BeGreen
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Environmental Performance of the Ingerslev Å 65MW Solar Park

A Life Cycle Perspective

Reviewer

Dimitrios Lergios, Project Manager - LCA Specialist, Audit and Verification, FORCE Technology.

Reviewed study

The review is performed on the following Life Cycle Assessment (LCA) report: "Environmental Performance of the Ingerslev Å 65MW Solar Park - A Life Cycle Perspective", dated 29/10/25 (version 3). The study was commissioned by BeGreen A/S and conducted by BeGreen A/S environmental team. The LCA study does not include any comparative assertions. The object of assessment is the Ingerslev Å 65 MWp solar park, in Denmark, developed and constructed by BeGreen A/S. The LCA study evaluates the environmental impacts associated with the Ingerslev Å 65 MWp solar park and addresses the environmental impact indicators included in the Environmental Footprint (E.F.) 3.1 life cycle impact assessment (LCIA) methodology. The following review statement refers to the above-mentioned study and cannot be used for any other study.

Review procedure

The purpose of the review was to provide an independent 3rd party assurance that the study follows the procedural and methodological requirements in ISO 14040, 14044 and good LCA practice. The review is of the type "Critical review by internal or external experts", as described in ISO 14044, Section 6.2., and was performed in the period from 27/08/25 to 29/10/25 by a single reviewer. The reviewing process took place after the report was finalised. The report was delivered to the reviewer who in turn initiated a dialogue with the study's practitioner and provided comments over the study's content. Afterwards the report was amended one more time, based on further comments and dialogue.

Review statement

The LCA report has been reviewed with respect to compliance with ISO 14040, 14044 and the Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity prepared by the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS Task 12). The review was performed by a single reviewer. The methods applied in the attributional LCA report are consistent with the ISO standards and the product specific guidelines and are in general scientifically and technically valid. Further, the used data in this context is in general appropriate and reasonable according to the goal and scope of the LCA. Interpretations presented in the report reflect the goal of the study and the identified limitations. In general, the report is sufficiently transparent, consistent and of high quality.

Further, and specifically on the phases in the report:

The ***goal and scope*** of study is well described and clearly states that the focus of the study is to quantify and evaluate the environmental impacts associated with the Ingerslev Å 65 MWp solar park (based on EF 3.1 environmental impact indicators). Additional goals are to identify impact hotspots in the life cycle of the solar park, assess material consumption with a focus on circularity and resource efficiency, calculate the energy payback time (EPBT) and energy return on investment (EROI), as well as assess the impact of solar park on the energy system of Norddjurs Municipality. The study does not include any comparative assertions however, the study's results will be disclosed to the public, which can lead to comparisons. In that content, the reviewer would like to highlight that the study contains some major assumptions and methodological choices. The end-of-life scenario includes a high recycling rate for metals. This assumption is considered representative of reality since the treatment of waste, after the dismantling of the solar park, will take place in a controlled environment, while most components/parts are made of metals with high recyclability and value as scraps. No sensitivity analysis was performed to assess the sensitivity of the results to this end-of-life scenario however, the results are not expected to be significantly impacted given that metals are not expected to be incinerated at the end-of-life stage. Yet, for some environmental impact categories this may not be the case. The cut-off approach was chosen as the allocation method for modelling the recycled content and recycling of materials. This means that the recycled content of incoming materials is burden-free (only the impacts from the recycling process are considered) while no benefits from recycling of waste are allocated to the system under study. The methodology choice may lead to unfair comparisons if the results of this study are compared with other studies that follow a different methodology. Although methodological choices, assumptions and limitations were found to be consistent in the study, those can be different in other studies where similar systems are assessed. It is noted that the average electricity grid mix was used to describe the electricity consumption during the construction stage of the solar park and the production of components/parts (upstream).

Finally, any communication of the results (e.g., marketing claims, calculation tools etc.) is not covered by this review, since it cannot be reviewed according to the requirements in ISO 14040/14044.

Primary data used in the study is collected by BeGreen A/S from suppliers and the solar park project itself. ***Secondary data*** were retrieved from statistics, EPDs, the professional LCA software databases Ecoinvent and Managed LCA Content, and data from IEA-PVPS. The chosen LCA modelling tool was LCA for Experts. The general geographical, temporal, and technological representativeness of the data was described in the study, while a quality assessment of secondary data was performed. The technological representativeness of secondary data is considered appropriate and the use of proxies where data is unavailable does not affect the overall quality. Finally, data from EPDs were used to describe some components/parts since no secondary data was available.

The ***Life Cycle Impact Assessment (LCIA)*** is presented in a simplified and adequate way, where calculations are performed for the whole life cycle and individual life cycle stages of the solar park. A contribution analysis of each environmental impact from each life cycle stage, as well as individual activities/materials, to the total results, can also be seen.

In that context, the ***interpretation*** describes sufficiently the results in terms of the LCA modelling processes used. A proper ***uncertainty and sensitivity analysis*** is missing in the report (according to the ISO standards) however, a ***sensitivity analysis*** was performed qualitatively for several parameters and choices. Overall, the approach is in general considered reasonable, even though there could have been more focus on the uncertainty of the study. However, given the results, choices and arguments presented in the study the uncertainty appears to be relatively low and within the normal range for LCA studies.

The ***conclusions*** in the LCA study relate well to the main aim of the study and mention some major limitations, even though they could have been more thorough in terms of assumptions and uncertainty, as well as the impact of those to the results.

If significant changes take place on supplier, product, or market level, then the LCA study needs to be revised to evaluate whether those changes significantly affect the results.

29/10/25
Date

Dimitrios Lergios
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Key sustainability figures

Ingerslev Å 65MWp specification

Plant size capacity (peak)	65 MWdc
Plant size capacity (to grid)	48 MWac
Land area	66 ha
PV technology	Single-crystalline silicon
PV panel type	Bifacial monocrystalline (605W & 610W)
Module-rated efficiency	22.4% and 22.5%
Number of panels	107,576
Type of system	Ground mount, fixed tilt
PV orientation	Pitched, south facing
Module degradation rate	1% first year, 0.4% per year for 30 years
Lifetime	30 years
Annual production	68 GWh (first year)
Total production (30 years)	1932 GWh
Capacity factor	11% (average 30 years)
Location	Ørsted, Denmark
Production per m^2/yr	1019.9 kWh/m^2/yr

Ingerslev Å 65MWp key figures

Ingerslev Å carbon footprint (Global Warming Potential)	26g CO_2e/kWh
PV panel carbon footprint per Wp	760g CO_2e/Wp.[1]
Ingerslev Å Energy Payback Time (EPBT)	17 months.[2]
Ingerslev Å Energy Return On Investment (EROI)	14 times.[3]
Ingerslev Å recyclability	86 %

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[1] Per Wp includes all the solar park Balance of System (BOS) components including High Voltage (HV) transformer substation

[2] Calculated using the life-cycle consumption of non-renewable primary energy

[3] Ibid

Environmental Impact Summary

This table shows all the potential life-cycle environmental impacts caused by Ingerslev Å per 1 kWh of electricity produced over 30 years.

Whole-life environmental impacts of Ingerslev Å 65MWp solar park per 1 kWh

Impact category	Unit	Total	Description
Climate Change - total	kg CO_2 eq.	0.026	Represents the overall contribution to global warming from all sources. It leads to rising temperatures, sea level rise, extreme weather events, and disruptions to ecosystems and human livelihoods.
Climate Change, fossil	kg CO_2 eq.	0.024	Focuses on greenhouse gases from fossil fuel combustion. These emissions intensify global warming, affecting human health through heat stress and increasing risks to biodiversity and agriculture.
Climate Change, biogenic	kg CO_2 eq.	0.0015	Accounts for emissions from biological sources (e.g., biomass burning). While sometimes considered carbon-neutral, they can still contribute to climate change depending on land management and carbon sequestration dynamics.
Climate Change, land use and land use change	kg CO_2 eq.	0.000054	Captures emissions from changes in land cover (e.g., deforestation). These changes reduce carbon sinks and increase atmospheric CO_2, impacting climate regulation and leading to habitat loss.
Ozone depletion	kg CFC-11 eq.	0.00000000051	Refers to the breakdown of the stratospheric ozone layer, which protects life from harmful UV radiation. Increased UV exposure can cause skin cancer, cataracts, and harm to terrestrial and aquatic ecosystems.
Acidification	Mole of H+ eq.	0.00011	Describes the release of acidifying substances (e.g., SO_2, NOx) that lower pH in soils and water bodies. This harms aquatic life, reduces forest health, and degrades soil fertility, affecting food production and biodiversity.
Eutrophication, freshwater	kg P eq.	0.0000021	Caused by nutrient overloads (mainly phosphorus) in freshwater systems, leading to algal blooms, oxygen depletion, and fish kills. It disrupts aquatic ecosystems and water quality.
Eutrophication, marine	kg N eq.	0.000027	Driven by nitrogen emissions affecting coastal and marine environments. It causes dead zones, loss of marine biodiversity, and impacts fisheries and recreation.
Eutrophication, terrestrial	Mole of N eq.	0.00028	Results from nutrient deposition on land ecosystems, altering plant species composition and reducing biodiversity. It can lead to soil degradation and ecosystem imbalance.
Photochemical ozone formation, human health	kg NMVOC eq.	0.000078	Involves the formation of ground-level ozone from VOCs and NOx under sunlight. This ozone is a harmful air pollutant, causing respiratory issues, cardiovascular problems, and premature death.
Resource use, mineral and metals	kg Sb eq.	0,00000095	Measures the depletion of non-renewable mineral and metal resources. It affects long-term resource availability, increases environmental burdens from mining, and can lead to geopolitical tensions.
Resource use, fossils	MJ	0.29	Tracks the consumption of fossil fuels. It contributes to resource scarcity, climate change, and environmental degradation from extraction and combustion processes.
Water use	m^3 world equiv.	0.0076	Assesses freshwater consumption and its impact on local water availability. Excessive use can lead to water scarcity, affecting ecosystems, agriculture, and human health, especially in water-stressed regions.

Executive summary

This Life Cycle Assessment (LCA) report presents a comprehensive evaluation of the environmental impacts associated with the Ingerslev Å 65 MWp solar park in Denmark, developed and constructed by BeGreen. The assessment spans a 30-year operational period and is aligned with BeGreen's commitment to minimising greenhouse gas emissions and reducing the depletion of natural capital. The report has been critically reviewed.

The LCA was conducted in accordance with ISO 14040/44 standards and follows the Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity prepared by the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS Task 12).[4]. It covers the full life cycle of the solar park - from raw material extraction, manufacturing, and transportation to construction, operation, and end-of-life disposal.

The system boundary includes the high-voltage (HV) transformer substation and extends to the point of electricity delivery to the grid. The functional unit is 1 kWh of AC electricity delivered to the Danish electricity grid downstream of the HV transformer. The operating lifetime of the solar park is 30 years.

The primary objectives of this study were to:

- Identify and interpret life cycle stages with the highest environmental impacts
- Calculate the energy payback time (EPBT) and Energy Return on Investment (EROI)
- Assess material consumption with a focus on circularity and resource efficiency
- Determine the environmental impact reversal time and process
- Assess the impact of solar park on the energy system of Norddjurs Municipality
- Assess the robustness and reliability of the study

Results

The majority of the environmental impact associated with Ingerslev Å 65 MWp stems from the manufacturing of components - accounting for over 95% of the total impact. Of this, solar PV modules contribute between 70% and 90%, making them the most significant factor. Most of the impact arises from cell production. The mounting structure follows, responsible for up to 10% of the impact. The park's carbon footprint is estimated at 26 g CO_2/kWh.

Interpretation and Conclusions

The park is energy-efficient, capable of returning its embodied energy within 17 months of operation. It achieves an energy return on investment (EROI) of 14 times the initial investment, highlighting its long-term sustainability.

The solar park demonstrates a high recyclability rate of 86%, indicating that most materials contributing to its environmental impact can be recovered and reused, thereby reducing the footprint in future applications. However this can only happen if the necessary infrastructure and logistics and know-how for recovery and recycling is accessible.

When evaluating the circularity of the solar park - which extends beyond recycling to include factors such as the use of virgin materials, lifespan, and reuse - the circularity score is relatively low at 49%. This is primarily due to the high use of virgin materials during construction and the limited reuse of components after the park's operational lifetime. Consequently, the park exhibits a high linear material flow of 56%, meaning that materials are typically used once and then discarded without further reuse.

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[4] IEA_Task12_LCA_Guidelines.pdf

Most of the environmental impact occurs as a one-time pulse during the first year of the park's lifecycle. Therefore over time, natural processes can gradually mitigate these effects. Based on environmental scientific methods, several impact recovery estimations were calculated, for example how much time the earth can sequester carbon dioxdie released from the solar park. The results are presented in the Interpretation section but should be seen as estimations and not a direct outcome from the LCA.

Looking ahead, future solar park developments should consider Environmental Product Declaration (EPD) data, particularly for wafering and cell production, which currently account for 24% of the park's total impact. An EPD can capture the impact from improvements made to these processes since these processes can be controlled by PV module manufacturers that produce cells.

The findings aim to support informed decision-making among stakeholders, including regulators, and reinforce BeGreen's commitment to sustainable and responsible energy development.

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1. Introduction

1.1. Background

At BeGreen, we strive to understand our environmental impacts. Our Environmental policy acknowledges our environmental responsibility to ensure that our activities within all our operations do not cause harm to the environment, and that we have a societal responsibility to be responsible actors in the communities in which we operate. We systematically assess our environmental impact for the whole life cycle of our developments and continuously strive to improve environmental performance and mitigate any negative impacts. We strive to ensure our projects are always nature positive through ecological enhancement and ongoing improvement through feasible and targeted environmental initiatives.

To achieve these goals, it is necessary for BeGreen to incorporate scientific research into our decision making, and where meaningful, seek partnership with academia to drive improvement. Therefore, we create a comprehensive Life Cycle Assessment (LCA) for each project, identifying all environmental impacts and their primary causes.

This study focuses on the Ingerslev Å 65 MWp solar park (herein referred to as Ingerslev Å) which began construction in 2024 and was completed in 2025, taking 12 months to complete. It was connected to the grid in June 2025.

1.2. Life Cycle Assessment

LCA is a structured and science-based method used to evaluate the environmental impacts of a product, service, or system throughout its entire life cycle. This means looking at every stage - from the extraction of raw materials, through manufacturing, transportation, construction, and operation, all the way to end-of-life disposal or recycling.

For a solar park such as Ingerslev Å, this includes assessing the environmental effects of producing solar panels, transporting and installing them, operating the park over decades, and eventually decommissioning and discarding the components via recycling, incineration with energy recovery or landfilling. LCA is important because it:

- Provides a full picture of environmental impacts, not just during operation but across the entire lifespan
- Identifies hotspots - the stages or materials that contribute most to emissions or resource use - so improvements can be targeted effectively
- Supports transparency and accountability, helping stakeholders understand the true environmental impact of a project
- Guides better decision-making, ensuring that environmental goals are met without shifting burdens from one stage or impact category to another

By using LCA, BeGreen can ensure that its solar parks deliver clean energy with the lowest possible environmental footprint, aligning with our Environmental policy and commitment to responsible development. This Life Cycle Assessment was developed internally by BeGreen following requirements in ISO standard 14040/44 and the Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity prepared by the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS Task 12) and provides a foundation for understanding the environmental footprint of the solar park and supports continuous improvement in sustainable project development.

1.2.1. Four phases in an LCA

According to the International Organization for Standardisation (ISO) 14040/44 standards, a LCA study consists of four interconnected phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. This report is structured in line with these four phases to ensure a transparent, consistent, and comprehensive assessment of Ingerslev Å.

Goal and Scope Definition: This phase sets the framework for the study, including its purpose, system boundaries, and the level of detail. It defines what the LCA aims to achieve and how the results will be used.

Life Cycle Inventory (LCI): In this phase, data is collected on all relevant inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with each stage of the product or system's life cycle.

Life Cycle Impact Assessment (LCIA): The LCI data is analysed to evaluate the potential environmental impacts, such as climate change, resource depletion, and pollution. This helps identify which stages or processes contribute most to environmental burdens.

Interpretation: The results are interpreted in relation to the original goal and scope. This phase identifies key findings, assesses data quality, and highlights opportunities for reducing environmental impacts.

2. Goal of the study

The goal of this LCA study is to evaluate the full range of environmental impacts associated with Ingerslev Å throughout its entire life cycle - from raw material extraction and component manufacturing to construction, operation, and end-of-life treatment.

The purpose of the study is to:

1. Identify the life cycle stages and processes with the highest and significant environmental impacts
2. Explore the Environmental Impact Mitigation Potential
    - Determine the energy payback time (EPBT) and Energy Return on Investment (EROI)
    - Understand material consumption and assess the potential for circularity, including reuse, recycling, and resource efficiency
    - Determine the environmental impact reversal time and process
    - Assess the impact of solar park on the energy system of Norddjurs Municipality
3. Evaluate the robustness and reliability of the results

The intended application of the LCA is to support BeGreen's broader environmental commitments by providing data-driven insights that guide sustainable project development and help reduce the environmental footprint of future solar installations. As well to be transparent about its environmental impacts to the public. The intended target audience is BeGreen employees and the public.

The LCA will not make comparative assertions with other electricity generation technologies, however the study is done in a way that could allow this.

2.1. Data Quality Requirements

The LCA study requires high-quality data to ensure the results are robust, representative, and aligned with current best practices. The data must meet specific criteria across temporal, geographical, and technological dimensions, as well as adhere to standards for precision, completeness, consistency, and reproducibility.

2.1.1. Temporal Coverage

All primary data must reflect the year of installation, ideally sourced from 2024 financial and procurement records. For major components such as PV modules and inverters, the most recent Environmental Product Declarations (EPDs) provided by suppliers are required. In cases where EPDs are unavailable, technical datasheets should be used to derive material composition and specifications, particularly for components like cabling. Secondary data must be drawn from the latest available LCI databases, such as Ecoinvent or Sphera Managed LCA Content, to ensure temporal relevance.

2.1.2. Geographical Coverage

The geographical origin of all major components must be identified and incorporated into the inventory. This includes modelling the electricity mix of the manufacturing location and accounting for transport distances and modes. Unless more specific data is available, upstream material inputs should be assumed to originate from the same country or region as the manufacturing site.

2.1.3. Technological Coverage

The study must reflect the actual technologies deployed at the site, including the specific brand, model, and technical specifications of each component. Where detailed data is not available, representative data must be selected to reflect current manufacturing technologies and practices, ensuring technological relevance.

2.1.4. Precision, Completeness, Representativeness, Consistency, and Reproducibility

Component quantities and masses must be calculated accurately using datasheets or derived from physical dimensions and material densities. The system model must include over 99% of total mass and energy flows, with exclusions only permitted under justified cut-off criteria. Representativeness must be confirmed through qualitative assessment to ensure the data reflects the actual temporal, geographical, and technological context. Consistency in methodological approaches must be maintained across all components and processes, and the study must be documented in sufficient detail to allow independent replication.

