclusion.

6

Conclusion

The municipality of Amsterdam rapidly wants to transform its city into a climate neutral city as part of the EU's Climate Neutral Cities Mission. To stimulate this transition, it has set the target of using 50% of all the suitable rooftop surface for solar panels and 100% of the suitable rooftop surface by 2050. Simultaneously the city also wants to become 50% circular by 2030 and 100% circular by 2050. However, residential PV system owners are currently incentivized to replace their PV panels before their technical lifetime has been reached, as explained in **Section 1.0.4**. The objective of this study is therefore to find the environmental impact of early disposal at city scale and identify the environmental effects of lifetime extension strategies. The key findings are highlighted below:

1. The technological developments of contemporary design PV technologies do not compensate for the environmental impact of early disposal, in both optimistic and pessimistic RCP scenarios

2. Amsterdam can reduce its net environmental impact by an additional 790 to 1910 million kilograms of CO2-Equivalent emissions or 126 to 327 million euros of shadow costs, if it reused all its disposed functional panels.

The Problem

This study has identified a key research gap in the field of prospective LCA studies, for the environmental implications of early disposal of PV modules. Households are likely to replace their PV system much earlier than the operational lifetime suggested by the IEA-PVPS for LCA studies on PV systems. Unfortunately, prevailing End-of-Life management regulations currently steer PV collectors towards low-value recycling of perfectly operational PV panels. Resolving this issue could potentially have enormous benefits on the environmental performance of a city, looking to become climate neutral in the near future.

Environmental Implications of Early Disposal

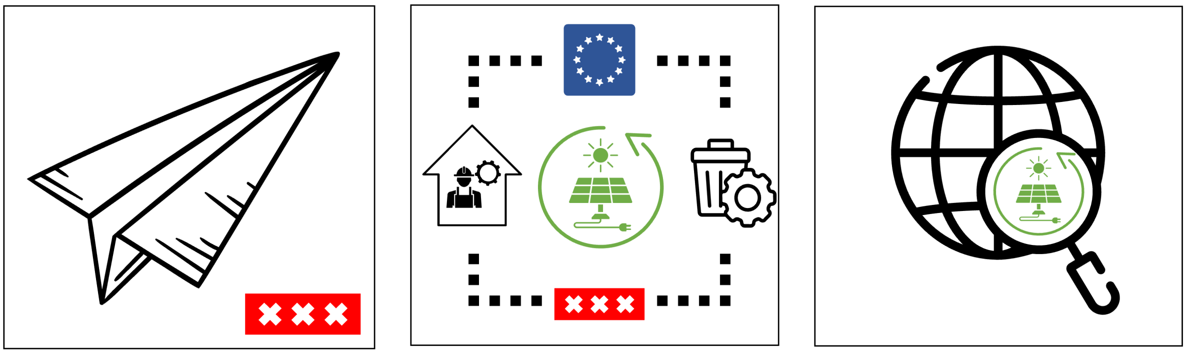
This study definitively challenges the perceived environmental benefits attributed to the premature disposal of contemporary design PV technologies. The potential environmental advantage of the early disposal scenario has been disproven by the outcomes of this research. Even when considering a scenario of robust technological progress, where lowered induced impact and heightened avoided impact were anticipated, these positive factors fail to offset the additional impact incurred through the increased production of new system elements. However, it is important to note that potential emerging technologies that have a proven significantly lower environmental impact than technologically advanced contemporary design PV technologies, combined with notably enhanced performance, could potentially reshape this balance. Additionally, the implementation of advanced closed-loop recycling processes has the potential to significantly influence the final outcomes. However, the environmental advantages of reusing functional disposed PV panels remains undisputed.

Opportunities for Reusing Disposed Functional PV Modules

Amsterdam has the potential to achieve a reduction in its net environmental impact ranging from 790 to 1910 million kilograms of CO2-equivalent emissions. When broadening the analysis to encompass other impact categories such as Human Toxicity and Freshwater Eco-Toxicity, the projected societal cost savings stemming from reuse interventions range from 126 to 327 million euros. When disregarding the dynamic nature of this assessment, the reuse of just 10% of the functional disposed panels could lead to a notable reduction of 79 to 191 million kilograms of CO2-equivalent emissions, or equivalently, societal cost savings ranging from 12.6 to 32.7 million euros. However, factoring in the dynamic nature of the analysis highlights a pivotal point: reusing the functional disposed panels over the coming decade will yield the most significant impact. This is attributed to the displacement of less environmentally friendly production processes and grids, which are substituted by the reused panels' contributions. Therefore, early interventions have the biggest potential for strategic environmental cost saving and rapid city-wide environmental impact reductions, taking a broader system scope. The next section provides recommendations for municipal authorities to effectively implement the acquired insights into practical actions.

6.1. Recommendations for the Municipality

This study has identified the opportunity for cities to further extend the effectiveness of their energy transition, and integrate net climate neutrality targets with circularity targets. Although practicalities of this opportunity should be further investigated, key recommendations for municipalities looking to effectively mitigate their city's climate impact are provided in this section.



(a) Initiate pilot projects on public property **(b)** Engage with key stakeholders to scale up **(c)** Find effective region for PV reuse

Figure 6.1: Key strategy recommendations for municipality of Amsterdam

Initiate Pilot Projects

Just like any new project, the re-installation of functional panels that were once discarded should start with testing on a smaller scale. At present, the quantity of disposed panels remains insufficient to establish an efficient industrial system. However, the successful reuse of these panels transcends the mere connection of suppliers, installers, and customers. It requires a comprehensive process involving collection, rigorous testing, certification, strategic marketing, and expert installations. This sequence of processes must therefore be thoroughly tested, identifying potential pitfalls and proactively implementing solutions during the initial stages to expand once many more functional panels get disposed at an effective pace. Moreover, the entire workflow should be fine-tuned to minimize costs on a larger scale, a task that likely demands a substantial workforce due to the diverse range of services required. Fortunately, pilot projects have already been established and companies such as ZonNext have already taken the initiative of re-installing functional second-hand panels. Furthermore, WEEE NL, a key player in the Dutch End-of-Life management of PV systems, has already developed a testing and certification facility for disposed PV panels (Project manager WEEE NL, personal communications). Additionally, they have collaborated with Tesla, which also provides batteries, to install off-grid PV systems in Niger for communities which lack an electricity grid. It would therefore be wise to cooperate with these valuable stakeholder which have already engaged in various relevant pilot projects. The municipality of Amsterdam holds various strategic opportunities to position itself as a significant participant, even outside of city borders, as further elaborated in the next paragraphs.

Engage Citizens and involve Installers

The municipality of Amsterdam possesses various strategic advantages that could serve as catalysts for establishing a large-scale PV reuse system beyond the city's boundaries. To begin with, the feasibility of expanding an effective reuse plan largely depends on a consistent inflow of disposed functional panels. The municipality has already compiled GIS data that indicates the timing and locations of installed PV panels, as depicted in Figure 6.2. This data could also be used to predict when the inverter is likely to fail at specific addresses – a pivotal point influencing households to replace their PV installations. At this juncture, the municipality can encourage residents to participate in reuse initiatives, substantially increasing the supply of functional second-hand PV modules suitable for reuse projects both within and beyond the city limits. It remains essential to involve installers when approaching households, since the installers are required to collect 65% of the products they brought into to market for recycling (Project manager WEEE NL, personal communications)

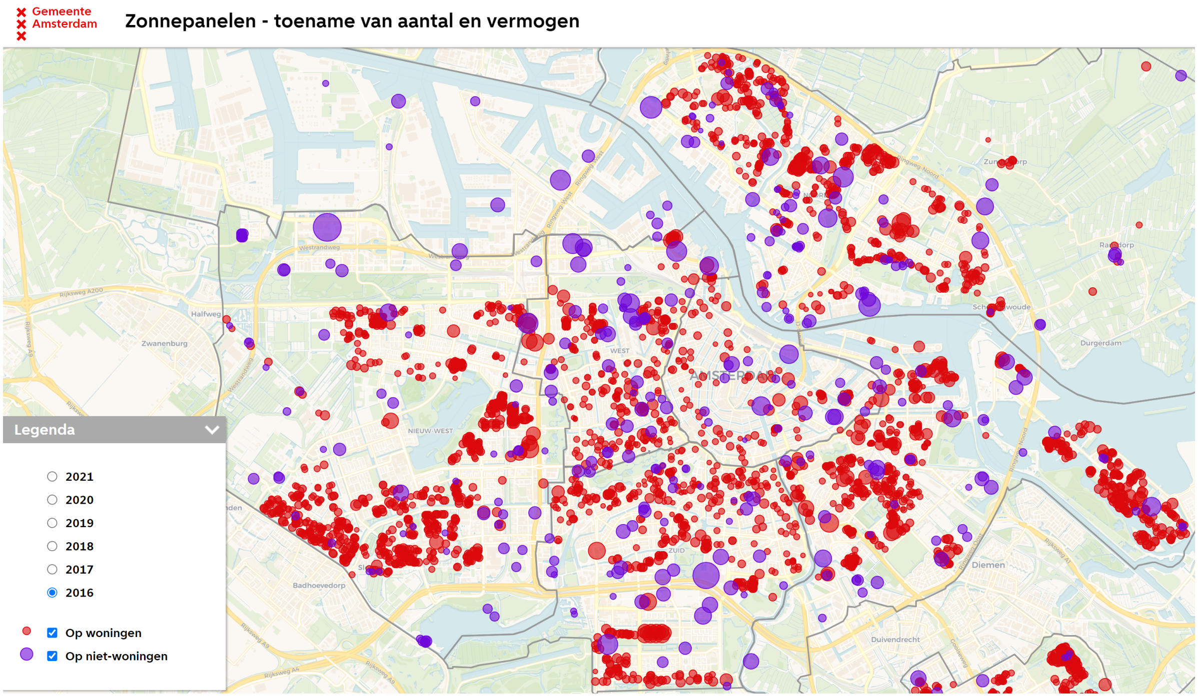


Figure 6.2: Map of solar panels installed in specific year at specific address, Gemeente Amsterdam (2023)

Use Public Property for Reuse Projects
The municipality has plenty of space available that can be used to reinstall solar panels. Upcoming construction sites could be targeted for this purpose through initiatives that promote green public procurement, establishing a solid foundation for early-stage reinstallation projects. Furthermore, sites destined for demolition within the next decade also offer potential as suitable candidates for the re-installation of disposed functional panels.