2.1.5. Data Accuracy and Uncertainty

All data sources must be critically assessed for accuracy and reliability. Where assumptions are necessary or data points have a significant influence on the results, uncertainty and sensitivity analyses must be conducted to evaluate their impact on the study's conclusions.

3. Scope of the study

The product system being studied is the Ingerslev Å 65 MWp solar park in Denmark, which was connected to the grid in June 2025. Its function is to produce renewable electricity from sunlight and deliver it to the national grid over 30 years.

The LCA is cradle-to-grave and uses data from the park's design and construction phases, including a yield study to estimate future electricity generation. The LCA was conducted in accordance with ISO 14040/44 standards and follows the Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity prepared by the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS Task 12).[5].

This LCA is based on a retrospective analysis conducted by BeGreen, using data collected from the actual construction and design of the park. Since the park was completed in 2024/2025, construction data is historical, while operational data is based on prospective modelling over an expected 30-year lifetime.

The Life Cycle Assessment (LCA) is attributional in nature, meaning it uses specific primary data collected by BeGreen, supplemented, when necessary, with secondary data based on average environmental metrics. These data are used to assign impacts to each life cycle stage through Life Cycle Inventory (LCI) databases. The LCA is also process-based, relying on detailed, process-level data rather than environmentally extended input-output (EEIO) or hybrid models. This approach provides a high-resolution understanding of the environmental performance of each component and activity.

At the end of its life, the solar park is decommissioned, and all components are disposed of through recycling, incineration with energy recovery, or landfill. The allocation procedure for recycling follows the cut-off approach, which is standard procedure for this type of LCA, and which includes the recycling burden within the scope of this study but excludes the credit for producing recycled content, as that lies outside the study's scope. Similarly, the credit from incineration with energy recovery is also excluded.

The LCA study was critically reviewed by an external independent expert.

3.1. Functional Unit and Reference Flow

The functional unit is the quantified performance of the product system used as a reference for consistent comparison. All inventory data and impacts are scaled to this unit. For this study, the functional unit is defined as:

1 kWh of AC electricity delivered to the Danish grid by a 65MWp solar park over a 30-year lifetime downstream of the HV transformer

This unit allows for determining the life cycle impact and is consistent with LCA practice for electricity production technologies. It allows to understand the impact from consuming electricity from the park during its 30-year lifetime. The total electricity produced over 30 years is expected to be 1,932 GWh.

This unit allows for meaningful comparison with other photovoltaic (PV) systems and electricity-generating technologies that provide the same function.

The reference flow represents the quantity of the solar park required to fulfil the function defined by the functional unit. It serves as the denominator for calculating cumulative emissions, resource use, and environmental impacts across the system.

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[5] IEA_Task12_LCA_Guidelines.pdf

In this study, the functional unit is derived from the reference flow of the predicted total electricity generation over 30 years, amounting to 1,932 GWh. This estimate is based on a detailed yield study and the degradation rates of the PV modules. The reference flow is calculated as 1/1,932,000,000 kWh, or approximately 5.18 × 10^{-10} solar parks per 1 kWh delivered.

3.2. System Boundaries

The system boundaries define the scope of the analysis and specify which processes are included in the life cycle inventory. The system boundaries for this LCA are presented below. (Figure 1).

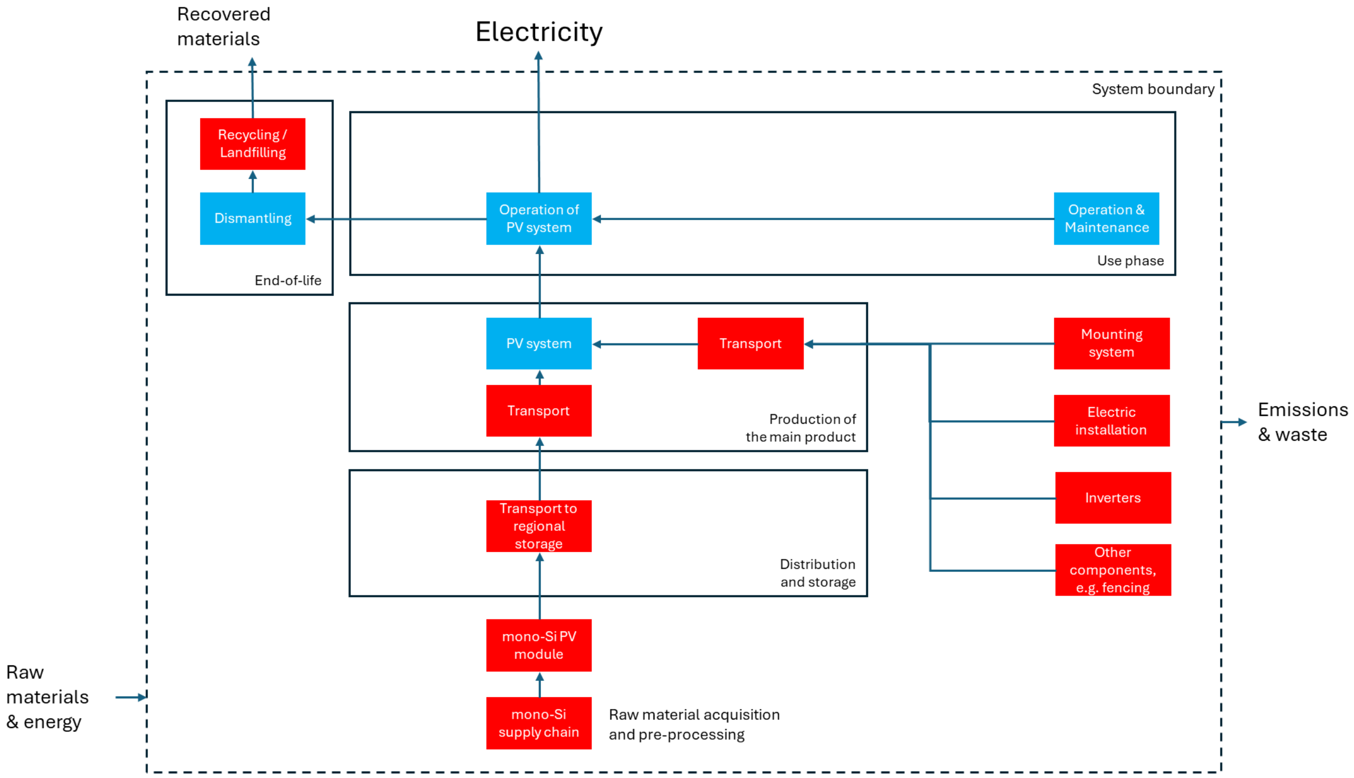

Figure 1. Product life cycle system boundaries of Ingerslev Å (dotted line). Foreground sub-systems (blue box) are controlled by BeGreen. Background sub-systems (red box) are controlled by other entities.

This study follows a cradle-to-grave approach and includes the following stages:

Product Stage

- Raw material and energy supply
- Manufacturing of:
    - PV panels
    - Mounting structures
    - Cabling
    - Inverters
    - Transformers and all other components required to generate and deliver electricity to the grid
    - Packaging
- Energy and material flows related to:
    - Manufacturing and warehousing
    - Climate control, ventilation, and lighting in production facilities
    - On-site emissions

    - On-site waste treatment
    - PV manufacturing equipment

Construction Stage

- Transportation of components to the site
- On-site construction and installation, including foundations, mounting structures, and fencing

Use Stage

- Auxiliary electricity demand
- Routine maintenance
- Repairs and component replacements

End-of-Life Stage

- Deconstruction and dismantling
- Transportation of waste materials
- Waste processing
- Recycling and reuse of materials
- Final disposal of non-recyclable components

Exclusions

The following elements are excluded from the system boundaries due to their relatively minor contribution, or lack of available data:

- Employee commuting (transport to and from work)
- Administrative, marketing, and R&D activities
- Minor material inputs such as bolts, screws, fasteners etc.
- Minor maintenance materials such as fuses, connectors, and lubricants are excluded
- Transmission and distribution losses beyond the transformer

This comprehensive scope ensures that the LCA captures all significant environmental aspects of Ingerslev Å, enabling robust analysis and informed decision-making in line with ISO 14040/44 standards.

3.3. Main assumptions made in this study

Assumptions are a necessary part of Life Cycle Assessment (LCA) to address data gaps and uncertainties. In this study, several assumptions were made to ensure completeness and consistency. Their validity was assessed using scientific literature, expert judgment, comparisons with similar studies, and evaluations of their contribution to the overall environmental impact and material/energy flows of the solar park. Where assumptions could significantly influence results, sensitivity analysis is typically recommended. However, in this study, no sensitivity analyses were deemed necessary to report, since during the modelling numerous sensitivity analyses were carried out when deemed necessary each time the impact was insensitive and negligible therefore did not need to be reported. This continuous sensitivity analysis helped to validate the results of the study. Nonetheless, recommendations for improving future assessments are provided in Section 7.1.

Component Data Assumptions

- HV Transformer: A detailed Bill of Materials (BoM) for the HV transformer was unavailable. Therefore, data from a similar transformer of comparable size and function were used. A proxy transformer (63 MVA manufactured by Tamini) and its material types and quantities were scaled up proportionally to match the 88 MVA capacity used in the Ingerslev Å solar park

- MV Switchgear Holtab building: Specific BoM and material quantities for the Holtab switchgear building were unavailable. Instead, data were sourced from a comparable solar park (Freerslev, 77 MWp), which includes a similar Holtab building

Life Cycle Inventory (LCI) Data Assumptions

- All background LCI datasets were selected based on relevance to technology, geography, and time-period to reflect real-world conditions as closely as possible
- For components with significant environmental impact or material mass, the most accurate and representative datasets were prioritised. Significance was determined based on expert knowledge and best practices from previous solar LCA studies
- Common assumptions in utility-scale solar LCAs include the use of average European or global datasets for upstream processes (e.g., aluminium production, glass manufacturing), and assuming standard transportation distances for imported components

Operational Data Assumptions

- The solar park is assumed to operate for 30 years, which is a standard lifetime assumption for utility-scale PV systems.
- Electricity yield over the 30-year period was estimated using specialised simulation software, incorporating degradation rates and site-specific solar irradiance data. Among several yield scenarios, the average-case scenario was applied in this study.
- Maintenance activities are assumed to follow standard industry practices, with minimal environmental impact beyond replacement of minor components.

End-of-Life Assumptions

- The treatment of components at end-of-life is uncertain and subject to future technological and regulatory developments. Therefore, disposal routes (recycling, incineration with energy recovery, landfill) were estimated using conservative assumptions and current best practices.
- The allocation procedure for recycling follows the cut-off approach, which includes the environmental burden of recycling within the system boundary but excludes credits to produce recycled materials, as these fall outside the scope of this study.
- Similarly, energy recovery credits from incineration are excluded.

3.4. System description

Ingerslev Å is in Norddjurs Municipality, in the eastern part of Jutland, Denmark, between latitudes 56.30° and 56.45° N (Figure 2). The park contributes to the municipality's transition toward a low-carbon energy system by supplying renewable electricity to the grid. This supports the goals outlined in Norddjurs' Strategic Energy Plan and Climate Plan, helping to reduce greenhouse gas emissions and increase the share of renewables in the local energy mix.

The solar park has a total installed capacity of 65 MWp and consists of a combination of 605 W and 610 W bifacial dual-glass monocrystalline PV modules supplied by Trina Solar (Table 1). These modules have high efficiencies of 22.4% and 22.5%, respectively, and are designed to capture sunlight from both the front and rear sides, increasing energy yield.

The system operates at a DC voltage range of 500–1500 V, which is typical for utility-scale PV installations. The generated electricity is converted to AC via central inverters and delivered to the grid through dedicated transformers, ensuring compliance with grid voltage and frequency standards.

Figure 2. Location of Ingerslev Å in Denmark

Table 1. Park specific details

Total number of modules installed	43,030 (605 W) and 64,546 (610 W)
Mounting system type	Fixed-tilt, galvanized steel with tilt angle of 20.1°
Inverter specifications	168 string, Sungrow SG350HX, rated capacity 254 A input 1080 V, AC 800 V
Transformer specifications	MV: 6 Sungrow, 8960 kVA, with efficiency (Tier 2). HV: 88 MVA
Land area occupied	66 hectare, previously agricultural land
Grid connection details	60kV at point of interconnection, 800m to substation
Expected annual electricity generation	68.4 GWh with performance ratio of 0.884
Design lifetime of the system	30 years
Site-specific conditions	Ground reflectivity (0.2 albedo), average solar irradiation (1,019.9 kWh/m^2/year), mean annual temperature 8°C

3.4.1. Expected annual electricity generation

Ingerslev Å has a maximum installed capacity of 65 megawatts peak (MWp), which refers to the total power the solar panels can produce under ideal conditions. However, the maximum power that can be delivered to the grid is limited to 48 megawatts AC (MWac) due to grid connection constraints.

Each year, the park is expected to generate approximately 68.4 gigawatt-hours (GWh) of electricity, which is enough to power around 19,900 average Danish households. This electricity is delivered to the grid after passing through a high-voltage transformer. The solar panels cover an area of 290,583 square meters, resulting in an annual energy output of 235.46 kWh per square meter.

Over its expected 30-year lifetime, the park is projected to generate a total of 1,932 GWh, accounting for the gradual decline in panel performance over time (Figure 3). This corresponds to an average capacity factor of 11%, which reflects the average output compared to the maximum possible output if the system ran at full capacity all year.

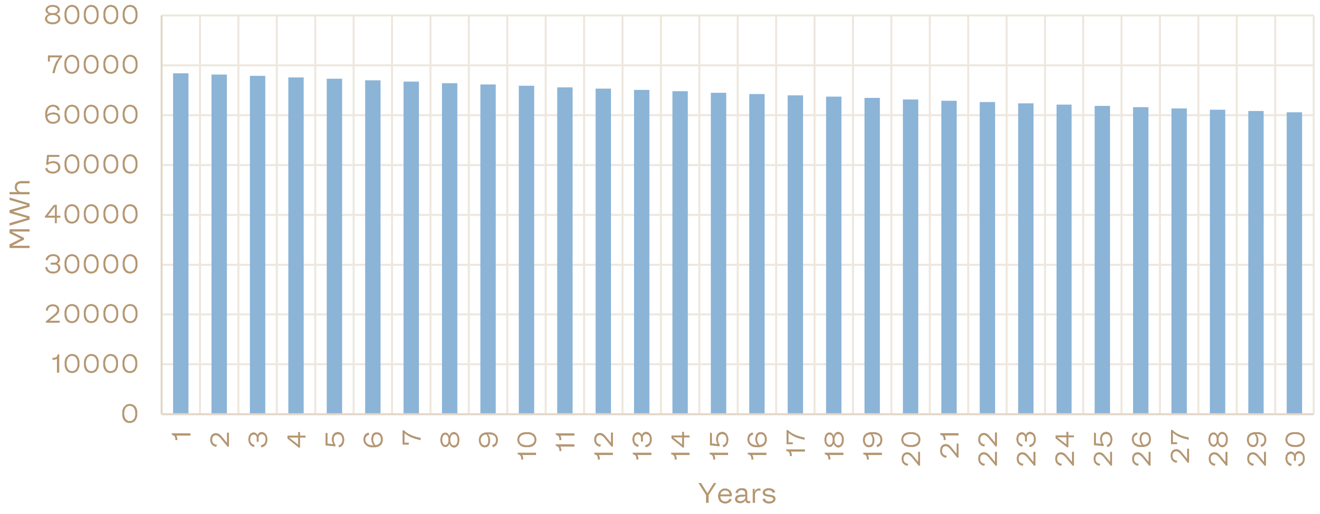

Figure 3. Expected annual generation after degradation over 30 years

Panel Orientation and Sunlight

The solar panels are fixed in place, facing south with a tilt angle of 20.1° and an azimuth angle of 1.4°, which helps optimise sunlight capture throughout the year. The site receives an estimated 1,019.9 kWh/m^2/year of solar energy based on its location and panel orientation. In the first year, the system is expected to produce 1,046 kWh/kWp of installed capacity.

System Efficiency

The yield study determined the performance ratio of the system as 0.884, meaning that 88.4% of the solar energy captured is converted into usable electricity. The remaining 11.6% is lost due to factors like heat, dust on panels, shading, and equipment inefficiencies. This ratio is a key indicator of how well the system performs in real-world conditions.

The performance estimates were calculated using specialized PV system modelling software, which simulates how the system will perform over time based on local weather, equipment specifications, and layout.

DC to AC Ratio and Grid Limitations

The DC:AC ratio - the relationship between the total power from the solar panels (DC) and the capacity of the inverters (AC) - is 1.363. This means the panels can produce more power than the inverters can convert at any one time, which is a common design choice to maximise energy production during lower sunlight hours. However, during peak sunlight, some energy may be lost due to this limitation.

Additionally, grid curtailment - when the utility limits how much electricity can be fed into the grid - has been estimated at 1.25%, which slightly reduces the total energy delivered.

Degradation Over Time

Solar panels naturally degrade over time, producing slightly less electricity each year. The Trina Solar panels used at Ingerslev Å are expected to lose 1% of efficiency in the first year, followed by 0.4% per year thereafter[6]. Over 30 years, this results in a total energy loss of about 120 GWh, or a 1.4% reduction in total efficiency.

3.5. PV Park system

In this LCA, the product system was divided into three main subsystems: 1) PV module production, 2) balance of system (BOS) and 3) end-of-life treatment.

PV Module Production: A detailed model was built for the manufacturing of the bifacial monocrystalline PV modules, including raw material extraction, wafer production, cell processing, module assembly, and packaging.

Balance of System (BOS): The Balance of System (BOS) includes all components of the solar park aside from the PV modules. These elements are essential for supporting, converting, and delivering the electricity generated by the PV modules to the grid. The BOS components for Ingerslev Å include inverters, cabling (LV and MV), transformers (MV and HV) and switchgear and housing, mounting structures, and other supporting infrastructure.

End-of-life recycling: At the end of its 30-year operational life, Ingerslev Å is assumed to undergo systematic decommissioning, with a focus on maximising material recovery and recycling. A model was built in line with current best practices for recycling utility-scale PV systems with other materials going to incineration with energy recovery or landfill.

Table 2. Amount of each component in Ingerslev Å (including O&M)

Component	Quantity (O&M)	Unit	Data type
PV modules	107,576 (1,918)	Pieces	Primary, foreground
Balance of system (BOS)			
Inverters	168 (50)	Pieces	
Mounting system	1,839	Tonnes	
Cabling	620,234	Metres	
MV transformer	6	Pieces	
HV transformer	1	Pieces	
MV switchgear	4	Pieces	
Fencing	4,821	Metres	
TOTAL Weight of Ingerslev Å (including O&M)	**6,529 (6,600)**	**Tonnes**	

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[6] https://pages.trinasolar.com/rs/567-KJK-096/images/Datasheet_Vertex_NEG19RC.20_EN_2023.pdf

3.6. Material breakdown

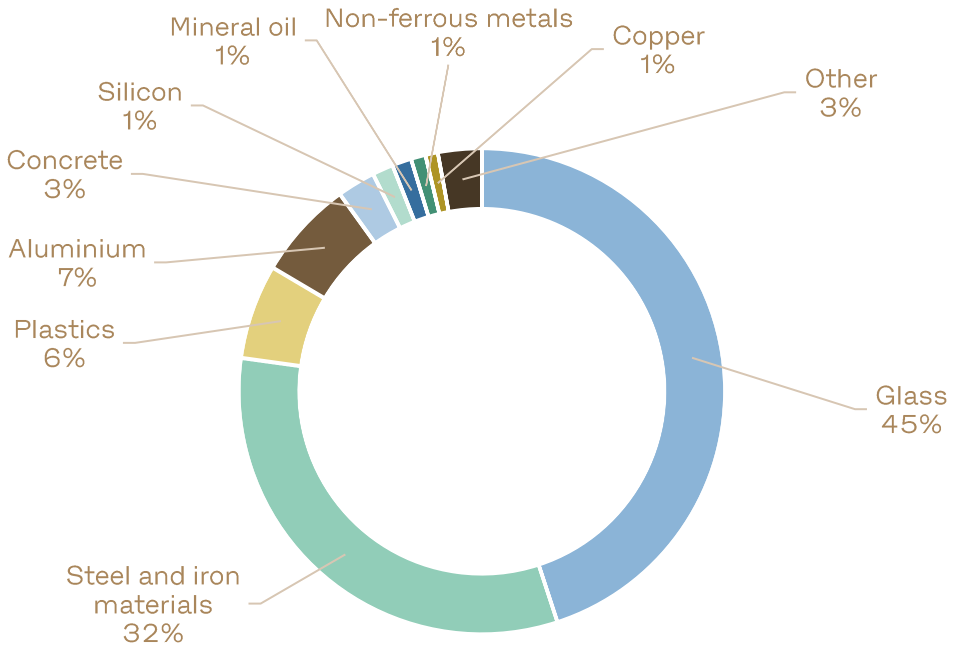

Figure 4. Main materials in Ingerslev Å 65MWp, including O&M

Table 3. Total weight of materials in each component including O&M

Material classification	Unit	Solar panels	Mounting	Inverters	Cabling	Transformers & switchgear	Miscellaneous	Total
Aluminium	Tonne	280	1.7	11.4	120	20		**433**
Cellulose and paper	Tonne					3	36	**39**
Ceramic	Tonne					0,012		**0.012**
Concrete	Tonne					168		**168**
Copper	Tonne	7.4		4.3	17	26		**55**
Electronics	Tonne			0.2		0.15		**0.34**
Fiberglass	Tonne					0.27		**0.27**
Glass	Tonne	2,968						**2,968**
Insulating materials	Tonne					0.21		**0.21**
Mineral oil	Tonne					85		**85**
Non-ferrous metals	Tonne	18.4	45.6	0.14		0.39		**65**
Not specified	Tonne					0.017		**0.02**
Other ferrous metals	Tonne			3		3		**6**
Other plastics and rubbers	Tonne					0.17		**0.17**
Plastics	Tonne	288		6.5	70,7	0.18	17.9	**383**
Resins and glues	Tonne					1.7		**1.7**
Silicon	Tonne	92						**92**
Silicon steel	Tonne					117		**116.60**
Silicone product	Tonne	33				0.06		**33**
Stainless steel	Tonne			1.4		0.02		**1.43**
Steel	Tonne		1,791			95	117	**2,003**
Wood	Tonne				21	0.08	129	**149.84**
Total mass	**Tonne**	**3,687**	**1,839**	**27.3**	**228.4**	**519**	**300**	**6,600**
Total number of pieces		**109,494**	**n/a**	**218**	**n/a**	**6 (MV) & 1 (HV)**	**1 x perimeter & 1 x HV substation**	**n/a**
Mass per piece	**kg**	**33.7**	**n/a**	**125**	**n/a**	**n/a**	**n/a**	**n/a**

3.7. Transport and Supply Chain Data

Components are sourced from various locations across Europe and internationally. At BeGreen, we apply a diligent and structured approach to supplier selection, prioritising partners based on risk assessments, ESG (Environmental, Social, and Governance) performance, and traceability of materials. This ensures that our supply chain aligns with both sustainability goals and regulatory expectations.

As part of this process, we can obtain highly specific information about the origin of materials and components, including country of origin for key components, manufacturing locations for PV modules, inverters, and mounting systems, and transport modes and distances, including road, rail, sea, and air freight, from supplier to construction site.

This detailed sourcing information allows us to model transport-related environmental impacts with a high degree of accuracy in the LCA. We can apply realistic transport distances. This improves the precision of the life cycle inventory and ensures that the environmental footprint of logistics is transparently accounted for.

Table 4. Transport distances (kilometres)

	Origin	Truck	Capacity (t)	Ship	Dead weight tonnes	Capacity (%)	Data type
PV panels	China	800	34-40	20,000	74,130	53	Secondary, background
Mounting structure	EU average	1,000	34-40				
Inverters	China	800	34-40	20,000	74,130	53	
Cabling	EU average	1,000	34-40				
MV transformers	China	800	34-40	20,000	74,130	53	
HV transformer	Italy	1,500	34-40				
Fencing	EU average	1,000	34-40				

3.8. Construction

The construction of the solar park involves several activities that contribute to environmental impacts, primarily using fossil fuels and electricity.

Overall, while the construction phase represents a relatively short period in the life cycle of the solar park, it contributes to the embodied energy and emissions that are accounted for in the LCA. These impacts are later offset by the renewable energy generated during the operational phase.

Site preparation includes excavation, grading, and soil levelling, which are carried out using diesel-powered machinery such as bulldozers, excavators, and graders. These activities consume diesel fuel and result in direct emissions of CO_2, NO_x, and particulate matter.

Foundation and mounting structures include installation of mounting systems for the photovoltaic panels requires drilling or pile driving, depending on soil conditions. These processes also rely on diesel-powered equipment.

Electrical infrastructure construction includes the installation of cabling, inverters, transformers, and grid connection infrastructure. This phase involves the use of cranes, trenching machines, and other equipment, contributing to both energy use and material consumption.

Diesel consumption for construction was 64,299 kg. In the LCA model the diesel is modelled as being consumed in an excavator using an LCI dataset called "GLO: Excavator, 100 kW, construction". The study includes a dataset for producing diesel and the combustion emissions from diesel in the machine.

Temporary facilities consume electricity for temporary site offices, lighting, and equipment during the construction period. This electricity is drawn from the local grid and was estimated based on another LCA project and was 4 MWh.

3.8.1. Waste generation from construction

Waste generation from construction activities generate packaging waste, surplus materials, and minor construction debris, which were sorted and sent to treatment. The waste types and amounts are presented in Table 5. The waste was either treated via recycling, incineration with energy recovery or landfilling which is described in Section 3.10.2.

All waste generation data was collected onsite and is primary, foreground data.

Table 5: Waste materials generated during construction

Unit	Wood pellets	Paper	Foil (Low density Polyethylene)	Mixed packaging (assumed Low density Polyethylene)	Plastic strips (Polyethylene terephthalate)	Steel strips	TOTAL
Tonne	129	36	6.8	3.1	8.0	5.9	**189**

3.9. Operation and maintenance

The operation and maintenance (O&M) phase of Ingerslev Å spans the full 30-year lifetime of the system. Over the lifetime of the solar park, there are routine activities such as monitoring, minor repairs, and scheduled component replacements. This phase is critical for ensuring optimal performance and minimising downtime, and it also contributes to the overall environmental footprint of the system.

3.9.1. Component Replacements

Certain components are expected to be replaced due to wear, degradation, or failure. All replacements are included in the life cycle inventory, with associated material, energy, and transport impacts modelled accordingly (Table 6).

Solar modules will be replaced with an assumed 2% replacement rate over 30 years. This accounts for potential damage from weather events, manufacturing defects, or early degradation. Replacements are modelled using the same module type and production assumptions as the original installation.

Inverters typically have a shorter lifespan than PV modules. A 30% replacement rate is assumed, reflecting 10%-part replacement over every 10 years which equals a full replacement of 30% inverters during the system's lifetime. This aligns with the recommendation in the IEA-PVPS LCA guidelines and is a conservative assessment considering the inverter model in Ingerslev Å has an expected lifetime of 25 years.

Periodic site visits by maintenance crews are modelled using average vehicle distances and frequencies. Generally, two vehicles are used for maintenance and grass is cut once a year. It is estimated that diesel consumption would equal 18,907 litres over 30 years (based on data from the Vandel III solar park in Denmark).

Table 6. Expected lifetimes and replacement strategies for the main components

Component	Expected Lifetime	Replacement Strategy
PV Modules	30 years	2% replacement rate over 30 years assumed; performance degradation is accounted for in yield estimates
Inverters	30 years	10% of parts replacement over 10 years (based on PVPS), modelled as 30% inverter replacement over 30 years
Transformers	30 years	No replacement assumed unless failure occurs; routine maintenance required
Mounting Structures	30 years	Designed for full lifetime; corrosion-resistant materials used to minimize degradation
Cabling	30 years	No replacement assumed; periodic inspections and minor repairs included in maintenance

3.9.2. Auxiliary Electricity Consumption

During operation, the solar park consumes a small amount of electricity from the grid for auxiliary functions such as monitoring and control systems, inverter standby power, lighting and security systems and occasional heating or cooling of enclosures.

The annual auxiliary electricity demand was estimated based on data from previous BeGreen projects, with a similar scale and configuration. The electricity consumption is 1,600MWh over 30 years modelled as Danish grid electricity (2021) and included in the operational phase of the LCA.

3.10. End-of-life disposal and recycling

The end-of-life phase of the solar PV system was modelled to include the transport and recycling of photovoltaic panels and Balance of System (BOS) components. PV modules were assumed to be transported to Reiling PV-Recycling GmbH in Germany. Reiling's process enables the recovery of valuable materials such as glass, aluminium, and silicon, with mechanical treatment methods that minimise environmental impact.

BOS components - including inverters, mounting structures, and cabling - were modelled as being transported to regional recycling facilities for disassembly and recovery of metals such as copper, steel, and aluminium. Transport distances were estimated based on typical logistics routes within Europe. This end-of-life scenario reflects current best practices and supports circular economy principles by enabling material recovery and reducing landfill waste.

3.10.1. Recyclability of Ingerslev Å

Recyclability refers to the proportion of the solar park's components - including concrete foundations and replacements from operation and maintenance - that can be recycled at end-of-life. Each component is assigned a specific recycling rate and disposal method, and the overall recyclability is calculated using the following formula:

$$\textit{Solar park recyclability } (\%) = [\textit{sum of all solar park parts}]\ \frac{\textit{recycling rate } (\%) * \textit{ part mass } (kg}{\textit{total part mass } (kg)}$$

Based on this approach, the overall recyclability of the Ingerslev Å solar park is estimated at 86%. The primary contributors to this figure are metals such as steel, aluminium, and copper, which together account for approximately 40% of the total mass. Glass, which makes up 45% of the mass, is also considered recyclable, although in this study it is modelled as being sent as glass cullet outside the system boundaries.

Silicon, used in photovoltaic cells, represents only 2% of the total mass but contributes significantly to the environmental impact. While silicon recycling technologies do exist - such as those offered by companies like ROSI - they are not included in this study due to a lack of detailed data. It is strongly anticipated that these technologies will be widely available in future therefore future studies should aim to incorporate these processes to improve accuracy.

It is important to note that not all materials are recycled. For example, plastics are typically sent to incineration with energy recovery, as detailed in Table 7. As a result, the current recyclability estimate may be conservative and could be improved with more comprehensive data and modelling.

Recycling rates for metals are based on expert judgment and data from previous LCA studies. These rates reflect typical end-of-life treatment scenarios for utility-scale solar parks in Europe. Common assumptions include:

- Use of average European recycling rates for metals and glass.
- Exclusion of recycling credits for materials processed outside the system boundary.
- Conservative estimates for components with uncertain end-of-life pathways.

In Section 7, the future improvements to enhance the recyclability assessment methodology and increase transparency in subsequent studies is outlined.

3.10.2. End-of-life treatment of the Solar Park

The end-of-life treatment of the solar park is modelled in a comprehensive and detailed manner. It is assumed that the entire solar park is collected and dismantled at the end of its operational life. However, the components are not recycled uniformly, as outlined below.

Solar modules and inverters are sent all to recycling at a capture rate of 100%. The mounting structure and cabling is assumed to be 99% captured and sent to recycling (see Table 7). Other major components - including transformers, and cabling - are estimated to be captured at 100% and recycled, based on current industry practices and available data. All remaining components are treated according to the breakdown provided in Table 7.

Concrete foundations are fully removed and sent to landfill, as recycling of concrete is not modelled in this study.

All components are assumed to be disassembled and collected with a high capture rate of 99–100%. Once collected, materials are sorted and directed to appropriate treatment pathways: recycling, incineration with energy recovery, or landfill. In cases where components are sent to recycling facilities, non-recyclable fractions are subsequently diverted to incineration or landfill.

While a high proportion of metals are sent to recycling, the proportion of certain materials recycled at the facility is assumed to be lower (95%) due to process losses and the recycling efficiency is assumed to be 80% for metals, meaning that some material losses occur during the recycling process. This reflects typical recovery rates for metals in industrial recycling systems.

Importantly, only the environmental burdens associated with recycling and incineration are included in the study. Credits for recycled content or energy recovery are excluded, as they fall outside the scope of this assessment.

This approach aligns with common assumptions in utility-scale solar LCAs, which often:

- Assume full decommissioning and collection of components.
- Use conservative estimates for recycling rates based on available literature and expert judgment.
- Exclude downstream benefits (e.g., avoided impacts from recycled materials) to maintain a clear system boundary.

Future studies may refine these assumptions further, especially as recycling technologies and end-of-life treatment practices evolve.

Table 7: Capture rate for components to be treated and treatment types for materials of captured components

		Treatment type of material in component			**Data type**	**Source**
Component/ Material	**Capture rate of component**	Recycling	Incineration with energy recovery	Landfill		
PV modules	100%				Secondary, foreground	Estimated
Aluminium		99%		1%	Secondary, background	
Copper		95%		5%		
Glass		95%		5%		
Plastics			50%	50%		
Silicon		95%.[7]		5%		
Other non-ferrous metals		95%		5%		
Mounting structure & fencing	99%			1%	Secondary, foreground	
Steel		100%			Secondary, background	
Inverters (based on EPD)	100%				Secondary, foreground	
Metals		90%		10%	Primary, background	Sungrow EPD
Plastics		60%	40%			
Electronics		65%	10%	25%		
Other			100%			
Cabling	99%			1%	Secondary, foreground	Estimated
Aluminium		100%			Secondary, background	
Copper		100%				
Plastics			50%	50%		
Wood			100%			
Transformers & switchgear	100%					
Aluminium		95%		5%		
Copper		95%		5%		
Steel		95%		5%		
Non-ferrous metals				100%		
Plastics			50%	50%		
Concrete				100%		
Others			100%			
Packaging	100%					
Plastics		95%		5%		
Steel		95%		5%		
Paper		95%		5%		
Wood			100%			

Recycling of solar modules

BeGreen is participating in a research project called SPICE (Solar Panels in Circular Economy).[8]. The aim is to setup a strategy for disposal of PV modules and recycling along with industry partners. The recycler is Reiling in Germany. Therefore, data from Reiling has been used for PV module recycling which is sourced from PVPS Task 12.[9]. Table 21 in Section 4.4.1, presents the LCI data used for modelling Reiling's recycling process.

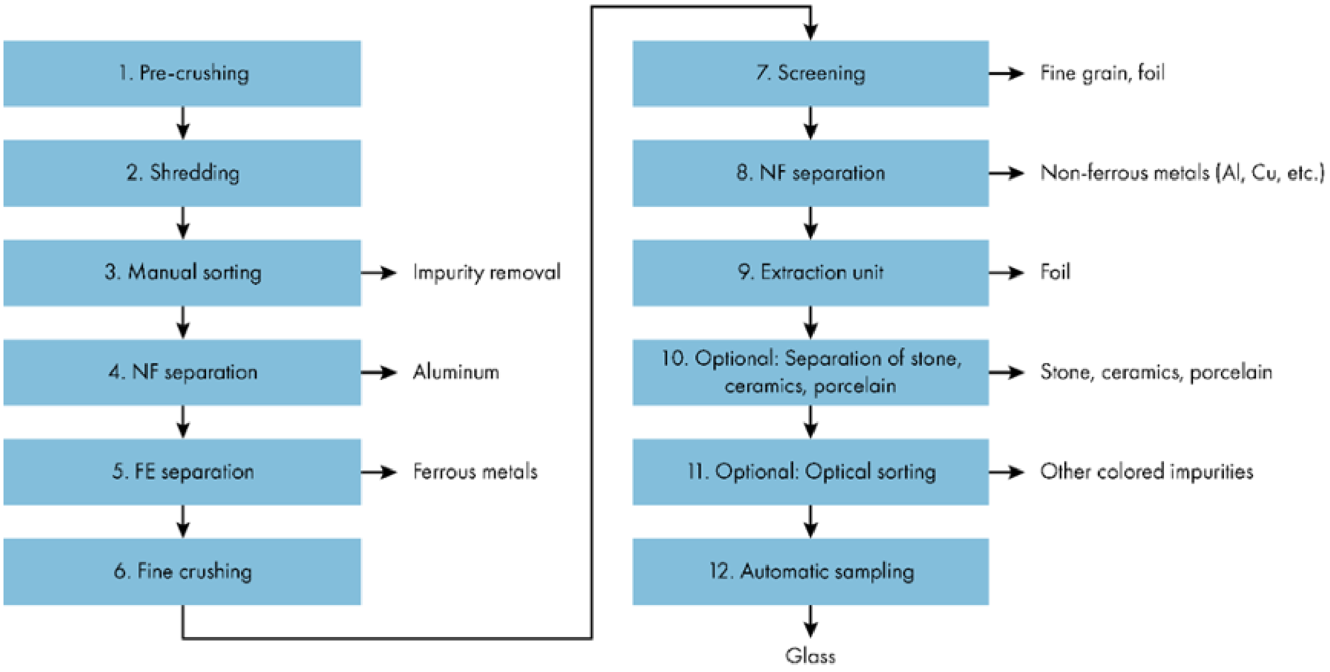

Figure 5. Reiling mechanical recycling process; all steps are included in the LCI data[10]

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[7] Silicon and "other non-ferrous metals" (i.e. silver, tin) are recovered via the recycling process, but they require further treatment to recover them in a purer form, and this treatment process is outside the scope of the study due to lack of data

[8] SPICE - Solar Panels In a Circular Economy - Grøn Projektbank

[9] IEA-PVPS-T12-28-2024-Report-PV-Recycling-LCI_EPRI.pdf

[10] Ibid

Reiling Glass Recycling, Germany

Reiling is a family-owned recycling company that began recycling photovoltaic (PV) modules around 2010, during the expansion of the solar industry in Germany (www.reiling.de). The company currently operates four glass recycling facilities - located in Marienfeld, Torgau, Osterweddingen, and Burgbernheim - which accept crystalline silicon (c-Si) PV modules. Reiling also offers logistics services to support the collection and transport of PV waste.