Collaborate with Climate Neutral Cities
Amsterdam is an active participant in the Climate Neutral Cities Mission, an initiative launched by the European Commission that encourages over 100 cities to accelerate their progress towards achieving climate neutrality. This is facilitated through financial support for pilot projects and a collaborative platform that brings together numerous forward-looking cities. This platform presents a unique opportunity to not only catalyze similar initiatives in other cities but also to stimulate the adoption of reuse projects. Moreover, it has the potential to facilitate a larger, more consistent, and efficient supply of disposed yet functional PV modules. As we anticipate a substantial increase in the disposal of functional PV panels in the coming decades, it becomes imperative to explore collaboration beyond local borders. The early engagement with other ambitious European cities holds the potential to drive the re-installation of disposed panels on a continental scale. In this context, the municipality of Amsterdam is positioned to extend its focus beyond its city borders, tapping into a broader network of like-minded cities.

Figure 6.3: The Climate Neutral Cities Mission, NetZeroCities (2022)

Find Effective Relocation Regions
While many residents in Amsterdam have the financial means to invest in new panels that promise quick returns on investment, this is not the case in every corner of the world. In many regions, households opt for the most affordable and accessible option due to constraints on investing in solar PV systems. If the industrial process encompassing collection, testing, certification, and distribution for repurposed PV panels can be streamlined, it could mirror the flourishing market for second-hand mobile phones. Developing nations have witnessed a surge in the second-hand mobile phone market due to their relatively lower cost, making them more accessible for households. Applying a similar principle, if PV panels from Amsterdam can find reuse in places where affordability of PV systems is the primary challenge and the local grid is predominantly non-renewable, the impact of PV panel reuse would be significantly increased. However, the end-of-life management in these regions could form another environmental threat, if not disposed properly. Therefore, it is crucial to ensure that proper re-installation and end-of-life management practices are always considered as priorities.

7

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A

Baseline LCA

This Appendix provides an overview of the results of the static/baseline LCA, of which the LCI is used and transformed for the prospective LCA. First, the normalized baseline results are presented in **Section A.1**. In this study, normalized refers to the normalization of system components to 1m2 of module. **Section A.2** provides additional information on the contribution of system elements and production processes.

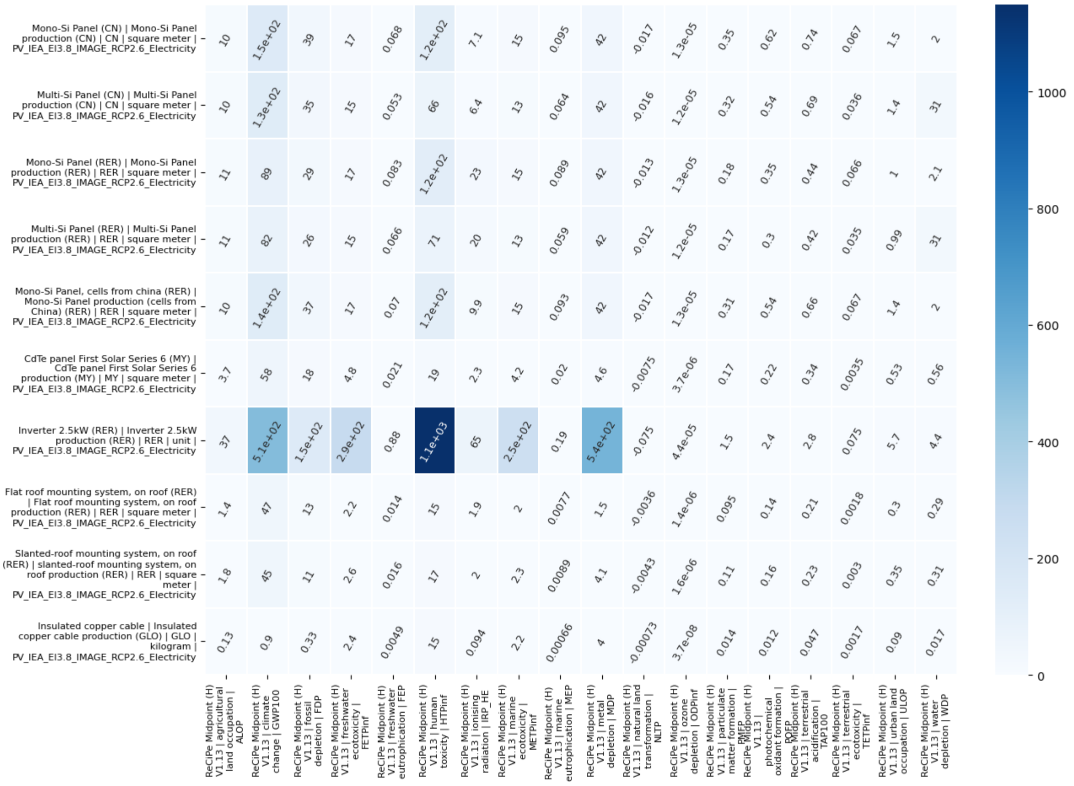


Figure A.1: Overview of environmental impact system elements in baseline LCA

A.1. Normalized Baseline LCA Results

A normalized baseline LCA was conducted for the system elements and functional units as described in **Section 3.3**. The goal and scope of the LCA, general procedure and key assumptions can be found in **Section 3.1**. Process specific assumptions can be found in **Appendix D**. **Figure A.1** gives an overview of the environmental impact of each of these system elements, for each ReCiPe v1.13 impact category. It should be noted that this overview presents results for all system elements normalized to $1m^2$ of module, with the exception of the inverter. The inverter is modified based on the electricity generated per building, in the prospective LCA.

A.2. Contribution Analysis Baseline LCA

This section serves to provide more information on the contribution of specific system elements and processes in the supply chain. In **Section A.2.1**, a specific building is taken as example, where the system elements are integrated manually, following the same procedure as the Python model used for the prospective LCA. However, in this case, the IEA-PVPS LCI is used without modifications. **Section A.2.2** provides a contribution analysis of each foreground process in the supply chain of a Mono-Si module.

A.2.1. System Element Contributions

In this section, a random building from the PV works model is equiped with a PV system, following the standard procedure as described in **Section 3.1**. The building selected has $43m^2$ detected available roof area and a flat rooftop. A maximum of 13 c-Si panels with 120 G1 half-cells can be installed on this roof, according to the PV WORKS model. This panel has an area of $1.69m^2$, which means a total panel area of roughly $22m^2$. In this case, the impact of the panels, the cabling and mounting system can be derived, since these have been normalized to one square-meter panel. The panels and the mounting system have already been normalized to $1m^2$ by Frischknecht et al. (2020) and are included directly in the LCI. The impact of the mounting system is quite considerable, as shown in **Figure A.1**, because of its high Aluminium consumption. The cabling is normalized indirectly and the inverter size and corresponding environmental impact are calculated based on a set of assumptions.

Cabling Normalization

The IEA PVPS life cycle inventory report (Frischknecht et al., 2020) mentions that on average 2.2m of DC cable and 0.1m of AC cable is required per squared meter of module. This assumption is taken with an average copper weight of 45 grams per meter and TPE weight of 27 grams per meter, which results in a total of 0.16 kilograms of cable per m2 of module. The cabling would only slightly affect the environmental impact at system scale, as shown in **Figure A.1**.

Inverter Contribution

The first thing to notice is the substantially higher impact of the inverter for all impact categories in **Figure A.1**. However, this is due to the different normalization factor applied, where the inverter has not been normalized to 1m2 of module but to 2.5 kW power capacity. For this case study of the above mentioned building, we take a well-known Phono Solar panel with 120 G1 half cells, an area of $1.69m^2$ and a peak power of 325Wp. It is assumed that the peak power in ideal environment of each module can be added up to determine the building specific peak power, although in reality this will be location-specific and lower due to shadow, electric and mechanical losses. This corresponds to a peak power of 4225Wp, which is assumed to be equal to the inverter's power capacity.

The IEA PVPS LCI provides data for four inverter capacities: 2.5kW, 5kW, 10kW and 20kW. In their LCI, it is assumed that the flows and corresponding impact increases by a factor 1.6 per doubling of capacity. For example, a 5kW inverter requires 1.54E-2kg of tin and a 10kW inverter 2.46E-2kg. This study takes the same assumption for each inverter and takes the 2.5kW inverter as baseline. **Equation A.1** is used for each building to determine the environmental impact of the inverter, where I represents the impact of a particular impact category and C represents the inverter's power capacity. The calculation for Global Warming in this case study is shown in **Equation A.2**. The Global Warming impact for an inverter with 2.5kW power capacity is 5.1E+02 kg CO2-Eq emissions.

$$I_C = I_{2.5} * 1.6^{log_2(\frac{C}{2.5})} \tag{A.1}$$

$$GW_{inverter} = 510 * 1.6^{log_2(\frac{4.2}{2.5})} = 730 \text{ kg CO2-Eq emissions} \tag{A.2}$$

Building-Specific System Element Contributions

Figure A.2 shows the relative contribution of each system element in the building-specific case study. In general, the panels contribute to about 50-60% of the impact, but this varies considerably per impact category. In this Figure only Mono-Si panels from China are considered.

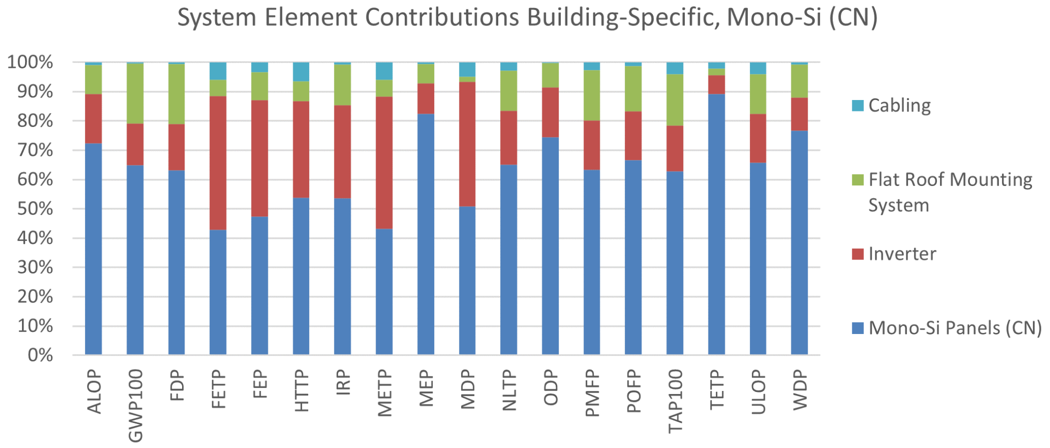


Figure A.2: System element contributions for building with Mono-Si panels (CN) and flat roof

Impact Module Technology

As shown in **Figure A.3**, the Cadmium Telluride (CdTe) modules have a much lower environmental impact than the c-Si modules for all impact categories. Furthermore, Multi-Si modules score slightly lower than Mono-Si panels for most impact categories. However, it should be noted that nowadays the Multi-Si panels score much lower in performance and have not undergone the same upscaling transition as the Mono-Si panels over the past 5 years. In the prospective LCA, it is assumed that Multi-Si panels have left the market by 2022.

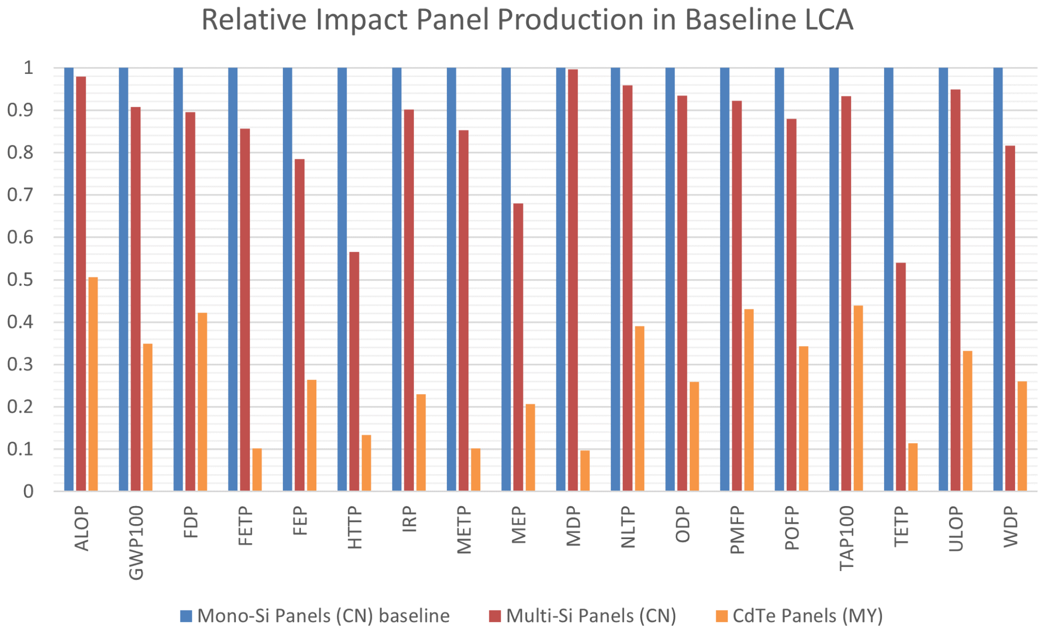


Figure A.3: Impact of different module technologies relative to a Mono-Si module (CN)

Regional impact Mono-Si panels

The Chinese c-Si panels have a higher environmental impact for most impact categories than the panels produced in Europe, based on the the IEA PVPS life cycle inventory (Frischknecht et al., 2020). The Chinese Mono-Si panels have a Global Warming impact of 148 kg CO2-Eq emissions compared to 89 kg CO2-Eq emissions for the European panels. It should be noted that this difference can mainly be attributed to the different electricity mix, where the Chinese mix mainly consists of coal. Interestingly, the Ionising Radiation impact of European panels is more than three times as high as for the Chinese panels. Contribution analysis shows that this can mainly be attributed to the higher use of nuclear energy for the ENTSO-E electricity mix than for the Chinese electricity mix. Both the Global Warming and Ionising Radiation show the substantial influence of the electricity mix on the environmental impact during production. In the prospective LCA, the electricity mix will be manipulated based on future projections of the Integrated Assessment Model (IAM) IMAGE.

Panel production in Europe, with Chinese cells only shows a slightly lower Global Warming imapct (140 CO2-Eq) compared to Chinese panels (148 CO2-Eq). It should be taken in mind that the ENTSO-E electricity mix and the Chinese Electricity mix are used. Production in some countries in Europe may utilize a different mix of electricity corresponding to a different environmental impact. Furthermore, some factories in China as well as Europe use their own electricity source such as solar power, where the electricity mix gives an unrepresentative outcome. The effects of this assumption will be further analysed in the sensitivity analysis.

A.2.2. Contribution analysis Mono-Si supply chain

The IEA PVPS life cycle inventory report specifies on the amount of material used for production phase, for Mono-Si modules (Frischknecht et al., 2020). The production phases and amount of material required are visualized in **Figure A.4**. Based on these numbers, a contribution analysis can be done for each foreground production process for the supply chain of a Mono-Si panel. **Figure A.5** provides an overview of the environmental impact contribution for each foreground process along the supply chain. The darkest red cells indicate the highest contributor in that impact category. It should be noted that these contributions also consist of the background processes connected to each foreground process.

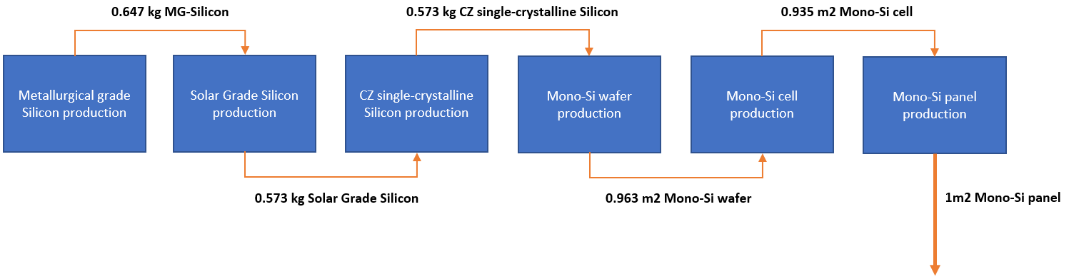
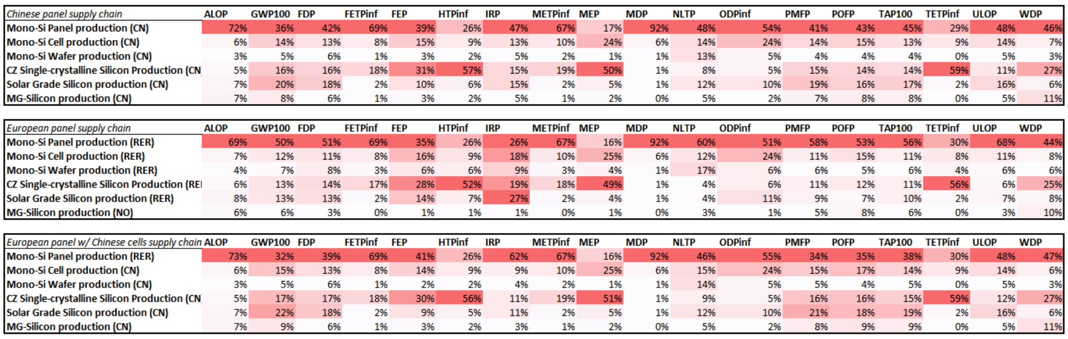


Figure A.4: flow diagram of foreground processes and functional flows for Mono-Si panel production



Chinese panel supply chain	ALOP	GWP100	FDP	FETPinf	FEP	HTPinf	IRP	METPinf	MEP	MDP	NLTP	ODPinf	PMFP	POFP	TAP100	TETPinf	ULOP	WDP
Mono-Si Panel production (CN)	72%	36%	42%	69%	39%	26%	47%	67%	17%	92%	48%	54%	41%	43%	45%	29%	48%	46%
Mono-Si Cell production (CN)	6%	14%	13%	8%	15%	9%	13%	10%	24%	6%	14%	24%	14%	15%	13%	9%	14%	7%
Mono-Si Wafer production (CN)	3%	5%	6%	1%	3%	2%	5%	2%	1%	1%	13%	5%	4%	4%	4%	0%	5%	3%
CZ Single-crystalline Silicon Production (CN	5%	16%	16%	18%	31%	57%	15%	19%	50%	1%	8%	5%	15%	14%	14%	59%	11%	27%
Solar Grade Silicon production (CN)	7%	20%	18%	2%	10%	6%	15%	2%	5%	1%	12%	10%	19%	16%	17%	2%	16%	6%
MG-Silicon production (CN)	7%	8%	6%	1%	3%	2%	5%	1%	2%	0%	5%	2%	7%	8%	8%	0%	5%	11%