In response to growing demand, Reiling opened a dedicated PV module recycling plant in Münster in 2023, with a expanded capacity of 50,000 tonnes per year, compared to the existing plants' combined capacity of 10,000 tonnes per year.

The recycling technology employed is based on mechanical treatment methods originally developed for laminated glass from the construction and automotive sectors. Initially, PV modules were processed in discrete batches using available capacity at the glass recycling plants. As the volume of PV waste increased, Reiling invested in R&D projects to enhance the efficiency and yield of its mechanical treatment processes. These improvements have been implemented in the new Münster facility.

In 2022, Reiling recycled approximately 4,200 tonnes of PV modules. The Life Cycle Inventory (LCI) data presented in this study includes a simplified representation of the shredding and separation process, where aluminium frames are automatically extracted after crushing. Reiling has successfully increased the glass cullet yield by 6% compared to 2017, while maintaining moderate electricity consumption.

The Münster plant is powered by electricity from Reiling's own on-site PV installation, and modules are evaluated for second-life potential before being processed. The recycling workflow includes:

- Pre-crushing and shredding to remove aluminium frames.
- Separation of ferrous metals (e.g., screws) from the frames.
- Fine crushing to expose glass and polymer layers.
- Separation of non-ferrous metals (e.g., aluminium and copper from interconnectors).
- Extraction of polymer fractions from the glass.
- Optional treatments such as optical sorting and removal of stone, ceramics, and porcelain, commonly used in other glass recycling applications.
- A final quality check to ensure output consistency.

Despite these advancements, cross-contamination remains a challenge, and some output fractions are of low purity, occasionally resulting in downcycling. Reiling is certified under several standards, including:

- DIN ISO 9001:2015 (Quality Management)
- DIN ISO 50001 (Energy Management)
- Specialist Waste Management Company certification
- Declaration of Compliance with the Minimum Wage Act

Upon request, Reiling provides a certificate of destruction for processed modules. The company is recognized as one of the top two PV module recyclers in Germany, alongside First Solar, and focuses exclusively on crystalline silicon and amorphous silicon modules.

Recycling of silicon

Founded in 2017 in France, ROSI specialises in reclaiming high-purity silicon and other critical metals from PV modules through its innovative processes. It collaborates with France's PV take-back system, Soren, and the social enterprise Envie. ROSI can recover valuable materials that are typically lost during the end-of-life phases of photovoltaic (PV) systems.

ROSI's recycling plant near Grenoble opened in Spring 2023 uses a proprietary batch pyrolysis and metal recovery process, and the facility can treat both fully intact and partially dismantled PV modules without requiring pre-treatment. ROSI can help mitigate the environmental burden particularly the energy-intensive extraction and refinement of silicon and silver. By recovering these materials, ROSI contributes to lowering the overall carbon footprint of solar technology.

3.11. Electricity Mix Assumptions in Supply Chain Modelling

In this study, the environmental impacts associated with the manufacturing of PV components were modelled using the Sphera Managed LCA Content database, which includes region-specific electricity grid mixes. The type of electricity used in the supply chain reflects the average national grid mix of the country where each production stage occurs.

This approach allows for a realistic and geographically accurate representation of the energy used in the supply chain, which is essential for understanding the true environmental footprint of the PV system.

The PV modules, which were manufactured in China including upstream processes such as silicon purification, ingot casting, wafer slicing, and cell processing., were modelled using the average Chinese electricity mix. This mix is primarily based on coal-fired power, with additional contributions from hydropower, wind, solar, and nuclear energy. The electricity data used corresponds to the most recent available year in the Sphera Managed LCA Content database, which is 2021.

For processes occurring in Europe such as assembly, or production of certain BOS components the country specific or European medium-voltage grid mix (ENTSO-E) were used.

3.12. Cut-off criteria for initial inclusion of inputs and outputs

The LCA covers approximately 99% of the total mass of the Ingerslev Å solar park. A small fraction of materials - primarily minor components such as fasteners, bolts, washers, and other small hardware - were cut-off and excluded due to a lack of specific material data and very low environmental impact. These components are assumed to have a negligible impact on the overall environmental results.

No scaling to 100% was applied, in line with standard LCA practice when the excluded materials fall below a 1% mass or impact threshold and are unlikely to significantly influence the results.

4. Life cycle inventory analysis

The Life Cycle Inventory (LCI) phase of the LCA involves the systematic collection and quantification of all relevant material and energy inputs, emissions, and product outputs associated with each stage of the solar park's life cycle. This includes everything from raw material extraction and component manufacturing to construction, operation, maintenance, and end-of-life treatment.

For Ingerslev Å, the LCI was developed using a conventional process-based LCA approach, as defined by the Society of Environmental Toxicology and Chemistry (SETAC) and standardized under ISO 14040/44. All modelling was conducted using the LCA software called LCA For Experts from Sphera, which enables detailed tracking of environmental flows and impact categories.

4.1. Life Cycle Inventory (LCI) Datasets and the Hidden Structure of LCA Tools

In Life Cycle Assessment (LCA), materials, such as steel, are represented by detailed datasets stored in specialised LCA databases like ecoinvent, Sphera Managed LCA Content, or ELCD. These datasets are known as Life Cycle Inventory (LCI) datasets, and they form the backbone of any LCA model. While users of LCA software often interact with high-level components (e.g., "1 kg of hot-rolled steel"), each of these components is underpinned by a complex, pre-aggregated chain of environmental data.

What are LCI datasets?

LCI datasets typically cover the cradle-to-gate phase of a product's life cycle. This means they include all environmental inputs and outputs from the extraction of raw materials (the "cradle") up to the point where the product leaves the manufacturing facility (the "gate").

Example: Steel Production Dataset

For steel, this includes:

- Mining and processing of iron ore and other raw materials
- Production of coke, sintering, and blast furnace operations
- Basic oxygen furnace steelmaking
- Rolling, casting, and finishing processes
- Energy use (electricity, natural gas, coal)
- Water consumption and emissions to air, water, and soil
- Waste generation and by-products (e.g., slag)

A typical LCI dataset for 1 kg of hot-rolled steel might include:

Inputs:	**Outputs:**
1.4 kg of iron ore	**1 kg of hot-rolled steel (product)**
0.6 kg of coal (coke)	**1.8 kg of CO_2 emissions**
0.1 m^3 of water	**0.02 kg of SO_2 emissions**
5 MJ of electricity	**0.1 kg of slag (by-product)**
15 MJ of thermal energy	**0.05 kg of solid waste**

These values are aggregated averages based on industrial data from multiple facilities and regions. They represent the environmental profile of producing steel and are used in LCA models to calculate the total impact of products that include steel as a component.

Upstream Impacts: Iron Ore as an Input to Steel

Importantly, each input in the steel dataset - such as iron ore - also has its own cradle-to-gate dataset. This means that the environmental impacts of mining and processing iron ore are embedded within the steel dataset. The iron ore dataset includes:

Inputs:

- Diesel and electricity for mining
- Water for dust suppression and ore processing
- Explosives and beneficiation chemicals

Outputs:

- Iron ore concentrate (product)
- Emissions to air (CO_2, NO_x, particulate matter)
- Waste rock and tailings
- Waterborne pollutants and solid waste

These upstream impacts are automatically included when steel is selected in an LCA model, due to the tiered structure of LCI databases. This structure ensures that the full environmental burden - from raw material extraction to finished product - is captured without requiring the user to manually model each step.

Why This Matters?

This hidden structure is what makes LCA tools both powerful and complex. It allows practitioners to model the environmental impacts of entire systems - such as a solar park - without collecting primary data for every material. It also ensures consistency, transparency, and traceability, as each dataset is built on standardised, peer-reviewed data.

For example, choosing steel made from recycled scrap instead of virgin iron ore would automatically reduce the upstream impacts in the model, and this change would be reflected in the LCA results. This makes LCA a valuable tool for material selection, design optimisation, and sustainability decision-making.

4.2. Foreground and Background Systems

The models consist of foreground and background processes. Foreground processes are processes that BeGreen can directly influence or control, such as procurement choices, construction methods, and maintenance practices. Data for these processes was collected as primary data, including supplier-specific information, on-site measurements and internal project documentation.

Background processes include upstream and downstream activities that are outside BeGreen's direct control, such as the production of raw materials, energy generation, and global supply chain processes. These were modelled using secondary data from reputable LCI databases, including Sphera Managed LCA Content, ecoinvent and IEA-PVPS.

4.3. Data Quality and Sources

Primary data was collected from manufacturers, construction partners, and internal records specific to Ingerslev Å which was relevant for 2024. The primary data is representative, consistent and allows for reproducibility of the LCA. Secondary data was sourced from the latest versions of LCI databases and peer-reviewed literature to ensure consistency and reliability.

Some of the main data sources from manufacturers or suppliers included:

PV modules	Trina
Mounting structure	ArcelorMittal
Inverters	Sungrow
Cabling	Nexans, TFKable, NKT
MV transformers	Sungrow
HV transformers	Siemens (Tamini used as proxy data)
MV Switchgear	ABB
MV switchgear house	Holtab
Transformer foundations	Bravida

4.3.1. Cut-off criteria

Specific cut-off criteria are applied to ensure that all material and energy flows with potential environmental significance are appropriately considered. These criteria help streamline the assessment while maintaining its integrity.

First, any material flow contributing less than 0.1% of the total mass at the product level may be excluded, provided it does not pose notable environmental concerns. Similarly, energy flows contributing less than 1% of the total energy input may also be excluded under the same condition. However, if a flow - despite meeting these thresholds - is deemed to have potential environmental relevance, it is included to avoid underestimating impacts.

Additionally, all emissions leaving the system boundary are evaluated for their contribution to environmental impact categories. If any emission accounts for more than 1% of the total impact within a given category, it must be included in the LCA.

This approach ensures that the assessment captures significant contributors to environmental burdens, such as greenhouse gas emissions, resource depletion, or toxicity, while allowing for the exclusion of negligible flows that do not materially affect the overall results. These criteria are essential for balancing comprehensiveness with practicality in large-scale systems like solar utility parks.

4.3.2. IEA PVPS Life Cycle Inventory Database

The Life Cycle Assessment (LCA) model for the photovoltaic (PV) modules used in Ingerslev Å was built using high-quality, internationally recognised data from the IEA PVPS (Photovoltaic Power Systems Programme) Task 12. This database is one of the most robust and transparent sources of life cycle inventory (LCI) data available for PV technologies.

The PVPS LCI database represents the latest consensus among global PV LCA experts from North America, Europe, Asia, and Australia. It is the result of extensive collaboration and data collection efforts across the PV industry and research institutions. The database includes:

- Detailed process-level data for the full PV module production chain - from quartz extraction to final module assembly
- Real-world data collected from operational manufacturing facilities and PV system installations
- Geographically specific information, including country-level electricity mixes and PV installation types (e.g., rooftop vs. ground-mounted systems)
- Coverage of multiple PV technologies, including monocrystalline silicon (c-Si)

For the monocrystalline silicon (mono-c-Si) modules used in Ingerslev Å, the LCI data reflects the status of the industry as of 2020, with some upstream manufacturing data (e.g., polysilicon production) dating back to 2011. While not the most recent, this dataset remains one of the most comprehensive and peer-reviewed sources available for public use.

The Swiss partners of the PVPS Task 12 initiative committed to integrating this LCI data into public LCA databases, such as ecoinvent and Sphera Managed LCA Content, ensuring broad accessibility and consistency. In this study, the PVPS data was implemented directly in LCA for Experts, enabling detailed modelling of the PV module life cycle with high transparency and traceability.

Access to high-quality LCI data is often the biggest barrier to conducting accurate LCAs. The PVPS database overcomes this by providing standardized, peer-reviewed datasets, with international comparability and compatibility with ISO 14040/44 standards.

PV unit process

The system model for the photovoltaic (PV) module production in the Ingerslev Å LCA was developed using LCA for Experts software, following a process-based, cradle-to-grave approach. The model represents the full manufacturing chain of monocrystalline silicon (mono-c-Si) PV modules, based on data from the IEA PVPS (Photovoltaic Power Systems Programme).[11] and the latest datasets from Sphera Managed LCA Content and supplemented with ecoinvent for minor inputs.

Production Chain

The PV production system was structured into the following sequential stages, based on PVPS, representing the transformation of raw quartz into a finished PV module (Figure 6).

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[11] Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems - IEA-PVPS

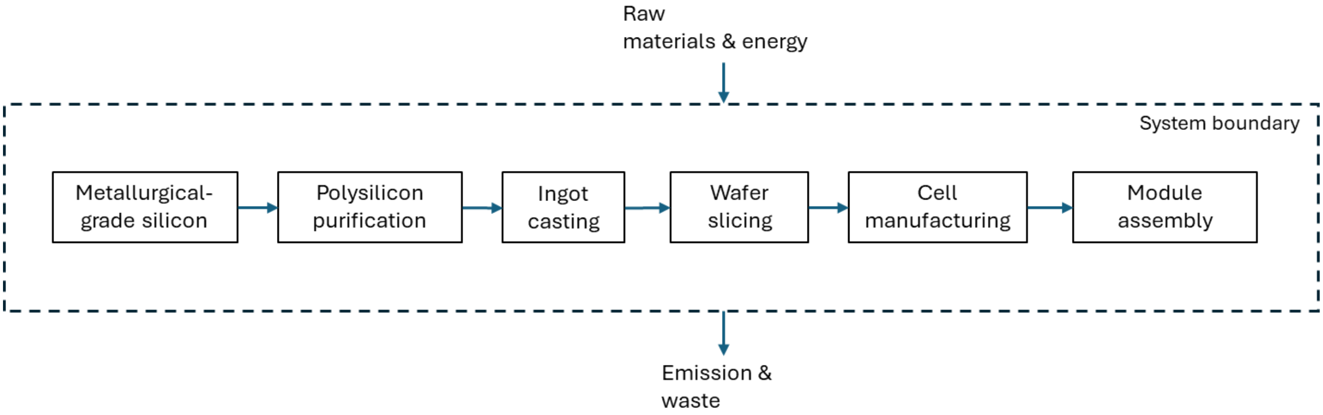

Figure 6. Production chain for solar PV module based on IEA-PVPS

Each stage includes material and energy inputs, emissions, and waste outputs, modelled with regional specificity where possible. The datasets used for each process step are presented in Appendix C.

Aligning with Trina PV Module EPD Data

To improve the accuracy and specificity of the LCA model for Ingerslev Å, the generic PVPS life cycle inventory (LCI) data was updated with product-specific Bill of Materials (BOM) data from the environmental Product Declaration (EPD) published by Trina Solar, the actual supplier of the PV modules used in the project. Only the material type and quantity were taken from the EPD, and the environmental impact results were calculated in BeGreen's own PV module model in the LCA software.

An EPD is a standardised, third-party verified document that provides transparent information about the product and materials and environmental performance of a product throughout its life cycle. It includes detailed data on:

- Material composition (BOM)
- Manufacturing processes
- Energy and resource use
- Emissions and waste
- End-of-life assumptions

The Trina EPD provides exact material breakdowns (e.g., grams of glass, aluminium, silicon, EVA, etc.), which improves the precision of the inventory model. EPDs are based on primary data from the manufacturer and are verified by independent third parties, ensuring credibility. Since Trina Solar was the actual supplier, using their EPD ensures that the LCA reflects the real environmental profile of the modules used - not just a generic estimate. The transportation and assembly of the PV module is taken from the PVPS data not the EPD. Supplementing generic data with EPDs enhances the traceability and auditability of the LCA, which is especially valuable for ESG reporting and stakeholder communication.

The BOM for the PV module from Trina consisted of the following materials and quantities (Table 8):

Table 8: Materials, weights and LCI datasets for the Trina PV modules (NEG19RC.20) installed in Ingerslev Å

Materials	Main substance	Percentage (%)	Weight (kg)	LCI dataset applied	Data type	Source
Solar cells	Silicon	2.5	0.84	Sourced from LCI model (includes numerous additional materials)	Primary, background	Trina EPD
EVA (ethylene vinyl acetate)	$(C_2H_4)x(C_4H_6O_2)y$	3.9	1.3	RoW: ethylvinylacetate production, foil (ecoinvent)		
POE (Polyolefin Elastomer)	$(CH_2CHR)n$	3.6	1.2	RER: Polypropylene film (PP)		
Ribbon	Sn	0.5	0.17	RoW: Tin production (ecoinvent)		
Busbar	Cu	0.2	0.07	GLO: Copper mix (99.999% from electrolysis)		
Frame	$AlMg_3$	7.6	2.6	CN: Aluminium extrusion profile		
Solar glass	$Na_2O.nSiO_2$	80.5	27	RER: Float flat glass.[12]; RoW: tempering, flat glass		
Junction box	Polyamide	0.3	0.1	RoW: Glass fibre reinforced plastic production		
Silicone product	SiO_2	0.9	0.3	RER: Silicone sealing compound (EN15804 A1-A3)		
TOTAL		**1**	**33.7**			

PV module cell production was modelled as occurring in China, using the PVPS datasets for process inputs and outputs and which are developed based on Chinese factories, reflecting the actual production and sourcing of modules for Ingerslev Å. The Chinese grid mix was used for all energy-intensive processes, including ingot, wafer, and cell production. This mix is typically coal-dominated, which significantly influences the environmental impact of the modules.

Solar-grade silicon was modelled as virgin metallurgical silicon before being processed into polysilicon, with energy-intensive purification and crystallisation processes included.

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[12] A European dataset is applied for glass however the environmental impacts are similar to Chinese impacts CO2 emission from container glass in China, and emission reduction strategy analysis

Glass is assumed to be virgin float glass produced in China, however a European dataset from Sphera Managed LCA Content was applied due to lack of data. The environmental impact of this dataset is similar in scale to the impact of float glass produced in China[13]. Glass accounts for a significant share of the module mass and energy use which causes the environmental impacts. In addition, the glass is tempered, and a tempering process was also included in the model.

For the module frame aluminium was modelled as virgin aluminium produced in China and moulded into an aluminium profile. A Chinese dataset was applied in the model. No secondary (recycled) aluminium was assumed due to lack of supplier-specific data which means the environmental impact of the aluminium is conservatively high.

EVA (ethylene-vinyl acetate) and other polymers were modelled using generic polymer datasets from Sphera Managed LCA Content.

No co-product allocation was required, as the PV module production chain does not generate significant co-products.