European panel supply chain	ALOP	GWP100	FDP	FETPinf	FEP	HTPinf	IRP	METPinf	MEP	MDP	NLTP	ODPinf	PMFP	POFP	TAP100	TETPinf	ULOP	WDP
Mono-Si Panel production (RER)	69%	50%	51%	69%	35%	26%	26%	67%	16%	92%	60%	51%	58%	53%	56%	30%	68%	44%
Mono-Si Cell production (RER)	7%	12%	11%	8%	16%	9%	18%	10%	25%	6%	12%	24%	11%	15%	11%	8%	11%	8%
Mono-Si Wafer production (RER)	4%	7%	8%	3%	6%	6%	9%	3%	4%	1%	17%	6%	6%	5%	6%	4%	6%	6%
CZ Single-crystalline Silicon Production (RE	6%	13%	14%	17%	28%	52%	19%	18%	49%	1%	4%	6%	11%	12%	11%	56%	6%	25%
Solar Grade Silicon production (RER)	8%	13%	13%	2%	14%	7%	27%	2%	4%	1%	4%	11%	9%	7%	10%	2%	7%	8%
MG-Silicon production (NO)	6%	6%	3%	0%	1%	1%	1%	0%	1%	0%	3%	1%	5%	8%	6%	0%	3%	10%

European panel w/ Chinese cells supply chain	ALOP	GWP100	FDP	FETPinf	FEP	HTPinf	IRP	METPinf	MEP	MDP	NLTP	ODPinf	PMFP	POFP	TAP100	TETPinf	ULOP	WDP
Mono-Si Panel production (RER)	73%	32%	39%	69%	41%	26%	62%	67%	16%	92%	46%	55%	34%	35%	38%	30%	48%	47%
Mono-Si Cell production (CN)	6%	15%	13%	8%	14%	9%	9%	10%	25%	6%	15%	24%	15%	17%	14%	9%	14%	6%
Mono-Si Wafer production (CN)	3%	5%	6%	1%	2%	2%	4%	2%	1%	1%	14%	5%	5%	4%	5%	0%	5%	3%
CZ Single-crystalline Silicon Production (CN	5%	17%	17%	18%	30%	56%	11%	19%	51%	1%	9%	5%	16%	16%	15%	59%	12%	27%
Solar Grade Silicon production (CN)	7%	22%	18%	2%	9%	5%	11%	2%	5%	1%	12%	10%	21%	18%	19%	2%	16%	6%
MG-Silicon production (CN)	7%	9%	6%	1%	3%	2%	3%	1%	2%	0%	5%	2%	8%	9%	9%	0%	5%	11%

Figure A.5: foreground process contribution analysis for the Mono-Si module supply chain

As can be seen in **Figure A.5**, in general the highest contributor is the production of the Mono-Si panel. Especially the metal depletion potential is predominantly affected by the panel production. The highest contributor for metal depletion in this production process is the required tin, which is usually used as a coating material for the frame. When considering the global warming potential, Aluminium production and glass production account for a relatively high share, as shown in **Figure A.6**.

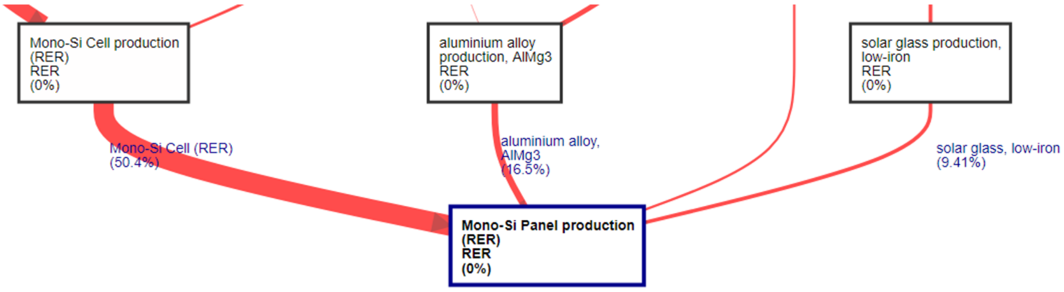


Figure A.6: Sankey diagram of contributions to Global Warming for Mono-Si production

Another interesting observation is the higher contribution in Global Warming for Silicon production in the Chinese supply chain, compared to the European case. The Global Warming impact of the complete Chinese supply chain is already much higher (148 CO2-Eq), compared to the European supply chain (89 CO2-Eq). This means that the use of Chinese cells in European panels would reduce the contribution of the panel production substantially, as can be seen in the 'European panel w/ Chinese cells supply chain', where the contribution of panel production is only 32%, compared to 50% for the full European supply chain.

In this static LCA it can thus be concluded that using European cells, with European raw materials, would substantially reduce the environmental impact, despite the generally high contribution of panel production. However, the changes in electricity mix and realistic market shift scenarios in the prospective LCA affect the future outlook of this result.

B

Additional Sensitivity Analyses

This section covers several sensitivity analyses for the model used in the prospective LCA. Based on the scenario specific results, several factors should be checked by means of a sensitivity analysis to verify the robustness of the model and its results.

B.1. Electricity Mix Development Sensitivity

Scenario 1 and scenario 2 show that the environmental impact is heavily dependent on the electricity mix and technological development. To determine the sensitivity of global developments in the electricity mixes used in this model, the variables in scenario 2 are left unchanged except for the global developments in electricity generation. In other words, the effect of optimistic or pessimistic global developments of the electricity generation mix are compared. To avoid unnecessary model computing time, the analysis is done at neighbourhood scale. The reuse case is taken as example, which does not affect the sensitivity results. **Table B.1** shows all values for the induced accumulated impact and avoided accumulated impact by 2050 in both scenarios. **Figure B.1** visualizes the accumulated induced and avoided impact of the optimistic scenario (SSP2-RCP2.6), relative to the pessimistic scenario (SSP2-RCP6.5).

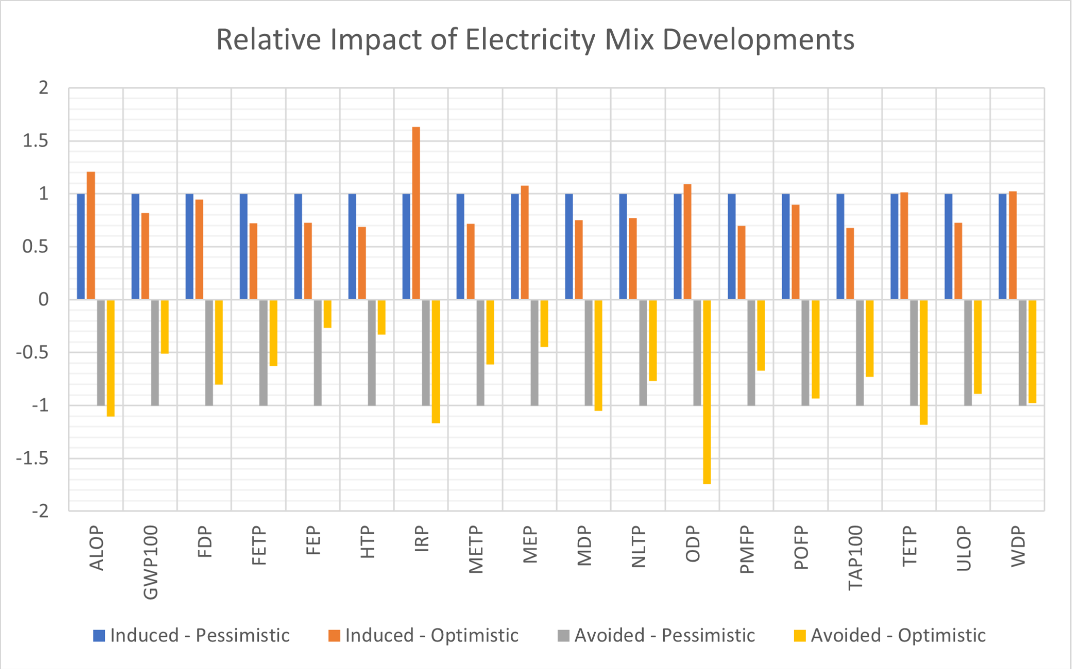


Figure B.1: Relative impact of electricity mix scenarios in the reuse case on the accumulated impact by 2050

Substantial Effects of Grid Development on the Overall Environmental Impact
The sensitivity analysis shows that the future scenario of electricity generation has enormous effects on the accumulated environmental impact. Especially when considering the avoided impact. The avoided impact on Global Warming is twice as high in the pessimistic global development scenario. The relative avoided impact is even higher for Freshwater Eutrophication and Human Toxicity. As shown in **Figure 5.8** in the contribution analysis of scenario 2, the difference in avoided impact can largely be explained by the difference in coal-generated power capacity of the ENTSO-E grid, which is the main contributor.

Marginal Effects on Op. LT Comparisons
The environmental impact for each operational lifetime scenario is heavily dependent on global developments of the electricity mix. However, the electricity mix does not have substantial effects on the relative difference, as shown in **Figure B.2**. Here the pessimistic scenario for the Op. LT = 12 case is chosen as baseline (-1), and all other scenarios show the net shadow cost impact relative to the baseline scenario. Similar proportionate differences are shown for optimistic (SSP2-RCP2.6) and pessimistic (SSP2-RCP6.5) grid developments.

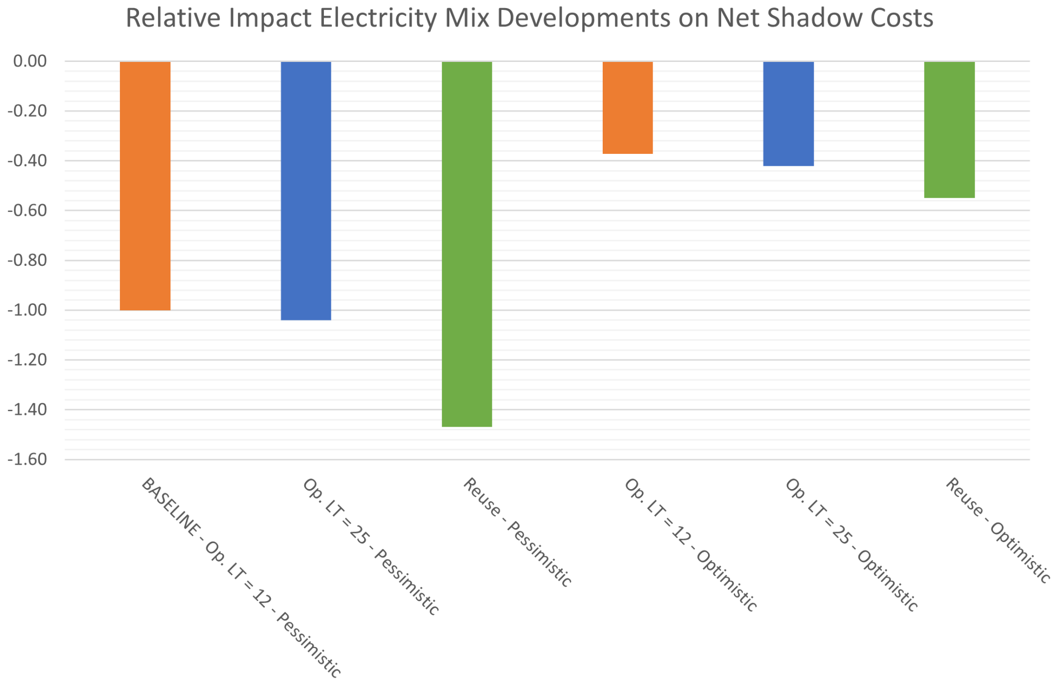


Figure B.2: Relative effect of electricity mix developments on the different operational lifetime scenario's net shadow costs

SENSITIVITY CHECK GLOBAL DEV. ELEC. MIX (NEIGHBOURHOOD SCALE

	Optimistic development		Pessimistic development		
	Induced 2050	Avoided 2050	Induced 2050	Avoided 2050	Unit
ALOP	2.09E+06	-3.56E+06	1.73E+06	-3.23E+06	Square meter-year
GWP100	1.92E+07	-5.77E+07	2.34E+07	-1.13E+08	kg CO2-Eq
FDP	6.65E+06	-2.75E+07	7.05E+06	-3.43E+07	kg oil-Eq
FETP	5.28E+06	-1.99E+06	7.34E+06	-3.18E+06	kg 1,4-DCB-Eq
FEP	1.60E+04	-3.00E+04	2.21E+04	-1.12E+05	kg P-Eq
HTP	2.75E+07	-2.40E+07	4.01E+07	-7.31E+07	kg 1,4-DCB-Eq
IRP	2.93E+06	-5.31E+07	1.80E+06	-4.55E+07	kg U235-Eq
METP	4.68E+06	-1.79E+06	6.53E+06	-2.93E+06	kg 1,4-DCB-Eq
MEP	1.23E+04	-1.44E+04	1.14E+04	-3.23E+04	kg N-Eq
MDP	1.13E+07	-1.72E+06	1.51E+07	-1.64E+06	kg Fe-eq
NLTP	-2.78E+03	4.08E+03	-3.62E+03	5.33E+03	Square-meter
ODP	2.19E+00	-4.27E+00	2.01E+00	-2.46E+00	kg CFC-11-Eq
PMFP	4.25E+04	-5.40E+04	6.08E+04	-8.02E+04	kg PM10-Eq
POFP	8.38E+04	-1.90E+05	9.35E+04	-2.03E+05	kg NMVOC-Eq
TAP100	9.45E+04	-1.38E+05	1.40E+05	-1.90E+05	kg SO2-Eq
TETP	9.25E+03	-3.56E+03	9.11E+03	-3.01E+03	kg 1,4-DCB-Eq
ULOP	2.40E+05	-4.52E+05	3.31E+05	-5.07E+05	Square meter-year
WDP	2.31E+05	-1.13E+06	2.26E+05	-1.15E+06	m3 Water-Eq

Table B.1: Sensitivity check for global developments electricity generation mix on induced and avoided accumulated impact

B.2. Technological Development Sensitivity

To determine the sensitivity of technological development on the results, all model variables in scenario 1 are unchanged except for technological development. To avoid unnecessary model computing time, the analysis is done at neighbourhood scale. The reuse case is taken as example, which will not affect the sensitivity results.

Sensitivity of Technological Development Scenarios

As shown in **Table B.2** and visualized in **Figure B.3**, the induced impact for strong technological development is lower than for conservative technological development. Furthermore, the avoided impact is higher for the strong technological development case. The relative avoided impact due to technological development is marginal (1-3%) for all impact categories, which makes sense because the module efficiency increases to roughly 3% more by 2050, in the strong development scenario. The effects of technological developments are lower than the effects of global developments, shown in **Figure B.1**.

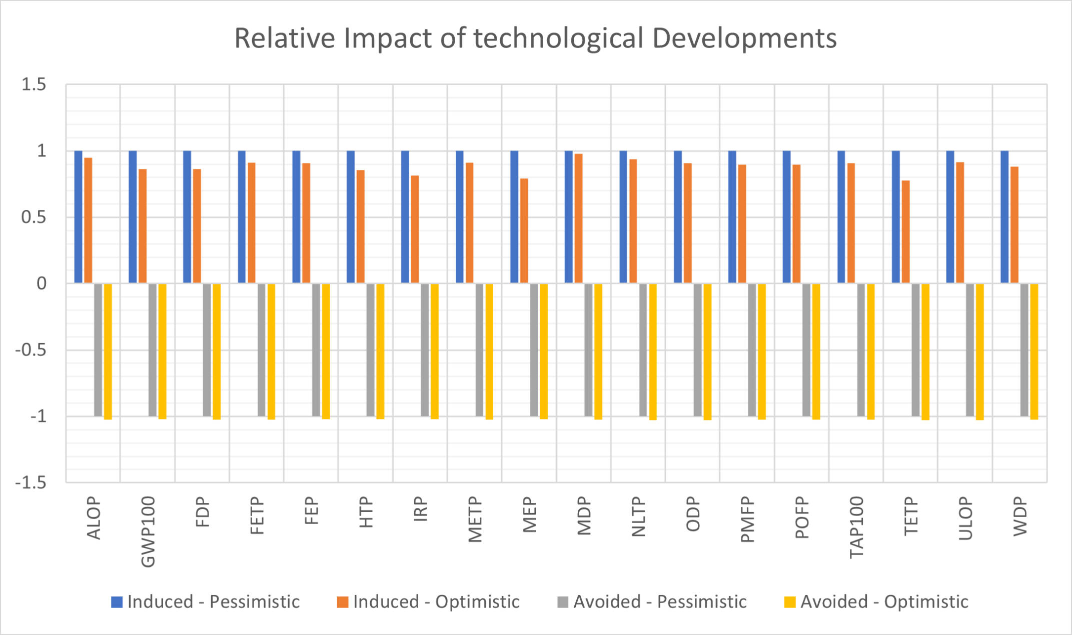


Figure B.3: Relative impact of technological development scenarios in the reuse case

Notable Effects on Op. LT Comparisons

In both technological development scenarios the proportional difference does not change substantially and similar conclusions can be drawn as for the electricity mix development scenarios. However, **Figure B.4** does show that the relative difference between Op. LT = 12 and Op. LT = 25 becomes lower in the optimistic technological development scenario. This proofs that, if global developments weren't inherently linked to technological development, even stronger technological developments would result in better results for the Op. LT = 12 scenario.

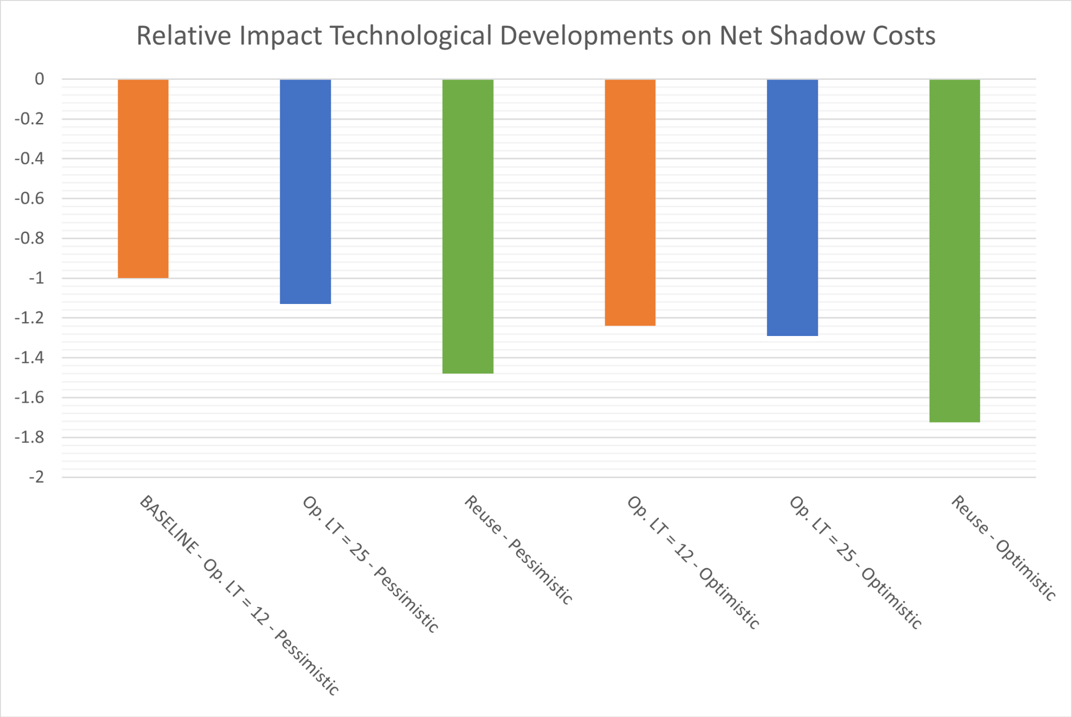


Figure B.4: Relative effect of technological developments on the different operational lifetime scenario's net shadow costs