Transport of intermediate products (e.g., wafers to cell factories) was included using average distances and modes based on industry data from PVPS.

4.3.3. Balance of system (BOS) unit processes

The data used to model BOS components in the LCA was sourced from a combination of manufacturer-specific documentation, construction records, and reputable LCI databases.

The quantities of the materials within the mounting structure, cabling, MV and HV transformers, were obtained from construction documentation, engineering specifications, and technical datasheets provided by suppliers. This includes detailed information on:

- Cable lengths and cross-sectional areas
- Transformer capacities and material breakdowns
- Structural steel quantities
- Protective fencing dimensions and materials

Primary data was used where available (e.g., supplier specifications for inverters and mounting systems) and some estimates were used based on previous solar parks. Secondary data from the Sphera Managed LCA Content and ecoinvent databases was used for generic components.

The electricity mix for each component's production was modelled based on the assumed country of manufacture.

Transport to site was included using average distances and modes (e.g., sea freight from China, road transport within Europe).

To model the environmental impacts of these components, the Sphera Managed LCA Content database was used. Where possible, region-specific datasets were applied (e.g., European steel, Chinese electronics) to reflect the actual supply chain of the project.

The solar park includes 168 inverters supplied by Sungrow (model: SG350HX). To ensure accurate environmental modelling, the environmental impacts from the Environmental Product Declaration (EPD) published by Sungrow were used, from cradle to gate. This EPD provides verified, product-specific life cycle inventory (LCI) data, including material composition, manufacturing energy use, and end-of-life assumptions. The life cycle environmental impact results for manufacturing the inverters (A1-A3) were taken from the EPD as opposed to the material types and quantities which

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[13] Investigation on CO_2 emissions from flat glass production in China https://doi.org/10.13671/j.hjkxxb.2017.0055

was done for the PV modules from Trina. Using the EPD results ensures that the LCA reflects the actual environmental profile of the inverters installed at the site.

Table 9: Materials, weights and LCI datasets for the Sungrow inverters (SG350HX) installed in Ingerslev Å

Materials	Percentage (%)	Weight (kg)	LCI dataset applied	Data type	Source
Aluminium and its alloys	42	52	EPD results were applied	Primary, background	Sungrow EPD
Stainless steel	5.2	0.26			
Other ferrous alloys, non-stainless steels	12	15			
Copper and its alloys	15.9	0.79			
Plastic components (Polypropylene + Polycarbonate + Polyamide)	23.7	1.2			
Other non-ferrous metals and alloys	0.5	0.004			
Other organic materials	0.7	0.006			
TOTAL	**1**	**124.5**			

Table 10. Materials, weights and LCI datasets for the mounting structure installed in Ingerslev Å

Materials	Weight (kg)	LCI dataset applied	Data type	Source
Galvanised steel (Magnelis coating)	1,838,562	RER: Steel hot dip galvanised (Worldsteel)	Secondary, background	Calculated from dimensions and densities

Table 11. Materials, weights and LCI datasets for the cabling installed in Ingerslev Å

Materials	Weight (kg)	LCI dataset applied	Data type	Source
Aluminium	12,203	RER: Aluminium ingot mix - production mix; RoW: wire drawing, copper	Secondary, background	Calculated from dimensions and densities
Copper	16,715	GLO: Copper mix (99,999% from electrolysis); RoW: wire drawing, copper		
XLPE (Cross-linked polyethylene)	67,289	DE: Polyethylene Cross-Linked (PEXa)		
HDPE (High-Density Polyethylene)	3,406	RER: Polyethylene pipe (PE-HD)		
Packaging (wooden drum)	20,760	DE: Timber pine		Extrapolated from similar PV park
TOTAL	**207,634**			

Table 12: Materials, weights and LCI datasets for the MV transformers installed in Ingerslev Å

Materials	Weight (kg)	LCI dataset applied	Data type	Source
Silicon steel	8,856	RER: steel production, 3.2% silicon alloy, for grain oriented electrical steel (ecoinvent)	Secondary, background	Proportion supplied by Sungrow
Steel	7,104	RER: Steel cold rolled coil (worldsteel)		
Aluminium	3,240	CN: Aluminium extrusion profile		
Mineral oil	4,800	RER: Light fuel oil at refinery		
Concrete foundation	19,151	RER: Concrete C20/25 (Ready-mix concrete) (EN15804 A1-A3)	Secondary, foreground	Calculated from dimensions and densities
TOTAL	**43,151**			

The solar park includes four MV switchgears (Medium Voltage air-insulated switchgear UniGear ZS2) and data from an EPD was used. The life cycle environmental impact results were taken from the EPD as opposed to the material types and quantities which was done for the PV modules from Trina. Using the EPD results ensures that the LCA reflects the actual environmental profile of the MV switchgear installed at the site, and ensures highest level data quality for temporal, geographical and completeness.

Table 13. Materials, weights and LCI datasets for MV switchgear installed in Ingerslev Å

Materials		**Percentage (%)**	**Weight (kg)**	**LCI dataset applied**	**Data type**	**Source**
Plastics and rubbers	Aluminium	2.04	36	ABB UniGear ZS2 EPD results applied	Primary background	ABB UniGear ZS2 EPD
	AluZinc	41	627			
	Brass	0.046	10			
	Copper	11	166			
	Other materials	0.067	1,02			
	Steel	23	347			
	Stainless steel	0.25	3,75			
	ABS	0.001	0,015			
	Polyamide and glass filled polyamide	0.42	6,3			
Metal	Polycarbonate	0.067	15			
	Polyester	00.23	3,4			
	Polyethylene	0.22	3,4			
	Polymers	0.059	13			
	Polypropylene	0.007	0,11			
	Polyvinylchloride	0.001	0,015			
	Other plastics and rubbers	0.068	15			
Others	Cables	0.012	0,18			
	Ceramics	0.02	3			
	Epoxy resin	18	271			
	Others	0.29	4,4			
Total		**1**	**1526**			

The MV switchgear is housed in a building at the site of the HV transformer substation. This building is supplied by Holtab. Material types and quantities were unavailable therefore the data was extrapolated from an LCA study of a similar sized solar park. The environmental impact on the study from this building is minimal at less than 1%.

Table 14: Materials, weights and LCI datasets for the MV switchgear building installed in Ingerslev Å

Materials	Weight (kg)	LCI dataset applied	Data type	Source
Steel	2,948	RER: Steel cold rolled coil (worldsteel)	Secondary, background	Extrapolated from similar size PV park
Wood	79	RER: Solid construction timber (softwood) (EN15804 A1-A3) (15% moisture; 13% H2O content)		
Insulation (mineral wool)	118	RER: Mineral wool (Facades) (EN15804 A1-A3)		
Zinc	354	RER: Special high grade zinc only from Zn concentrate (IZA)		
Concrete foundation	951	RER: Concrete C20/25 (Ready-mix concrete) (EN15804 A1-A3)		
TOTAL	**4,449**			

The HV transformer did not have material data available therefore data was extrapolated from the EPD of a similar sized HV transformer. The proxy transformer is built by Tamini and is 63MVA. The HV transformer at Ingerslev is 88MVA therefore it would require larger copper windings, core steel and cooling system. Therefore, in this study all materials were replicated and scaled up proportionally from the Tamini EPD by the difference in capacity.

Table 15: Material components in HV transformer and switchgear installed in Ingerslev Å

Materials	Percentage (%)	Weight (kg)	LCI dataset applied	Data type	Source
Silicon steel	32%	63,459	RER: steel production, 3.2% silicon alloy, for grain oriented electrical steel (ecoinvent)	Secondary, background	Extrapolated from Tamini 63MVA transformer EPD material types and quantities
Mineral oil	28%	55,873	RER: Light fuel oil at refinery		
Steel	24%	48,156	RER: Steel cold rolled coil		
Copper	13%	25,590	GLO: Copper mix (99,999% from electrolysis)		
Cellulose	1.59%	3,189	RER: Wood chips pine (10% water content) (Baltic silviculture)		
Wood	0.70%	1,402	RER: Solid construction timber (softwood) (EN15804 A1-A3) (15% moisture; 13% H2O content)		
Epoxy resin	0.29%	581	DE: Epoxy Resin (EP) Mix		
Aluminium	0.28%	555	CN: Aluminium extrusion profile		
Paper	0.42%	839	RoW: Corrugated board box production (ecoinvent)		
Polyester resin	0.16%	331	DE: Polyester Resin (unsaturated) (UP)		
Glue	0.12%	249	¨RoW: ethyl acetate production (ecoinvent)		
Iron alloy	0.10%	194	RER: Steel plate (Worldsteel)		
Fiberglass	0.12%	240	DE: Glass fibres		
Electric components	0.07%	147	GLO: Steel electrogalvanized (Worldsteel)		
Insulating foam	0.05%	96	RER: Polyethylene foam (EN15804 A1-A3)		
Silicone	0.03%	60	RER: Silicone sealing compound (EN15804 A1-A3)		
Rubber	0.05%	109	DE: Styrene-butadiene rubber (S-SBR) mix		
Plastic	0.02%	36	RER: Polypropylene, PP, granulate		
Concrete foundation		51,840	RER: Concrete C20/25 (Ready-mix concrete) (EN15804 A1-A3)		
TOTAL	**1**	**252,946**			

Table 16: Materials, weights and LCI datasets for the fencing installed in Ingerslev Å

Material	Quantity (kg)	LCI dataset applied	Data type	Source
Galvanised steel (Solar park)	40,094	RER: Steel hot dip galvanised (Worldsteel)	Secondary, foreground	Calculated from dimensions and densities
Galvanised steel (HV transformer substation)	900	RER: Steel hot dip galvanised (Worldsteel)	Secondary, foreground	Extrapolated from similar size solar park
TOTAL	**40,994**			

Table 17: Packaging materials, quantities and LCI datasets

Material	Quantity (kg)	LCI dataset applied	Data type	Source
Low density polyethylene	9,900	RER: packaging film production, low density polyethylene (ecoinvent)	Secondary, foreground	Calculated from dimensions and densities
Polyethylene terephthalate	8,000	DE: Polyethylene terephthalate granulate (PET via DMT)		
Paper	36,000	RoW: corrugated board box production (ecoinvent)		
Steel	5,900	RER: Steel hot dip galvanised (Worldsteel)		
Wood	129,000	RoW: EUR-flat pallet production (ecoinvent)		
TOTAL	**190,000**			

Table 18. BOS Components and Production Locations and Modelling Summary Notes

Component	Assumed Country of Production	Notes on Material and Modelling Assumptions
Mounting Structure	Germany	Modelled as galvanized steel. EU average steel mix.
Inverters	China	Includes housing, electronics, and cooling systems. Environmental impacts based on EPD data
Cabling	EU average	Copper/aluminium core with plastic insulation based on technical data sheets and measurements. Modelled using EU average production of materials. Assembly was excluded since the environmental impact is below the cut-off criteria of 1%. Verified with the PEP ecopassport for Nexans H1Z2Z2-K (DC solar cable).[14]
MV Transformers	China	Includes mostly steel, aluminium, and insulating oil and smaller materials. Modelled using mass data from supplier and generic EU datasets. Assembly was excluded since the environmental impact is below the cut-off criteria of 1%.
HV Transformers	China	Modelled based on similar HV transformer using EPD data. Assembly was excluded since the environmental impact sourced from the EPD is below the cut-off criteria of 1%.
MV Switchgear	China	Includes metals, plastics and other materials. Environmental impacts based on EPD data.
Fencing	EU average	Modelled as galvanized steel. EU average steel mix.

4.4. Modelling end-of-life allocation for recycling and incineration with energy recovery

4.4.1. End-of-Life Treatment of the Solar Park

At the conclusion of its 30-year operational lifespan, the Ingerslev Å solar park, with an estimated recyclability of 86%, is expected to undergo a structured decommissioning process that prioritises material recovery and responsible waste management. It is assumed that all components and materials are collected at end-of-life, but they are directed to different waste treatment pathways depending on their recyclability and material composition. It is expected that there will be energy consumed for vehicles to deconstruct the solar park however this is excluded due to lack of data and low environmental impact below the cut-off criteria since most deconstruction would be by manual labour.

Where possible, all recyclable components - including PV modules, steel mounting structures, cabling (aluminium, copper, and plastic insulation), inverters, and transformers - are sent to appropriate recycling facilities. These processes are modelled to produce secondary materials; however, credits for displacing virgin materials are excluded from the main LCA results and considered only in a scenario analysis in Section 5.1.1.

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[14] NXNS-00391-V01.01

Materials that cannot be recovered for recycling are sent to incineration with energy recovery or landfill, depending on their composition and treatment feasibility. The only components assumed to go directly to incineration without first passing through a recycling process are wooden materials, due to limited recovery options and lack of data. Concrete, which represents less than 3% of the total park mass, is assumed to be removed and landfilled, reflecting common practice in utility-scale solar decommissioning.

All other components are assumed to be disassembled and sorted, with a 99–100% capture rate. Recyclable fractions are processed accordingly, while non-recyclable residues from recycling facilities are diverted to incineration or landfill. For example:

- Aluminium and steel are recycled with high efficiency (80%), based on data from ecoinvent and Sphera Managed LCA Content.
- Cabling materials (aluminium and copper) are recovered and recycled, while plastic insulation is incinerated with energy recovery.
- Plastics embedded in PV modules, such as EVA and POE, are not recycled and are sent to incineration.
- Inverters and transformers are disassembled and recycled for their metal and electronic components, using data for inverters from the SunGrow EPD.
- PV modules are sent to specialised recycling facilities where glass and aluminium frames are recovered. Silicon and silver are not recovered in this study due to limited mainstream recycling capabilities, although technologies for their recovery do exist.

The cut-off allocation method is applied, assigning the environmental burdens of virgin material production to the Ingerslev Å system, while the benefits of recycled materials are allocated to future users. All recycling-related processes - such as energy used in shredding, smelting, and transportation - are included within the system boundaries. This approach aligns with ISO 14044 and is commonly used in attributional LCA studies, especially when the focus is on assessing the environmental impacts of the current system.

A transport distance of 1,000 km is assumed for recycling logistics, reflecting a conservative estimate for centralized treatment facilities.

The quantity of materials sent to each treatment approach is presented in Table 19. LCI datasets for materials and treatment methods are presented in Table 20.

Table 19. Material quantities recovered from different component and sent to different waste treatment pathways

	Treatment type of material in component		
Component/Material	Quantity sent to recycling (kg)	Quantity sent to incineration with energy recovery (kg)	Quantity sent to landfill (kg)
PV modules			
Aluminium	277,400		2,802
Copper	7,005		369
Glass	2,819,531		148,396
Plastics		160,379	160,379
Silicon	87,563		4,609
Other non-ferrous metals	17,513		922
Mounting structure & fencing			
Steel	1,934,839		19,544
Inverters			
Metals	18,418		2,046
Plastics	3,875	2,583	
Electronics	89	14	34
Others		191	
Cabling			
Aluminium	119,001		1,202
Copper	16,548		167
Plastics		34,994	35,701
Wood		20,761	
Transformers & switchgear			
Aluminium	21,515		1,132
Copper	24,942		1,313
Steel	201,322		10,596
Non-ferrous metals			399
Plastics		1,514	1,514
Concrete		166,748	
Others		90,381	
Packaging			
LD-PE	17,005		895
PET	5,605		295
Steel	34,200		1,800
Wood		129,000	
TOTAL	**5,606,371**	**606,564**	**394,114**

Table 20. LCI datasets for disposal methods for different materials and recycled form of metals

Material	Quantity sent to recycling	Quantity sent to incineration with energy recovery	Quantity sent to landfill
Aluminium	RER+EFTA+Turkey: Aluminium remelting: wrought alloys ingot from scrap (2021) Recycled form: RER: Aluminium ingot mix - production mix		CH: treatment of waste aluminium, sanitary landfill (ecoinvent)
Steel	Electric arc furnace steelmaking (Tiangong LCI Data Working Group) DE: Electricity grid mix (1061,9 MJ electricity/1000 kg steel coil) Recycled form: RAS: Steel plate (wordsteel)		RER: Ferro metals on landfill
Copper	Treatment of copper scrap by electrolytic refining (ecoinvent) Recycled form: GLO: Copper cathode, 99.99% Cu		RER: Ferro metals on landfill (used as proxy)
Glass	Recycled form: Glass cullet from Reiling process (no dataset applied since its outside the scope)		RER: Inert matter (Glass) on landfill
Plastics	N/A	RER: Municipal waste in waste incineration plant (32.2% H2O content)	RER: Plastic waste on landfill
Wood	N/A	RER: Municipal waste in waste incineration plant (32.2% H2O content)	N/A
Concrete	N/A	N/A	Europe without Switzerland: treatment of waste concrete, inert material landfill (ecoinvent)

Input and output data for PV Module recycling by Reiling is presented in Table 21.

Table 21. Data for recycling of PV modules by Reiling (outputs adapted to reflect Trina PV modules).[15]

	Material/emission	Quantity	Unit	Dataset applied
Inputs	Solar panel	1	kg	From LCA model
	Electricity	0.22	MJ	DE Electricity grid mix
	Diesel	0.095	MJ	GLO: Diesel, burned in building machine
	CNG/LNG	0.0013	MJ	DE: Thermal energy from natural gas
Outputs	Glass (external cullet)	0.81	Kg	Sent to recycler (not modelled)
	Aluminium scrap	0.076	kg	Sent to recycler (RNA: Secondary aluminium ingot (95% recycled content))
	EVA	0.039	Kg	Sent to incineration with heat recovery (RER: Municipal waste in waste incineration plant (32.2% H2O content))
	POE	0.036	Kg	Sent to incineration with heat recovery (RER: Municipal waste in waste incineration plant (32.2% H2O content))
	Silicon, silver(cells)	0.025	Kg	Sent to recycler (not modelled)
	Silicone product	0.009	Kg	Sent to incineration with heat recovery (RER: Municipal waste in waste incineration plant (32.2% H2O content))
	Ribbon (tin)	0.005	Kg	Sent to recycler (not modelled)
	Glass fibre reinforced plastic, polyamide	0.003	Kg	Sent to incineration with heat recovery (RER: Municipal waste in waste incineration plant (32.2% H2O content))
	Copper (busbar)	0.002	kg	Sent to recycler (not modelled)
	Mixture of glass cullet, foil and metals	0.07	Kg	Sent to landfill (RER: Inert matter (Glass) on landfill)
	Dust	0.006	kg	Sent to landfill (RER: Inert matter (Glass) on landfill)

4.5. Modelling water use

Water use is an important environmental aspect considered in the life cycle assessment (LCA) of Ingerslev Å. In this study, water consumption and emissions to water were modelled using high-quality, process-level data from Sphera Managed LCA Content, ecoinvent, and IEA PVPS databases. These databases provide detailed inventories of water use across all life cycle stages,

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[15] IEA-PVPS-T12-28-2024-Report-PV-Recycling-LCI_EPRI.pdf

including raw material extraction, component manufacturing, construction, operation, and end-of-life treatment.