SENSITIVITY CHECK TECH. DEV. (NEIGHBOURHOOD SCALE)					
	Optimistic development		Pessimistic development		
	Induced 2050	Avoided 2050	Induced 2050	Avoided 2050	Unit
ALOP	1.98E+06	-3.65E+06	2.09E+06	-3.56E+06	Square meter-year
GWP100	1.66E+07	-5.89E+07	1.92E+07	-5.77E+07	kg CO2-Eq
FDP	5.74E+06	-2.82E+07	6.65E+06	-2.75E+07	kg oil-Eq
FETP	4.81E+06	-2.04E+06	5.28E+06	-1.99E+06	kg 1,4-DCB-Eq
FEP	1.45E+04	-3.05E+04	1.60E+04	-3.00E+04	kg P-Eq
HTP	2.35E+07	-2.45E+07	2.75E+07	-2.40E+07	kg 1,4-DCB-Eq
IRP	2.39E+06	-5.42E+07	2.93E+06	-5.31E+07	kg U235-Eq
METP	4.26E+06	-1.83E+06	4.68E+06	-1.79E+06	kg 1,4-DCB-Eq
MEP	9.72E+03	-1.48E+04	1.23E+04	-1.44E+04	kg N-Eq
MDP	1.11E+07	-1.77E+06	1.13E+07	-1.72E+06	kg Fe-eq
NLTP	-2.61E+03	4.20E+03	-2.78E+03	4.08E+03	Square-meter
ODP	1.99E+00	-4.39E+00	2.19E+00	-4.27E+00	kg CFC-11-Eq
PMFP	3.80E+04	-5.53E+04	4.25E+04	-5.40E+04	kg PM10-Eq
POFP	7.50E+04	-1.94E+05	8.38E+04	-1.90E+05	kg NMVOC-Eq
TAP100	8.56E+04	-1.42E+05	9.45E+04	-1.38E+05	kg SO2-Eq
TETP	7.17E+03	-3.66E+03	9.25E+03	-3.56E+03	kg 1,4-DCB-Eq
ULOP	2.20E+05	-4.65E+05	2.40E+05	-4.52E+05	Square meter-year
WDP	2.04E+05	-1.15E+06	2.31E+05	-1.13E+06	m3 Water-Eq

Table B.2: Sensitivity check for technological development on induced and avoided accumulated impact

B.3. Dynamic or Static Displaced Grid Sensitivity

A big assumption in this study is the use of the dynamic ENTSO-E grid for grid displacement, which evolves while PV modules are being deployed. Using the dynamic grid to determine the avoided emissions due to electricity displacement is logical for the following reason: if the electricity consumed by a grid-connected household in year x would not be generated by a PV system, the electricity would be generated by the electricity mix in year x. However, one could also argue that the installation of PV systems are part of the reason for the dynamic nature of the grid, and therefore the electricity generated displaces the electricity generated by the grid before installation. To determine the effect of this assumption, scenario 1 is modelled at neighbourhood scale but with a dynamic displaced grid and a static displaced grid. The static displaced grid is the medium voltage ENTSO-E grid in 2015, as provided by the EcoInvent v3.8 database.

Early Disposal Advantage in Static Grid Displacement Scenario

As shown in **Figure B.6**, if the PV systems were to displace the static ENTSO-E grid of 2015, the Op. LT = 12 scenario would have a lower/better net shadow costs outcome than the dynamic grid displacement case. This would mean that it would be more environmentally advantageous to dispose old PV panels after 12 years and install new panels with a higher performance, than to leave the old panels on the rooftop until the technical lifetime of 25 years has been reached. This proofs the high sensitivity of the grid displacement choice. However, the differences are still marginal compared to the net shadow costs of the reuse scenario. The author of this study argues for using a dynamic grid, following the reasoning stated above.

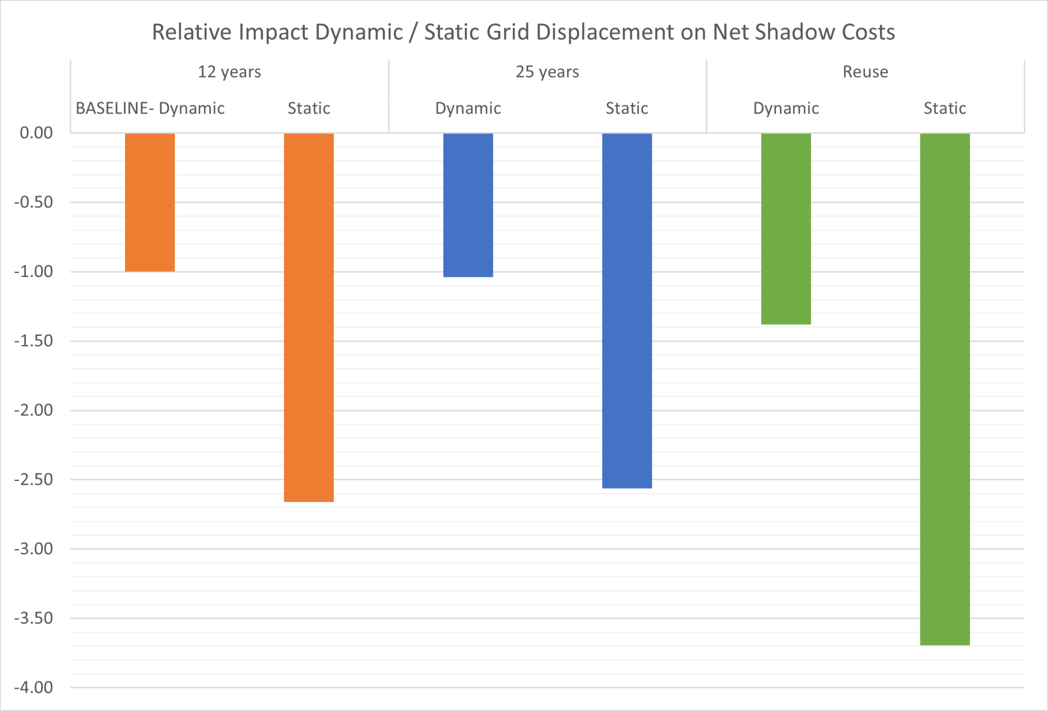


Figure B.5: Relative effect of displacing a dynamic or static ENTSO-E grid on net shadow costs in different Op. LT cases

SENSITIVITY CHECK DYNAMIC OR STATIC GRID DISPLACEMENT (NEIGHBOURHOOD SCALE)

	12 years		25 years		Reuse		
Grid displ.	Dynamic	Static	Dynamic	Static	Dynamic	Static	Unit
ALOP	-1.09E+06	-2.98E+06	-1.29E+06	-3.01E+06	-1.64E+06	-4.25E+06	Square meter-year
GWP100	-2.94E+07	-6.63E+07	-3.02E+07	-6.42E+07	-4.20E+07	-9.37E+07	kg CO2-Eq
FDP	-1.57E+07	-2.15E+07	-1.56E+07	-2.09E+07	-2.23E+07	-3.03E+07	kg oil-Eq
FETP	1.02E+06	5.02E+05	1.48E+06	1.00E+06	2.82E+06	2.10E+06	kg 1,4-DCB-Eq
FEP	-1.47E+04	-5.74E+04	-1.33E+04	-5.23E+04	-1.58E+04	-7.51E+04	kg P-Eq
HTP	-2.86E+06	-2.90E+07	-3.21E+06	-2.72E+07	-7.13E+05	-3.71E+07	kg 1,4-DCB-Eq
IRP	-3.89E+07	-4.84E+07	-3.61E+07	-4.49E+07	-5.15E+07	-6.54E+07	kg U235-Eq
METP	9.18E+05	4.07E+05	1.30E+06	8.29E+05	2.47E+06	1.76E+06	kg 1,4-DCB-Eq
MEP	-2.36E+03	-1.48E+04	-4.14E+03	-1.56E+04	-4.91E+03	-2.22E+04	kg N-Eq
MDP	6.53E+06	6.65E+06	5.74E+06	5.84E+06	9.44E+06	9.60E+06	kg Fe-eq
NLTP	8.77E+02	1.43E+03	1.18E+03	1.68E+03	1.55E+03	2.27E+03	Square-meter
ODP	-1.39E+00	-1.22E+00	-1.67E+00	-1.51E+00	-2.38E+00	-2.08E+00	kg CFC-11-Eq
PMFP	-8.52E+03	-6.60E+04	-1.37E+04	-6.63E+04	-1.69E+04	-9.57E+04	kg PM10-Eq
POFP	-7.99E+04	-1.62E+05	-8.42E+04	-1.59E+05	-1.18E+05	-2.30E+05	kg NMVOC-Eq
TAP100	-3.46E+04	-2.38E+05	-4.43E+04	-2.31E+05	-5.49E+04	-3.34E+05	kg SO2-Eq
TETP	4.14E+03	3.96E+03	2.08E+03	1.92E+03	3.58E+03	3.37E+03	kg 1,4-DCB-Eq
ULOP	-1.51E+05	-1.60E+05	-1.74E+05	-1.81E+05	-2.42E+05	-2.48E+05	Square meter-year
WDP	-6.69E+05	-7.21E+05	-6.56E+05	-7.05E+05	-9.45E+05	-1.02E+06	m3 Water-Eq

Table B.3: Sensitivity check net accumulated impact dynamic or static grid displacement at neighbourhood scale

B.3.1. Static Dutch Grid Comparison

Since the IMAGE model only allows for a dynamic grid at European scale, the Dutch grid cannot be chosen for the dynamic grid displacement. To assess the potential implications, the static Dutch grid results are compared to the dynamic ENTSO-E grid results, at neighbourhood scale. The static Dutch grid has an even bigger effect on the difference between dynamic and static grid displacement. Similar to the static ENTSO-E grid, the operational lifetime scenario of 12 years would score better than the operational lifetime scenario of 25 years. However, it is unlikely that similar differences would be given in a dynamic Dutch grid, as the Netherlands are also shifting towards more renewables in the coming decades. It does put emphasis on the sensitivity of grid displacement choices.

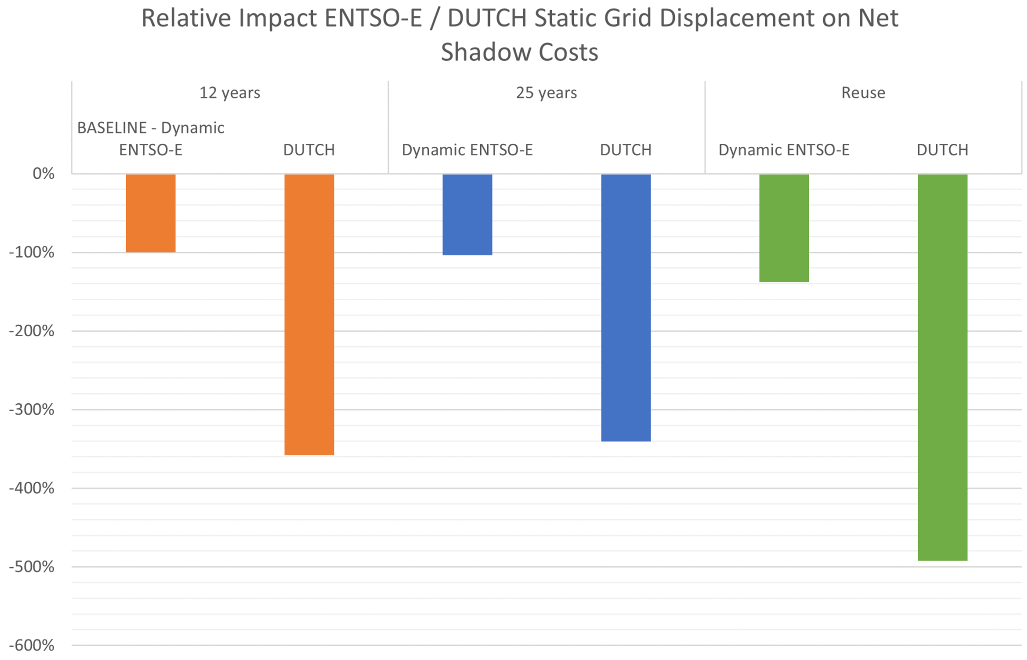
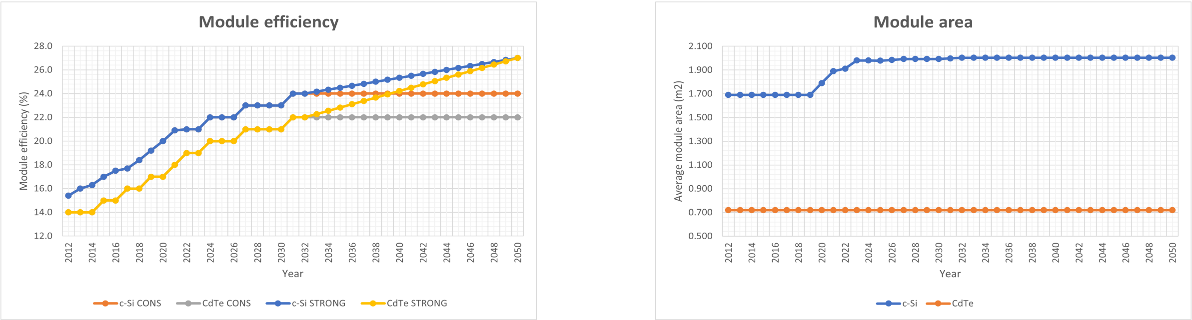


Figure B.6: Relative effect of displacing a dynamic or static Dutch grid on net shadow costs in different Op. LT cases

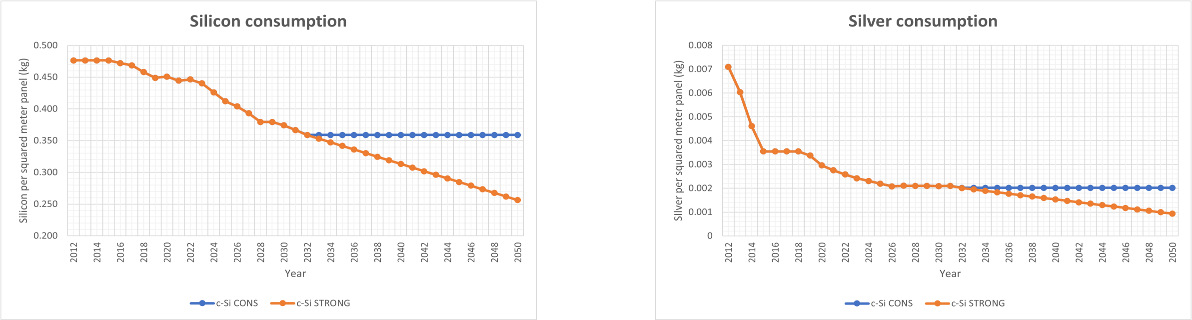
C

Technological Development Figures



(a) Module efficiency input values

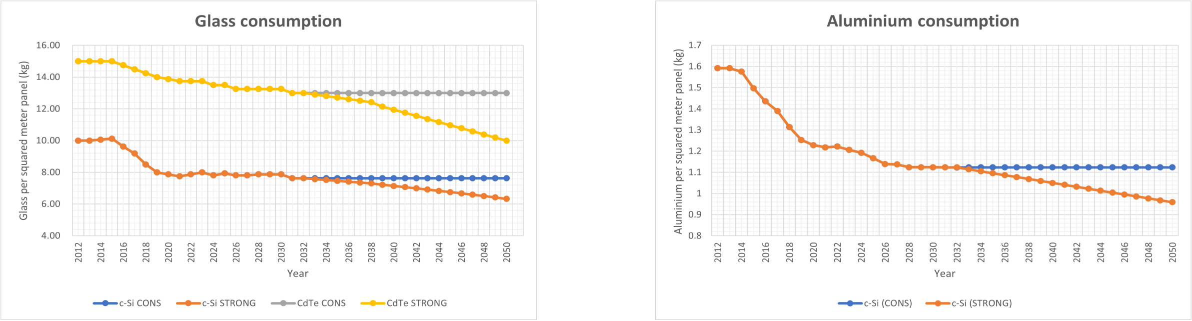
(b) Module area input values



(c) Silicon consumption input values

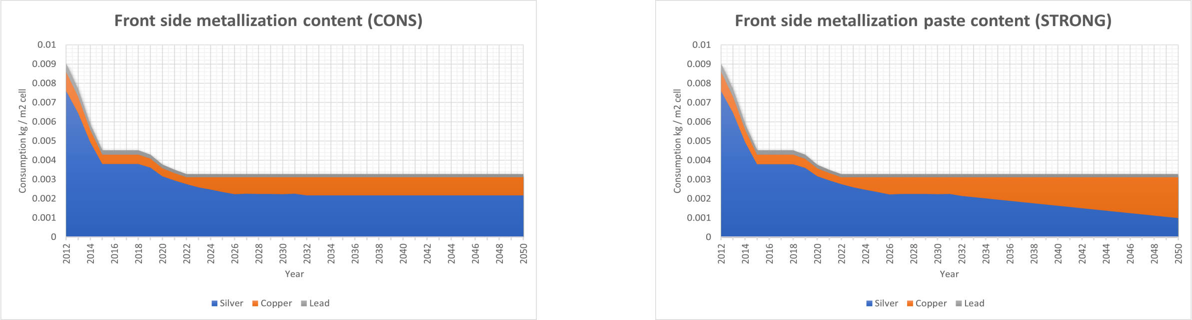
(d) Silver consumption input values

Figure C.1: Visualization of technological development input parameters for prospective LCA (Page 1)