4.5.1. Integration into Life Cycle Inventory (LCI)

Water use is embedded in the LCI datasets for all major components and processes, including PV module production (e.g., water used in silicon purification and wafer cleaning), manufacturing of BOS components (e.g., cooling and cleaning in metal processing), electricity generation in the supply chain (e.g., water used in thermal power plants), transport and construction activities and recycling and waste treatment processes.

These flows include both blue water consumption (e.g., freshwater withdrawals for industrial use) and emissions to water (e.g., wastewater discharges), ensuring a comprehensive representation of water-related impacts.

Impact Assessment Method

The environmental impacts associated with water use were assessed using the Environmental Footprint 3.1 (EF 3.1) method, developed by the European Commission. This method includes a dedicated impact category for “Water use” in m^3 world equivalent, which accounts for quantity of water consumed (withdrawal minus consumption), and regional water scarcity factors.

Using this method ensures that water use is evaluated in a regionally sensitive and scientifically robust manner, consistent with EU guidelines for product environmental footprinting.

5. Life cycle impact assessment (LCIA)

This LCA study assesses the environmental performance of the solar park using a specific set of the Environmental Footprint 3.1 (EF3.1) impact categories developed by the European Commission. These categories are recognised for their methodological rigor and are compatible with international standards such as the Environmental Product Declaration (EPD) framework (EN 15804+A2), and ISO 14040/44.

These categories cover a wide range of environmental concerns, from climate change and air pollution to resource depletion and water consumption. Their inclusion ensures that the LCA captures the most significant and policy-relevant environmental impacts, supporting transparent and credible environmental product declarations.

The EF3.1 categories that have been included are listed below and they are core impact categories applied for an Environmental Product Declaration (EPD) under EN 15804+A2.

1. Climate change
2. Acidification
3. Eutrophication (terrestrial)
4. Eutrophication (freshwater)
5. Eutrophication (marine)
6. Ozone depletion
7. Photochemical ozone formation
8. Resource use – fossils
9. Resource use –metals
10. Water use

The 10 core environmental impact categories represent well-established environmental mechanisms with high relevance across sectors. They are selected based on their relevance to a wide range of product systems and their ability to capture significant environmental burdens across the life cycle.

They are scientifically robust being based on mature models with high consensus in the LCA community. They align with policy being directly linked to EU environmental goals (e.g., climate neutrality, biodiversity protection). They are focused on comparability by enabling consistent benchmarking across products and sectors. Lastly, they are comprehensive by covering key environmental pressures including emissions, resource extraction, and water consumption.

EF3.1 distinguishes climate change impacts into four subcategories which are also included in this report to improve granularity and traceability. This disaggregation supports more accurate attribution of climate impacts, particularly relevant for systems involving biomass, land use, or renewable energy.

1. Climate change – Fossil: Emissions from fossil carbon sources (kg CO_2 eq)
2. Climate change – Biogenic: Emissions and removals from biogenic carbon flows (kg CO_2 eq)
3. Climate change – Land use and land use change: Emissions due to land transformation (kg CO_2 eq)
4. Climate change – Total: Aggregated climate change impact (kg CO_2 eq), summing the above three

Six EF3.1 indicators have been excluded since they are considered less critical and optional in the context of EPDs for several reasons and therefore not included in the results of this report, they include:

1. Human toxicity (cancer)
2. Human toxicity (non-cancer)
3. Ecotoxicity – freshwater
4. Ionising radiation

5. Particulate matter
6. Land use

They are optional because they have:

- Lower relevance for many product types, for example, ionising radiation is primarily relevant for nuclear-related systems
- Higher uncertainty, for example toxicity and land use models involve complex fate and exposure pathways, leading to greater variability and lower consensus.
- Limited policy integration, for instance these impacts are not yet consistently regulated or benchmarked in product-level environmental policy.
- Data intensity, for instance accurate modelling requires detailed inventory data that may not be available or reliable for all systems.

While these optional categories can provide valuable insights - especially in hotspot analyses or sector-specific studies - they are not required for EPD compliance and are typically excluded unless they are known to be significant for the product system under study. Therefore, they are excluded from this study as well.

What are midpoint indicators?

The impact categories applied in this study are midpoint indicators, which quantify potential environmental impacts at an intermediate stage in the cause-effect chain between emissions or resource use and their final damage to human health, ecosystems, or resource availability. This approach enhances scientific robustness and comparability by focusing on well-established environmental mechanisms rather than speculative endpoint modelling.

Midpoint indicators quantify the potential for environmental impacts before it fully manifests. For example: Climate change (midpoint) is measured in terms of greenhouse gas emissions (e.g., CO_2 equivalents), which are known to contribute to global warming, but the actual damage (e.g., sea level rise, biodiversity loss) occurs further down the line. Acidification potential reflects the release of acidifying substances like SO_2 and NO_x, which may later cause forest degradation or aquatic damage.

Using midpoint categories allows for more scientific certainty and comparability, as they are based on well-established environmental mechanisms and are less speculative than endpoint models. By applying EF3.1 midpoint categories, this LCA delivers a transparent and technically sound evaluation of the solar park’s life cycle impacts, with clear traceability and alignment to European policy frameworks.

5.1. Data Sources and Integration

All impact categories were calculated using life cycle inventory data from Sphera Managed LCA Content, ecoinvent and IEA PVPS Task 12.

These databases provide region-specific, process-level data that feed into the impact assessment methods, ensuring that the impact results are both geographically accurate and methodologically consistent.

Table 22. Summary of results per functional unit (1 kWh) and gross life cycle impact over 30 years

Impact category	Unit	Total for functional unit of 1 kWh	Gross life cycle impact over 30 years
Climate Change - total	kg CO_2 eq.	0.026	49,736,554
Climate Change, fossil	kg CO_2 eq.	0.024	46,727,658
Climate Change, biogenic	kg CO_2 eq.	0.0015	2,906,431
Climate Change, land use and land use change	kg CO_2 eq.	0.000055	103,936
Ozone depletion	kg CFC-11 eq.	0.00000000051	0.99
Acidification	Mole of H+ eq.	0.00011	211,749
Eutrophication, freshwater	kg P eq.	0.0000021	4,134
Eutrophication, marine	kg N eq.	0.000027	52,312
Eutrophication, terrestrial	Mole of N eq.	0.00028	535,923
Photochemical ozone formation, human health	kg NMVOC eq.	0.000078	151,091
Resource use, mineral and metals	kg Sb eq.	0.00000095	1,829
Resource use, fossils	MJ	0.29	558,767,730
Water use[16]	m^3 world equiv.	0.0076	13,446,346

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[16] Use of net fresh water is 393,281 m^3 total or 0,0002 m^3 per kWh which is in line with other studies however this volume is converted into an impact of world equivalent based on the scarcity of water in the region it is consumed

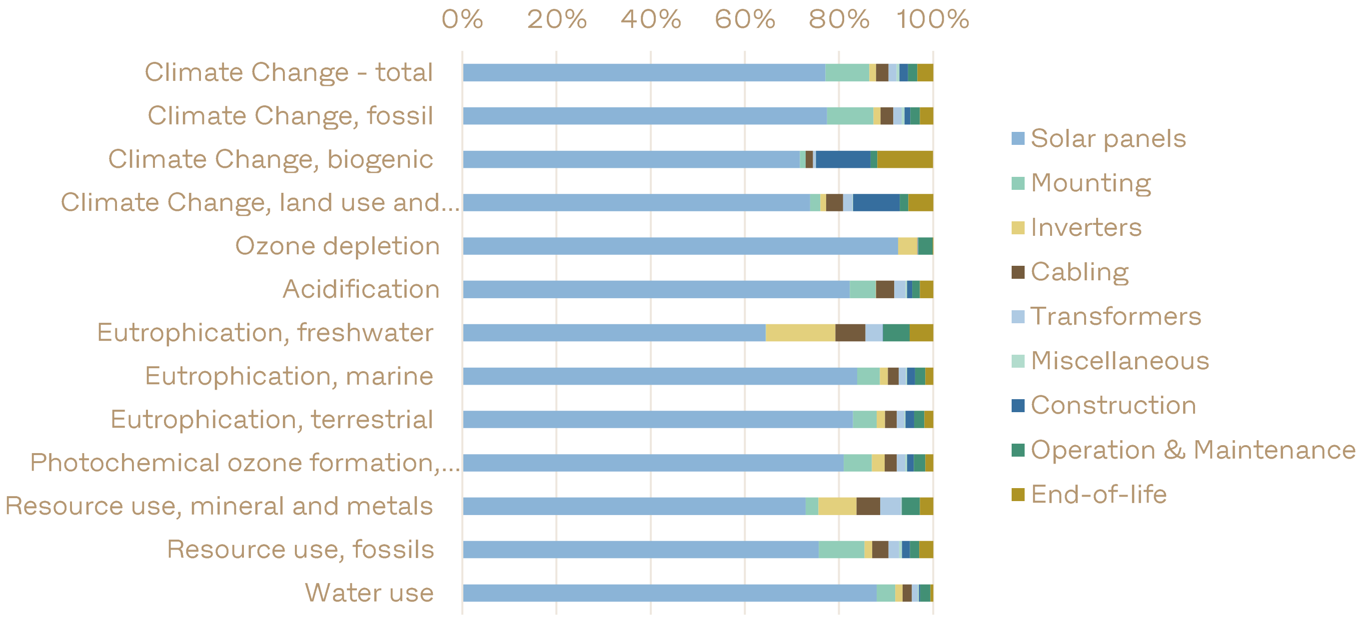

Figure 7. Distribution of impact between components and life cycle stage for Ingerslev Å 65MWp

Table 23. Summary of results for each component and life cycle stage for Ingerslev Å 65MWp

Impact category	Solar panels	Mounting	Inverters	Cabling	Transformers	Miscellaneous	Construction	O&M	EoL
Climate Change - total kg CO_2 eq.	1.99E-02	2.40E-03	3.69E-04	6.80E-04	4.39E-04	1.51E-04	4.51E-04	5.03E-04	8,7E-04
Climate Change, fossil kg CO_2 eq.	1.87E-02	2.38E-03	3.69E-04	6.56E-04	4.29E-04	1.50E-04	2.73E-04	4.81E-04	6,9E-04
Climate Change, biogenic kg CO_2 eq.	1.08E-03	1.92E-05	-4.66E-07	2.27E-05	8.70E-06	1.20E-06	1.74E-04	2.12E-05	1,8E-04
Climate Change, land use and land use change kg CO_2 eq.	4.07E-05	1.17E-06	6.81E-07	1.99E-06	1.09E-06	7.39E-08	4.20E-06	1.01E-06	2,9E-06
Ozone depletion kg CFC-11 eq.	4.75E-10	3.27E-16	2.08E-11	3.88E-13	6.92E-13	2.01E-17	4.28E-15	1.56E-11	6,6E-13
Acidification Mole of H+ eq.	9.03E-05	6.06E-06	6.81E-09	4.28E-06	2.58E-06	3.81E-07	1.07E-06	1.79E-06	3,1E-06
Eutrophication, freshwater kg P eq.	1.38E-06	1.26E-09	3.15E-07	1.37E-07	7.75E-08	7.94E-11	1.16E-09	1.21E-07	1,1E-07
Eutrophication, marine kg N eq.	2.27E-05	1.30E-06	4.59E-07	6.22E-07	4.05E-07	8.21E-08	4.17E-07	5.88E-07	4,6E-07
Eutrophication, terrestrial Mole of N eq.	2.30E-04	1.41E-05	4.79E-06	6.96E-06	4.28E-06	8.86E-07	4.73E-06	6.00E-06	5,2E-06
Photochemical ozone formation, human health kg NMVOC eq.	6.34E-05	4.68E-06	2.13E-06	2.03E-06	1.39E-06	2.95E-07	1.06E-06	1.89E-06	1,3E-06
Resource use, mineral and metals kg Sb eq.	6.92E-07	2.64E-08	7.68E-08	4.72E-08	4.22E-08	1.66E-09	7.79E-11	3.65E-08	2,7E-08
Resource use, fossils MJ	2.20E-01	2.83E-02	4.70E-03	1.01E-02	6.41E-03	1.78E-03	3.50E-03	5.76E-03	8,5E-03
Water use[17] m^3 world equiv.	6.69E-03	2.96E-04	1.19E-04	1.51E-04	9.67E-05	1.87E-05	1.83E-05	1.68E-04	4,4E-05

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[17] Use of net fresh water is 393,281 m^3 total or 0,0002 m^3 per kWh which is in line with other studies however this volume is converted into an impact of world equivalent based on the scarcity of water in the region it is consumed

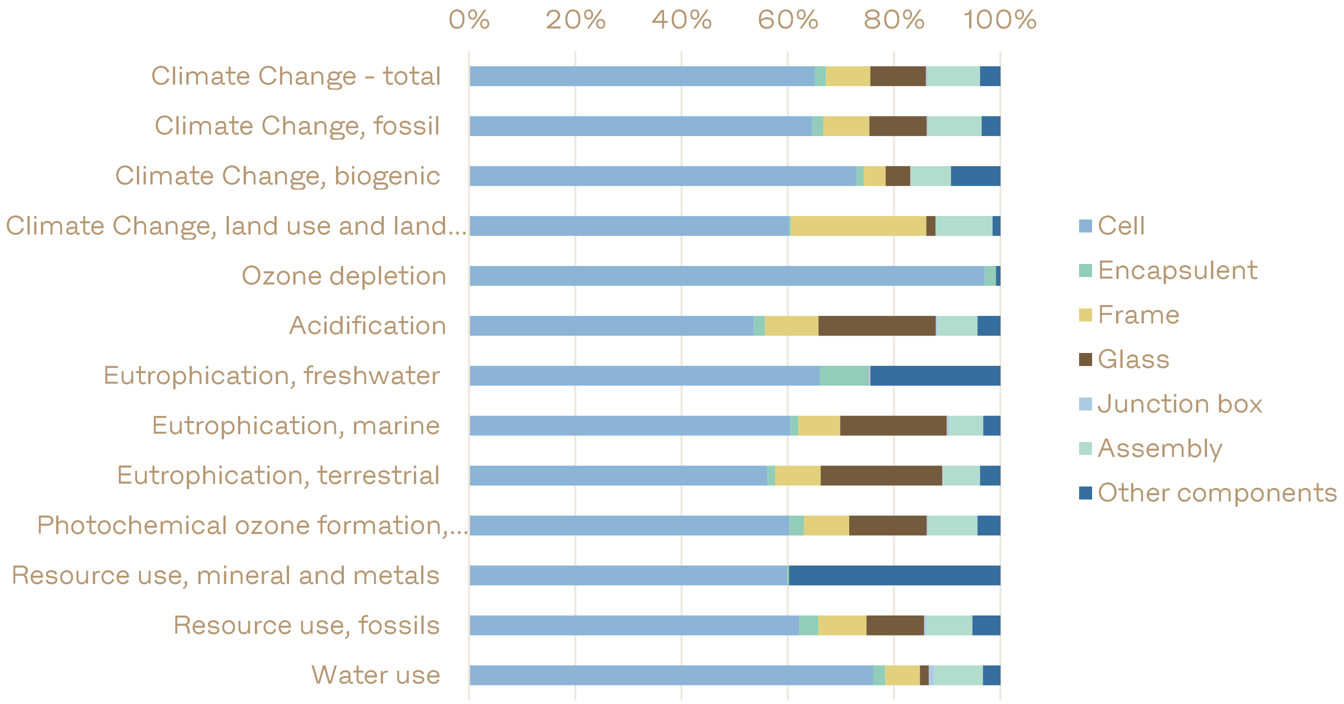

Figure 8. Distribution of impact between components of the solar PV module

Table 24. Summary of results for each component incuding assembly in the PV modules in Ingerslev Å 65MWp

Impact category	Cell	Encapsulent	Frame	Glass	Junction box	Assembly	Other components
Climate Change - total kg CO_2 eq.	1,1E+01	3,0E-01	2,9E+00	2,0E+00	5,5E-02	2,0E+00	6,9E-01
Climate Change, fossil kg CO_2 eq.	1,1E+01	3,0E-01	2,9E+00	2,0E+00	5,5E-02	1,8E+00	6,1E-01
Climate Change, biogenic kg CO_2 eq.	6,8E-01	6,0E-03	2,1E-02	5,1E-02	5,6E-04	2,4E-01	7,9E-02
Climate Change, land use and land use change kg CO_2 eq.	2,8E-02	2,6E-04	1,1E-03	8,9E-04	1,1E-05	8,5E-03	6,7E-04
Ozone depletion kg CFC-11 eq.	4,6E-07	6,5E-09	1,3E-11	3,1E-09	1,9E-10	3,7E-09	2,4E-09
Acidification Mole of H+ eq.	4,3E-02	1,1E-03	1,3E-02	1,9E-02	2,3E-04	6,8E-03	4,3E-03
Eutrophication, freshwater kg P eq.	8,7E-04	6,7E-05	4,0E-07	2,4E-05	4,0E-06	8,8E-05	3,3E-04
Eutrophication, marine kg N eq.	1,2E-02	2,3E-04	2,4E-03	4,1E-03	7,4E-05	1,8E-03	7,3E-04
Eutrophication, terrestrial Mole of N eq.	1,1E-01	2,3E-03	2,6E-02	4,8E-02	3,9E-04	1,7E-02	8,6E-03
Photochemical ozone formation, human health kg NMVOC eq.	3,3E-02	1,2E-03	7,1E-03	8,8E-03	1,4E-04	5,9E-03	2,4E-03
Resource use, mineral and metals kg Sb eq.	4,1E-04	1,7E-06	1,2E-07	1,6E-06	1,0E-07	8,7E-07	2,7E-04
Resource use, fossils MJ	1,2E+02	7,1E+00	2,7E+01	2,5E+01	8,5E-01	2,0E+01	1,2E+01
Water use.[18] m^3 world equiv.	3,7E+00	1,4E-01	4,6E-01	1,5E-01	5,4E-02	6,1E-01	9,5E-01

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[18] Use of net fresh water is 393,281 m^3 total or 0,0002 m^3 per kWh which is in line with other studies however this volume is converted into an impact of world equivalent based on the scarcity of water in the region it is consumed