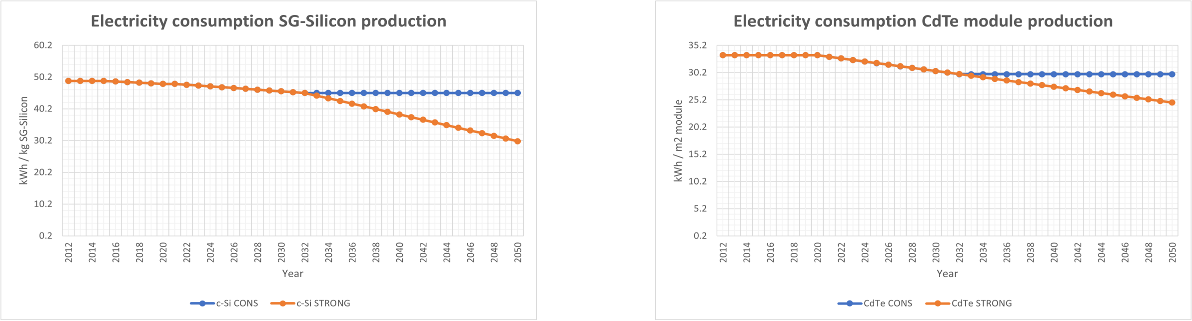
(a) Glass consumption input values

(b) Aluminium consumption input values



(c) Pessimistic metallization paste content input values

(d) Optimistic metallization paste content input values



(e) Solar grade Silicon electricity consumption input values

(f) CdTe electricity consumption input values

Figure C.2: Visualization of technological development input parameters for prospective LCA (Page 2)

D

Assumptions Overview

D.1. General Assumptions

A. Key Assumptions Normalized Baseline LCA

A1. No closed-loop recycling takes places. Only open-loop recycling according to current practice in Europe
A2. The average string inverter has a technical lifetime of 12 years
A3. The Balance Of System, including inverter, cabling and mounting system does have tech. Development
A4. European background processes used for processes which lack data for China
A5. National medium voltage electricity group used for electricity consumption Chinese processes
A6. ENTSO-E medium voltage electricity mix used for electricity consumption European processes
A7. Impact during maintenance and construction/deconstruction can be neglected
A8. End-of-Life management of the inverter is cut off/disregarded in this study

B. Key Assumptions Prospective LCA

B1. Linear upscaling rate assumed from 2012 to 2030 (50% capacity) and from 2030 to 2050 (100% capacity)
B2. End-of-Life (EoL) management remains similar to current process
B3. Only contemporary technologies with corresponding technological development installed
B4. BOS (inverter, mounting system and cabling) tech. development can be neglected
B5. Immediate replacement takes place after disposal
B6. The dynamic european ENTSO-E grid is displaced

Table D.1: Key assumptions of the normalized baseline LCA and prospective LCA

Clarification for Normalized Baseline LCA Assumptions

Several important assumptions of the normalized baseline LCA are clarified below:

- **Recycling:** No closed-loop recycling takes place along the supply chain of the system elements. This could have considerable effects on the environmental impact during production, as stated by previous studies (Deng et al., 2021). However, circular use of high-purity Silicon and intact Silicon wafers is still only done at lab scale and the currently well-established c-Si PV modules have a linear supply chain (Deng et al., 2021). Because of the high uncertainty in future developments of recycling practices, the current disposal practice for c-Si modules and CdTe, as provided by IEA PVPS (Frischknecht et al., 2020), is integrated in this prospective LCA. This disposal process mainly consists of recycling the glass and aluminium in bulk recycling facilities and shredding the cells to use them as fillers for concrete or asphalt (WEEE NL, personal communications; Yu et al., 2022).

- **Lifetime String Inverter:** The IEA PVPS methodology guidelines (Frischknecht et al., 2020) suggest a module operational lifetime of 30 years. However, the main focus of this study is the effect of different module operational lifetimes. This study compares an operational lifetime of 12 and 25 years for PV modules. The IEA also suggests a 15 year operational lifetime for inverters. However, other literature suggests an average lifetime of 10 to 15 years (Choi & Lee, 2020; European Commission, 2018). This study adopts an average string inverter lifetime of 12 years. Due to lack of data the end-of-life management of the string inverter is cut off/disregarded, which is a limitation of this study.

- **Tech. development of BOS:** Due to lack of data and time constraints, the technological development of electric and mechanical components outside of the PV module are not considered. This assumption may lead to slightly higher environmental impact estimates for future scenarios. However, the modules show by far the highest impact related to greenhouse gas emissions (Frischknecht et al., 2015) and future scenarios of background processes such as the electricity mix are still considered.

- **Background Process Regions:** Because of data, modelling and time constraints, various assumptions had to be taken in this LCA. First of all, the EcoInvent database lacks data for many processes in China. Therefore European background processes are used for processes which lack data for China. Although this gives relatively unrepresentative estimates for the environmental impact of production in China, most impact can be linked to the Chinese electricity mix, which is adopted in the foreground processes of Chinese production (Frischknecht et al., 2015). For European production the general electricity mix ENTSO-E is used. This mix gives a good general representation of the average electricity mix in Europe, and like the Chinese mix, is modified for future projections. The assumption is made that each production facility uses these electricity mixes, although some facilities may actually use electricity generated at the facility itself.

- **Impact maintenance/construction/deconstruction neglected** For simplification, the impact during maintenance, construction and deconstruction has been neglected in this LCA study. Transport of the system elements has already been incorporated in the normalized baseline LCA of the system elements. While the maintenance of utility scale power plants generally requires considerable maintenance, the services involved with maintenance, construction and deconstruction of residential PV systems merely require some manpower. This is insubstantial compared to the impact of production and is therefore neglected.

Clarification for Prospective LCA Assumptions

Several important assumptions of the prospective LCA are clarified below:

- **Linear Upscaling:** Although the amount of installations has increased almost exponentially last decade, the increase in installations is uncertain for the future. The rooftop capacity targets of Amsterdam are 50% by 2030 and 100% by 2050. Since installations started to increase in 2012, it can be assumed that the curve is linear when taking the entire time-frame.

- **Constant EOL Management:** Various innovative high-value recycling processes can be found in literature. However, it will likely take a long time before these processes are adopted at industrial scale. Furthermore, there is a lack of data of these emerging processes which can be regarded as a limitation of this study. Future research should focus on this issue since it may influence the results.

- **Only Contemporary Technologies:** As discussed in the theoretical framework, the environmental impact of emerging technologies and their probable market share is very uncertain. Although it is likely that some technologies may infiltrate the market in the coming decades, due to uncertainty, data and time constraints these technologies are neglected in this study. Future research should focus on the effects of emerging technologies.

- **No BOS Tech. Development:** Due to lack of data, the technological development has not been considered in this study and therefore assumes there is no tech. development. Multiple studies discussed in the theoretical framework have taken a similar approach for these system elements. However, the influence of this assumption should be addressed in future research.

- **Immediate Replacement:** It is assumed that when a household disposes its PV system, it will immediately replaced. In some cases households may choose to completely get rid of their PV system. However, in light of the targets set by the municipality, this study chooses to neglect these cases.

- **Dynamic ENTSO-E Grid Displaced:** It is assumed that the ENTSO-E grid, following a scenario-dependent RCP, is displaced by the installed PV systems. One may also choose a static grid. Reasoning for this choice is given in **Section B.3** of **Appendix B**.

D.2. Process-Specific Baseline LCA Assumptions

C.Assumptions MG-Silicon production
C1. 16-32 metric ton lorry used for freight transport
C2. EURO6 used for transport lorries
C3. Diesel powered freight trains used
C4. Softwood used for wood chip consumption in MG-Silicon production
C5. MG-Silicon from Europe produced in Norway (current main producer)
C6. Softwood used for wood chip consumption in MG-Silicon production

D. Assumptions Solar Grade Silicon production
D1. Regular Hydrogen + Chlorine reaction used for hydrochloric acid production
D2. Membrane cell used for hydrogen and sodium hydroxide production
D3. EURO6 used for transport lorries
D4. Diesel powered freight trains used

E. Assumptions single-crystalline Silicon production
E1. Czochralski production process for single-crystalline Silicon
E2. Sodium hydroxide produced with membrane cell
E3. EURO6 used for lorry
E4. 16-32 ton lorries
E5. Diesel powered freight trains used

F. Assumptions multi-crystalline Silicon production
F1. Sodium hydroxide produced with membrane cell
F2. EURO6 used for lorry
F3. 16-32 ton lorries
F4. Diesel powered freight trains used

G. Assumptions Mono-Si wafer production
G1. Membrane cell used for sodium hydroxide production
G2. Hydrochloric acid production from the reaction of Hydrogen with Chlorine
G3. 16-32 ton lorries
G4. EURO6 used for lorry

H. Assumptions Mono-Si cell
H1. Dimethyldichlorosilane used as silane gas for PV cell production
H2. Metallization paste backside: 80.8% Aluminium, 17% chemical, organic, 3% Silica sand
H3. Metallization paste frontside: 84% silver, 5% lead, 12% copper
H4. 16-32 ton lorries
H5. EURO6 used for lorry

Table D.2: All general and process specific assumptions baseline LCA (Table 1)

I. Assumptions Mono-Si panel
I1. Copper cathode used for copper in PV panel
I2. Copper cathode production through solvent extraction and electrowinning process
I3. 16-32 ton lorries
I4. EURO6 used for lorry

J. Assumptions CdTe panel production
J1. All CdTe panels produced in Malaysia
J2. Cadmium Telluride, semiconductor-grade produced in the US
J3. Copper cathode used for copper in PV panel
J4. No frame in First Solar Series 4 (no Aluminium or steel used)
J5. 16-32 ton lorries
J6. EURO6 used for lorry

K. Assumptions c-Si recycling avoided burdens
K1. Aluminium primary, ingot from IAI Area, EU27 & EFTA used for avoided burdens Aluminium recycling
K2. Soda ash, light, crystalline, heptahydrate produced by Solvay process used for avoided burdens soda

L. Assumptions CdTe recycling avoided burdens
L1. Market for Cadmium sludge from Zinc Electrolysis used as avoided burden Cadmium recycling
L2. Soda ash, light, crystalline, heptahydrate produced by Solvay process used for avoided burdens soda

Table D.3: Process specific assumptions baseline LCA (Table 2)