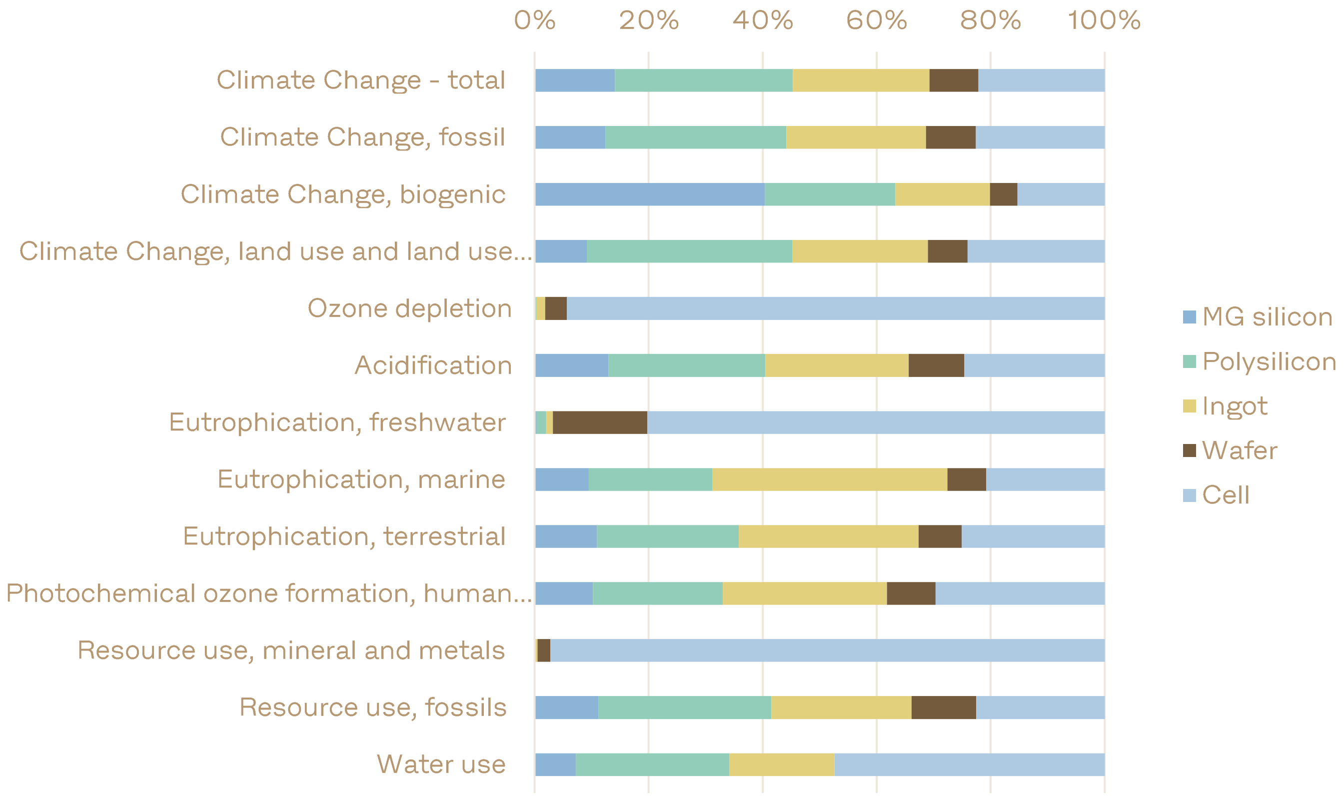

Figure 9. Distribution of impact between manufacturing process steps to produce the PV cell

Table 25. Summary of results for each manufacturing process step for the PV modules in Ingerslev Å 65MWp

Impact category	MG silicon	Polysilicon	Ingot	Wafer	Cell
Climate Change - total kg CO_2 eq.	1,6E+00	3,6E+00	2,8E+00	9,8E-01	2,5E+00
Climate Change, fossil kg CO_2 eq.	1,3E+00	3,4E+00	2,6E+00	9,5E-01	2,4E+00
Climate Change, biogenic kg CO_2 eq.	2,7E-01	1,6E-01	1,1E-01	3,3E-02	1,0E-01
Climate Change, land use and land use change kg CO_2 eq.	2,6E-03	1,0E-02	6,7E-03	2,0E-03	6,7E-03
Ozone depletion kg CFC-11 eq.	5,1E-11	1,5E-09	7,1E-09	1,7E-08	4,3E-07
Acidification Mole of H+ eq.	5,6E-03	1,2E-02	1,1E-02	4,2E-03	1,1E-02
Eutrophication, freshwater kg P eq.	2,5E-06	1,5E-05	1,0E-05	1,4E-04	7,0E-04
Eutrophication, marine kg N eq.	1,1E-03	2,6E-03	4,9E-03	8,0E-04	2,5E-03
Eutrophication, terrestrial Mole of N eq.	1,2E-02	2,8E-02	3,5E-02	8,5E-03	2,8E-02
Photochemical ozone formation, human health kg NMVOC eq.	3,4E-03	7,6E-03	9,6E-03	2,8E-03	9,9E-03
Resource use, mineral and metals kg Sb eq.	8,1E-08	4,2E-07	1,6E-06	9,4E-06	4,0E-04
Resource use, fossils MJ	1,4E+01	3,8E+01	3,1E+01	1,4E+01	2,8E+01
Water use.[19] m^3 world equiv.	2,7E-01	9,9E-01	6,8E-01	0,0E+00	1,7E+00

5.1.1. Recycling assumptions and end-of-life treatment: End-of-Life (Avoided Burden) Approach

In addition to the default cut-off approach used in the main LCA model, a scenario analysis was conducted using the end-of-life (EoL) avoided burden approach where all recycling burdens and credits are assigned to the solar park. This method accounts for the environmental benefits of recycling by assigning credits to the system for the net number of secondary materials recovered and reintroduced into the economy at the end of the Ingerslev Å's life.

Unlike the cut-off method, which excludes downstream benefits beyond the system boundary, the avoided burden approach reflects the potential environmental savings from displacing virgin material production. This is particularly relevant for utility-scale solar parks, where large quantities of recyclable materials - such as aluminium, glass, copper, and steel - are recovered.

This approach is supported by established LCA literature, including Frischknecht (2010).[20] and Stolz et al. (2018).[21], and aligns with ISO 14044 Clause 4.3.4.2, which allows for system expansion

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[19] Use of net fresh water is 393,281 m^3 total or 0,0002 m^3 per kWh which is in line with other studies however this volume is converted into an impact of world equivalent based on the scarcity of water in the region it is consumed

[20] Frischknecht (2010) LCI Modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency

[21] Stolz et al. (2018) Life Cycle Assessment of Current Photovoltaic Module Recycling

to capture downstream effects. When applied, the avoided burden method must be reported separately and transparently to avoid double counting.

When the avoided burden approach is applied to a utility-scale solar PV system, the credit for displacing virgin material in the materials next life cycle is deducted from the environmental impact of the solar park. All environmental burden from the recycling process and the credit is included whereas in the main LCA scenario only the environmental burden is included. However, the credit is not exactly 1:1 replacement since some of the material going into the solar park may have consisted of scrap which has zero environmental burden therefore this should not be credited. In this study the amount of avoided burden for each metal was taken from the Sphera Managed LCA Content datasets for scrap credit which is based on industry averages and was aluminium 93% (7% scrap in aluminium billet), steel 37% (63% scrap in steel billet), copper 80% (20% scrap in virgin copper).

For the Ingerslev Å solar park, applying the avoided burden approach would likely result in reductions in life cycle impacts, especially in resource depletion and climate change categories, further reinforcing the environmental value of the project.

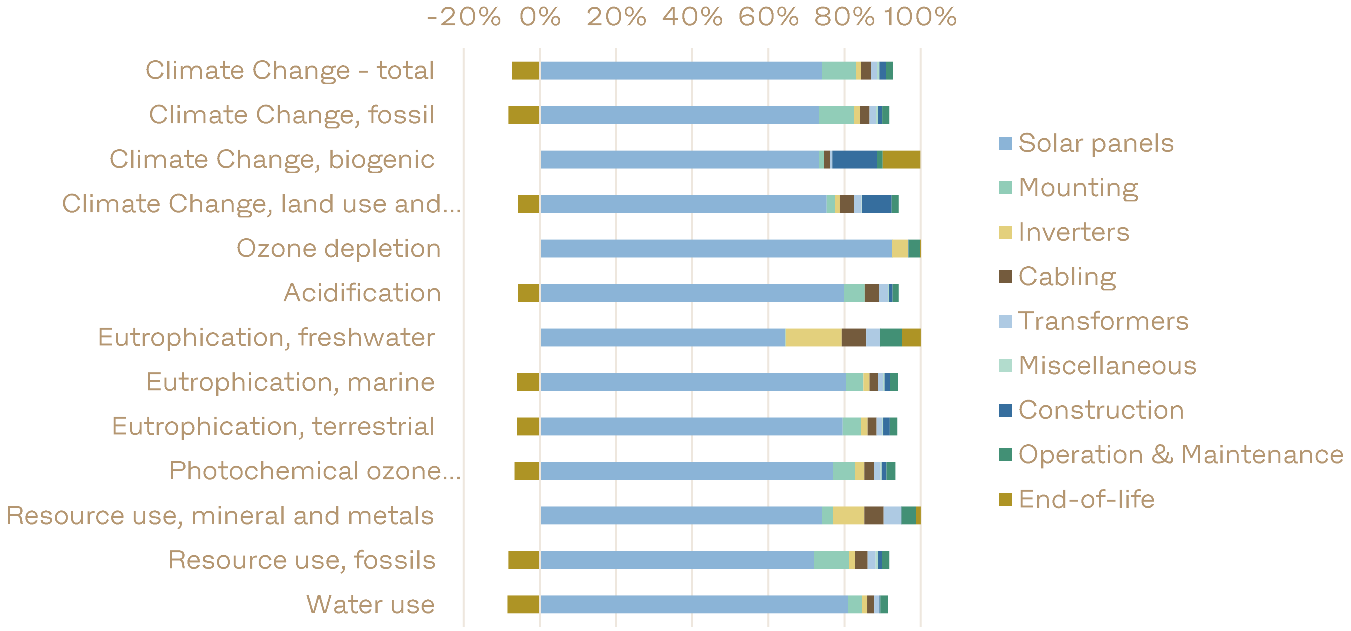

Figure 10. End of life using avoided burden approach

Table 26. Summary of results for each component and life cycle stage (avoided burden approach) for Ingerslev Å 65MWp

Impact category	Solar panels	Mounting	Inverters	Cabling	Transformers	Miscellaneous	Construction	O&M	EoL
Climate Change - total kg CO_2 eq.	1.99E-02	2.40E-03	3.69E-04	6.80E-04	4.39E-04	1.51E-04	4.51E-04	5.03E-04	-1.96E-03
Climate Change, fossil kg CO_2 eq.	1.87E-02	2.38E-03	3.69E-04	6.56E-04	4.29E-04	1.50E-04	2.73E-04	4.81E-04	-2.10E-03
Climate Change, biogenic kg CO_2 eq.	1.08E-03	1.92E-05	-4.66E-07	2.27E-05	8.70E-06	1.20E-06	1.74E-04	2.12E-05	1.46E-04
Climate Change, land use and land use change kg CO_2 eq.	4.07E-05	1.17E-06	6.81E-07	1.99E-06	1.09E-06	7.39E-08	4.20E-06	1.01E-06	-3.10E-06
Ozone depletion kg CFC-11 eq.	4.75E-10	3.27E-16	2.08E-11	3.88E-13	6.92E-13	2.01E-17	4.28E-15	1.56E-11	6.35E-13
Acidification Mole of H+ eq.	9.03E-05	6.06E-06	6.81E-09	4.28E-06	2.58E-06	3.81E-07	1.07E-06	1.79E-06	-6.49E-06
Eutrophication, freshwater kg P eq.	1.38E-06	1.26E-09	3.15E-07	1.37E-07	7.75E-08	7.94E-11	1.16E-09	1.21E-07	1.06E-07
Eutrophication, marine kg N eq.	2.27E-05	1.30E-06	4.59E-07	6.22E-07	4.05E-07	8.21E-08	4.17E-07	5.88E-07	-1.68E-06
Eutrophication, terrestrial Mole of N eq.	2.30E-04	1.41E-05	4.79E-06	6.96E-06	4.28E-06	8.86E-07	4.73E-06	6.00E-06	-1.76E-05
Photochemical ozone formation, human health kg NMVOC eq.	6.34E-05	4.68E-06	2.13E-06	2.03E-06	1.39E-06	2.95E-07	1.06E-06	1.89E-06	-5.47E-06
Resource use, mineral and metals kg Sb eq.	6.92E-07	2.64E-08	7.68E-08	4.72E-08	4.22E-08	1.66E-09	7.79E-11	3.65E-08	1.05E-08
Resource use, fossils MJ	2.20E-01	2.83E-02	4.70E-03	1.01E-02	6.41E-03	1.78E-03	3.50E-03	5.76E-03	-2.52E-02
Water use[22] m^3 world equiv.	6.69E-03	2.96E-04	1.19E-04	1.51E-04	9.67E-05	1.87E-05	1.83E-05	1.68E-04	-7.04E-04

A newer approach for end-of-life modelling designed to encourage recycling, is the Circular Footprint Formula (CFF) and this can also be used and should be used in future studies. The difference is this method includes all recycled or recyclable material *entering or leaving* the system (i.e. recycled material used in the manufacturing stage and recycling of material from the product's end of life).

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[22] Use of net fresh water is 393,281 m^3 total or 0,0002 m^3 per kWh which is in line with other studies however this volume is converted into an impact of world equivalent based on the scarcity of water in the region it is consumed

6. Interpretation

This section presents the interpretation of the results from the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) phases. The interpretation is conducted in accordance with the defined goal and scope of the study and serves as the basis for drawing conclusions, making recommendations, and supporting decision-making.

The interpretation aims to:

1. Interpret the life cycle stages and processes with the highest environmental impacts
2. Explore the Environmental Impact Mitigation Potential
    - Determine the energy payback time (EPBT) and Energy Return on Investment (EROI)
    - Understand material consumption and assess the potential for circularity, including reuse, recycling, and resource efficiency
    - Determine the environmental impact reversal time and process
    - Assess the impact of solar park on the energy system of Norddjurs Municipality
3. Evaluate the robustness and reliability of the results

6.1. Identification of the significant issues

As demonstrated in the Life Cycle Impact Assessment (LCIA), most of the environmental impact in Ingerslev Å stems from the components themselves - most notably the PV modules. In contrast, the construction phase and the operation and maintenance (O&M) activities over a 30-year lifespan contribute relatively little, typically accounting for 5% or less of the total impact.

A significant portion of the PV module's environmental footprint - around 65% - is attributed to the solar cell itself. The environmental data for the PV modules is primarily based on background datasets from established LCA databases. However, the specific selection of PV panel type and brand - such as those chosen by BeGreen - is considered foreground data, as it directly reflects project-specific decisions.

The background processes sourced from the IEA-PVPS database include the production of metallurgical-grade (MG) silicon, polysilicon, and ingot formation. Foreground data for wafering and cell production is derived from the Environmental Product Declaration (EPD) of Trina Solar since this is linked to the module design. These two stages - wafering and cell manufacturing - together represent approximately 20–55% of the environmental impact of the PV module production, or about 26% of the total impact of the solar park. Most of the impact of the cell is from the use of Chinese electricity as these processes are energy-intensive.

The amount of silicon used in each module is influenced by the dimensions of the wafer and cell, which are determined by the manufacturer's technology. In this case, Trina's specific cell architecture and efficiency play a key role. Therefore, when planning future solar parks, the choice of PV module and its EPD data - particularly for silicon-intensive processes - should be carefully considered.

6.1.1. Improvements in Solar Cell Manufacturing

While detailed proprietary improvements in Trina Solar's manufacturing processes are not publicly disclosed, several industry-wide advancements have contributed to reducing the environmental impact of solar cell production. These include:

- Higher efficiency cells generate more electricity per unit of material, reducing the overall material and energy intensity per kWh produced.
- Thinner wafers, reduced silver usage, and alternative metallization techniques have lowered the environmental burden of raw material extraction and processing.
- A shift toward renewable energy sources in PV manufacturing facilities has significantly reduced the carbon footprint of production.

- Emerging practices in silicon recovery, glass reuse, and closed-loop manufacturing are beginning to reduce waste and resource consumption.

Looking ahead, next-generation technologies such as tandem cells (e.g., silicon-perovskite) and bifacial modules are expected to further enhance efficiency and reduce lifecycle impacts. These innovations promise to deliver more energy output with fewer materials and lower emissions, making solar PV an increasingly more efficient energy solution.

6.2. Exploring the Environmental Impact Mitigation Potential

6.2.1. Energy payback time (EPBT)

Energy Payback Time (EPBT) is a key metric used to evaluate the sustainability of renewable energy systems. It is defined as the time required for a system to generate the same amount of primary energy (non-renewable) that was consumed throughout its entire life cycle. This includes all stages: manufacturing, transportation, installation, operation, maintenance, and end-of-life management.

In essence, EPBT measures how quickly a solar PV system "repays" its energy debt.

Methodology

In this study, EPBT is calculated by comparing:

1. The total non-renewable primary energy demand associated with the life cycle of the PV system (excluding the solar energy it captures during operation), and
2. The annual electricity output of the system, converted into its primary energy equivalent using the average electricity mix of Denmark.

The formula used is:

$$\mathrm{EPBT} = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{ins} + E_{EOL}}{\left(\frac{E_{agen}}{\eta G}\right) - E_{O\&M}}$$

Where:

- **E**$_{\mathbf{mat}}$: Primary energy demand for material production (MJ oil-eq)
- **E**$_{\mathbf{manuf}}$: Primary energy demand for manufacturing (MJ oil-eq)
- **E**$_{\mathbf{trans}}$: Primary energy demand for transportation (MJ oil-eq)
- **E**$_{\mathbf{inst}}$: Primary energy demand for installation (MJ oil-eq)
- **E**$_{\mathbf{EOL}}$: Primary energy demand for end-of-life processes (MJ oil-eq)
- **E**$_{\mathbf{agen}}$: Mean annual electricity generation (kWh/year)
- **ηG** : Grid efficiency (kWh electricity per MJ oil-eq)
- **E**$_{\mathbf{O\&M}}$: Annual primary energy demand for operation and maintenance (MJ oil-eq/year)

Primary Energy Conversion for grid efficiency

The grid efficiency (ηG) reflects the average conversion efficiency of the Danish electricity mix. The efficiency is calculated by primary input to produce electricity.

$$\eta\mathrm{G} = \frac{Electricity\ generation}{Primary\ input\ to\ generate\ electricity}$$

Based on Eurostat data, in 2023 the primary energy input is 49 TWh and the electricity generation is 33 TWh therefore the conversion factor is 0.68, meaning that 68% of primary energy is converted into usable electricity, while 32% is lost. Therefore, each kWh of electricity generated by the PV system is equivalent to displacing 1.32 kWh of primary energy in the Danish grid.

Results for Ingerslev Å Solar Park

- Total non-renewable primary energy demand over the system's life cycle from cradle to grave: 141,203 MWh
- EPBT: 1 year and 5 months

This means that within just under 18 months of operation, the Ingerslev Å solar park will have offset the total non-renewable primary energy used in its entire life cycle. After this point, the system continues to generate net energy benefits for the remainder of its operational life.

6.2.2. Energy Return on Investment (EROI)

Energy Return on Investment (EROI) is a key indicator of the energy efficiency and sustainability of a renewable energy system. It represents the ratio of the total usable energy output to the total non-renewable primary energy input required to build, operate, and decommission the system.

In simple terms, EROI answers the question: "How much energy do we get back for every unit of energy we invest?"

Definition and Formula

The EROI is calculated as:

$$\mathrm{EROI} = \frac{E_{out,el}}{E_{inv}}$$

Where:

- **$E_{out,el}$** : Total electricity generated by the PV system over its lifetime (in kWh)
- **E_{inv}** : Total non-renewable primary energy demand (in MJ oil-eq) for the full life cycle of the system, including material production, manufacturing, transport, installation, operation, maintenance, and end-of-life processes

Assumptions and Conversion Factors

- The analysis assumes a 30-year operational lifetime for the Ingerslev Å solar park.
- The grid efficiency is not included in this calculation since it extends for 30 years and the grid efficiency will improve during that time.

Results for Ingerslev Å Solar Park

- Total non-renewable primary energy demand over the system's life cycle from cradle to grave: 141,203 MWh
- Total lifetime electricity generation (without converting to primary energy equivalent): approx. 1,932,361 MWh
- EROI: ~14

This means that for every unit of non-renewable primary energy invested in the system, the solar park returns approximately 14 units of electricity over its lifetime. This high EROI highlights the strong energy performance of utility-scale solar PV, especially when compared to fossil fuel-based systems, which often have significantly lower EROI values once extraction and environmental costs are considered.

The fundamental principle behind EROI is that a system must produce more energy than it consumes to be viable. A positive net energy return is only achieved when:

$$\mathrm{OUT}_{\mathrm{net}} = E_{out,el} - E_{inv} > 0$$

Ingerslev Å clearly meets this criterion, demonstrating its contribution to reducing fossil fuel dependency and supporting long-term energy sustainability.

6.2.3. Levelised Cost of Energy (LCOE)

The Levelised Cost of Energy (LCOE) is a key economic metric that represents the average cost of generating one unit of electricity (typically expressed in EUR/MWh or EUR/kWh) over the entire lifetime of a power-generating system. It accounts for all relevant costs—capital investment, operations and maintenance, and decommissioning—divided by the total electricity output over the system's operational life.

$$\text{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Electricity Generation}}$$

Relevance in LCA

In the context of Life Cycle Assessment (LCA), LCOE serves as a bridge between economic performance and environmental impact. By comparing LCOE with environmental indicators (e.g., CO_2 emissions per kWh), stakeholders can assess the cost-effectiveness of sustainability and make informed decisions about energy investments.

Cost Components Included in LCOE

- Capital Costs – Initial investment for the construction and commissioning of the solar park.
- Fixed Operation & Maintenance (O&M) – Annual costs that are independent of electricity production (e.g., inspections, insurance, land lease).
- Variable Operation & Maintenance – Costs that scale with electricity generation (e.g., inverter replacements, cleaning, performance monitoring).
- System Costs
    - Balancing Costs: Expenses related to managing deviations from forecasted electricity production.
    - Profile Costs: Reflect the market value of electricity generated compared to a benchmark (e.g., average market price), accounting for the variability and timing of solar output.

LCOE for Ingerslev Å Solar Park

- LCOE: 56.3 EUR/MWh (or 5.63 euro cents/kWh)

This value places Ingerslev Å among the lowest-cost electricity generation technologies, comparable to onshore wind. The result aligns with findings from the Fraunhofer Institute's 2025 study[23], which confirms the competitiveness of utility-scale solar PV.

This LCOE value, when considered alongside the system's low environmental footprint and high EROI, underscores the economic and environmental viability of utility-scale solar PV as a cornerstone of a sustainable energy transition.

6.2.4. Material Consumption and the Potential for Circularity, Including Reuse, Recycling, and Resource Efficiency

The Ingerslev Å solar park uses 6,600 tonnes of materials in total, which is relatively high but typical for a utility-scale renewable energy project. This equates to around 100 tonnes per MWp of installed capacity.

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[23] Study: Levelized Cost of Electricity - Renewable Energy Technologies - Fraunhofer ISE

Utility-scale solar PV parks are among the most recyclable forms of energy infrastructure. Over 95% of the materials used in Ingerslev Å can be recovered and recycled using current technologies. Key recyclable components include:

- Steel structures (~32% of total mass)
- Glass panels (~45% of total mass)
- Aluminium frames
- Silicon wafers
- Copper wiring

Unlike wind turbine blades, solar PV systems do not contain major components that are difficult to recycle.

To evaluate the circularity of the solar park, this study applies the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation[24], in collaboration with Granta Design and co-funded by the EU LIFE programme. The MCI provides a quantitative measure of how restorative material flows are within a product system, expressed as a score between 0 and 1—where 1 represents maximum circularity.

The methodology considers four key aspects:

- Material input: Maximising the share of recycled and reused content,
- Product lifetime: Extending the system's operational life relative to industry norms,
- Material output: Maximising recycling and reuse at end-of-life,
- Disposal efficiency: Minimising unrecoverable waste and leakage from recycling processes.

The MCI calculation integrates both input and output flows, including virgin, reused, and recycled materials, as well as recyclable, reusable, and waste fractions. It also incorporates a utility factor that reflects the duration and intensity of the product's use.

The indicator is derived from three core parameters:

- V: the mass of virgin raw materials used in production,
- W: the mass of unrecoverable waste attributed to the product,
- X: a utility factor representing the product's usage over time.

A product manufactured solely from virgin materials and ending in landfill is considered fully *linear*, while one made entirely from recycled inputs, fully recovered for reuse or recycling, and processed with 100% efficiency is deemed fully *circular*. Most products fall between these two extremes, and the MCI captures this variation on a scale from 0 (linear) to 1 (circular).

Calculation Methodology

The MCI is calculated using the following formula:

$$\mathrm{MCI} = 1 - (\mathrm{LFI} * \mathrm{F(X)})$$

Where:

- LFI (Linear Flow Index) =

$$\frac{\text{Amount of material flowing in a linear fashion}}{\text{Total mass flow}}$$

- X (Utility factor) =

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[24] Material Circularity Indicator | Ellen MacArthur Foundation

$$\frac{\text{Product lifetime}}{\text{Industry average lifetime}} * \frac{\text{Functional units delivered}}{\text{Industry average functional units}}$$

As illustrated in Figure 11, the methodology accommodates both open and closed-loop systems. Recycled inputs need not originate from the same product type; sourcing from the broader market is acceptable. This flexibility reflects the mass-flow basis of the calculation, which remains consistent regardless of loop type.

The associated material flows are summarised for technical materials diagrammatically in Figure 11 and detailed results for the solar park are summarised in Table 27.

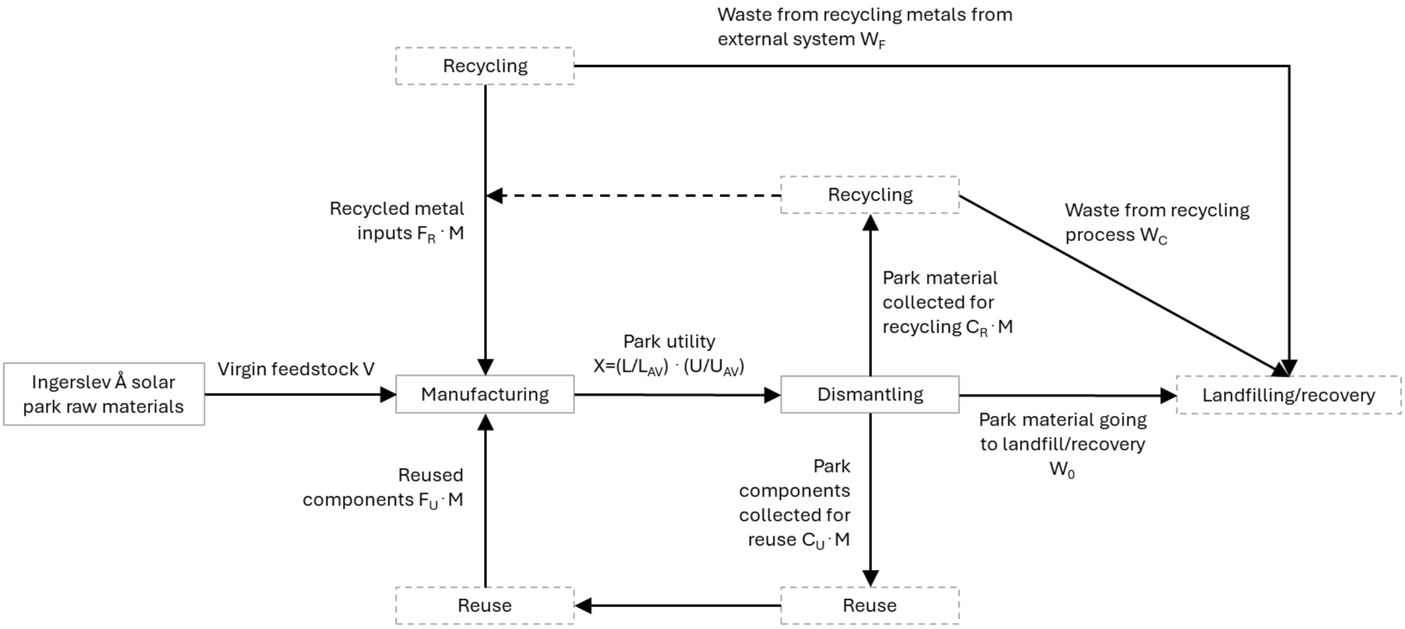

Figure 11. Diagrammatic representation of material flows used in the MCI calculations (based on the Ellen Macarthur foundation MCI methodology.[25])

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[25] Circularity Indicators - Methodology.pdf

Table 27: Detailed results for the circularity calculation for the solar park

Name	Variable	Unit	Formula	Value
Ingerslev Å weight[26]	M	tonne	Mass of solar park	6,600
Virgin feedstock	V	tonne	$V = M(1 - F_R - F_U - F_S)$	5,741
Recycled feedstock	$F_R.M$	tonne	$M - V$	859
Components reused	$F_U.M$	tonne	None	0
Components collected for reuse	$C_U.M$	tonne	None	0
Materials collected for recycling	$C_R.M$	tonne	$C_R * M$	5,549
Material going to landfill/energy recovery	W_O	tonne	$W_O = M(1 - C_R - C_U - C_C - C_E)$	1051,2
Waste from recycling process	W_F	tonne	$W_F = \frac{M(1 - E_F)FR}{E_F}$	177
Utility	X		Lifetime/industry average lifetime	1,000
Unrecoverable waste from recycling	W_C	tonne	$W_C = \frac{M(1 - E_C)}{C_R}$	1,110
Total waste	W	tonne	$W = W_O + \frac{W_F + W_C}{2}$	1,695
Linear flow index	LFI		$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$	56%
Materials Circularity Index	MCI		$MCI = 1 - LFI * F(X)$ $F(X) = \frac{0,9}{X}$	49%

Where:

F_R (feedstock recycled fraction) is 11%

F_U (feedstock reused fraction) is 0%

F_S (feedstock biological fraction from sustained production) is 0%

C_R (fraction collected for recycling) is 84%

C_U (fraction collected for reuse) is 0%

C_C (fraction collected for composting) is 0%

C_E (fraction collected as biological materials from sustained production used for energy recovery) is the amount of wood collected for incineration with energy recovery including energy recovery efficiency E_E

E_F (efficiency of the recycling process used to produce the recycled feedstock) is 80%

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[26] Includes O&M replacement of PV modules and inverters

E_C (efficiency of the recycling process used for recycling the product at the end of its use phase) is 80%

X (utility) is 1

Circularity Performance of Ingerslev Å

- MCI Score: 0.49 → Indicates that 49% of materials are managed in a closed-loop
- Linear Flow Index (LFI): 0.56 → Reflects the proportion of virgin material input and unrecoverable waste

The high recyclability of the system significantly enhances the MCI score. However, the score is penalised due to the relatively low proportion of recycled materials used in the initial construction and limited reuse of components at end-of-life.

Improvement Opportunities

The circularity performance of Ingerslev Å could be improved by:

- Increasing recycled content in the bill of materials
- Enhancing end-of-life recycling strategies to ensure materials are recovered to the highest possible standard
- Extending product lifetimes through reuse or refurbishment
- Reducing material leakage during recycling processes

6.2.5. Estimated impact in Norddjurs Municipality

One of the most significant environmental benefits of solar energy is its ability to contribute to the virtual electrification of the local energy system with renewable electricity. Thus, reducing greenhouse gas emissions and biomass demand. This section evaluates the impact on the local energy system in the Norddjurs municipality.

Energy Transition Assessment

Although the electricity generated by BeGreen's solar parks is physically fed into the national grid, it is considered to virtually electrify the local municipality. This interpretation aligns with Denmark's Strategic Energy Planning framework, which all municipalities are required to follow. Under this approach, locally produced renewable electricity is counted as contributing to the local grid, thereby supporting reductions in local carbon dioxide emissions, decreasing biomass dependency, and increasing both the share of renewables and overall electrification.

Each municipality must report annually on these impacts and track progress toward their climate targets for 2030 and 2050, as outlined in their Local Climate Action Plans. To support municipalities in meeting these goals, BeGreen conducts an Energy Transition Assessment for each solar project. This structured methodology evaluates the project's contribution to electrifying the local energy system and accelerating the transition to 100% renewable energy.

The assessment includes:

1. A baseline analysis – using data from SparEnergi.dk to understand the municipality's current energy balance,
2. Current system modelling where we simulate the existing energy system using an energy balance tool, aligned with national energy and CO_2 accounting standards, and
3. Future system modelling where we project the future energy system with the solar park integrated, updated every 2–3 years (this was not carried out in this study).

Key Environmental Benefits

Overall, by integrating Ingerslev Å into the local energy system, the solar park is not only a clean energy source but also a strategic climate asset for the municipality. The following positive impacts are observed:

- Increased renewable electricity capacity by adding substantial clean generation
- Higher share of renewable electricity supply which directly supplies local demand with renewable electricity
- Improved primary energy mix by displacing non-renewable sources, increasing the renewable share in the overall energy supply
- Support for electrification by enabling further electrification of heating and transport sectors with renewable electricity
- Reduced biomass dependency by offsetting the need for biomass combustion for electricity, preserving it for higher-value applications

Renewable share in the local energy system in Table 29 considers only the renewable share from more PV in the energy system and excludes the electrification effect on the other energy sectors such as transport or heating.

Table 28. Impact on Norddjurs Municipality energy system

Energy sector data	Unit	2023	2025 (incl. Ingerslev Å)	Improvement
Renewable electricity capacity	MWp	96	161	+68%
Renewable share in the local energy system (excluding electrification affects on other energy sectors)	%	62	67	+5
Imported electricity	TJ	438	192	-56%

Reduced Biomass Dependency

By supplying clean, solar-generated electricity to the local grid, Ingerslev Å helps offset the need for biomass-based electricity generation. Biomass - such as wood pellets, straw, or biogas - is often used in Denmark as a renewable energy source, particularly for combined heat and power (CHP) plants. However, while biomass is renewable, it is not impact-free:

- Combustion of biomass still emits CO_2, even if it is considered carbon-neutral over the long term due to regrowth of biomass feedstocks.
- Biomass supply chains can involve land-use change, deforestation, and biodiversity loss, especially when imported or sourced unsustainably.
- Biomass is a valuable and limited resource that can be more effectively used in hard-to-electrify sectors, such as heavy industry, aviation fuels, or high-temperature processes.

In this way, solar PV complements the energy system by freeing up biomass capacity, allowing it to be redirected toward sectors where it delivers greater climate benefits, while also reducing the environmental footprint of the electricity supply.

6.3. Robustness, Reliability, and Data Quality of the Results

To ensure the scientific integrity and credibility of this Life Cycle Assessment (LCA) study, a rigorous and methodologically consistent approach was applied throughout the data collection, Life Cycle Inventory (LCI) selection, and impact assessment processes. The datasets used accurately reflect the technologies under analysis - including photovoltaic modules, inverter systems, mounting structures, and balance-of-system components - and were selected to match the specific configurations and geographical context of the solar installation. Regional variations in energy mix, manufacturing practices, and transportation logistics were incorporated to localize environmental impacts effectively.

Foreground data representative of 2024 was sourced directly from manufacturers or Environmental Product Declarations (EPDs), reflecting actual design and construction practices. Background data was drawn from reputable databases such as IEA-PVPS, Ecoinvent, and Sphera Managed LCA Content (2024), ensuring high quality and relevance. The study employed the most recent datasets available, minimising outdated assumptions and enhancing the applicability of results to current industry standards.

All relevant material and energy flows, emissions, and waste streams were included within the system boundaries, covering upstream and downstream processes from raw material extraction to end-of-life management. The cut-off approach was applied for end-of-life modelling, treating recycled materials as burden-free at system entry and excluding credits for recycled outputs, in line with attributional LCA practice.

Three key data quality checks—completeness, sensitivity, and consistency—were conducted to validate the robustness of the results:

- Completeness: The model captures over 99% of total mass and energy flows. Minor components excluded due to cut-off criteria (e.g., fasteners, small electrical parts) were reassessed and confirmed to have negligible impact. End-of-life stages such as decommissioning and disposal were not fully modelled but are considered to have minimal influence on overall results.
- Sensitivity: Assumptions regarding component lifetimes (e.g., modules and inverters) were based on expected values and found to have limited impact on results per kWh. Electricity mix variations in manufacturing (e.g., China vs. Europe) were accurately modelled, and transport data was based on measured fuel use and actual distances, reducing uncertainty.
- Consistency: Uniform methodological choices were applied across all stages, including impact assessment methods, allocation procedures, and data sources. While mixed data sources (e.g., Ecoinvent and Sphera Managed LCA Content) were used, Ecoinvent was limited to minor inputs. Temporal consistency was maintained by using recent EPDs, and modelling approaches were harmonized to ensure comparability.

Critical datasets and life cycle stages with disproportionate influence on environmental impacts were subjected to detailed quality checks. Data quality details including data quality scores from 1-5 for geography, time and completeness for important LCI datasets are presented in Appendix B.

By prioritising representativeness, completeness, and methodological coherence, the study delivers robust and reliable LCA results. These findings provide a solid foundation for sustainability assessments and informed decision-making in the solar energy sector.

7. Conclusions, limitations and recommendations

This Life Cycle Assessment (LCA) evaluates the environmental performance of the 65 MWp Ingerslev Å solar park in Denmark over a 30-year operational lifetime. The study follows a cradle-to-grave, process-based approach in accordance with ISO 14040/44 and IEA-PVPS guidelines. The functional unit is defined as 1 kWh of AC electricity delivered to the Danish grid, enabling consistent comparison with other electricity generation technologies. Key impact categories assessed include climate change, resource use, and natural capital impacts, providing a comprehensive view of the solar park's environmental sustainability profile.

This Life Cycle Assessment (LCA) confirms that most environmental impacts associated with utility-scale solar energy systems stem from the production phase of photovoltaic (PV) panels. These impacts are primarily due to energy-intensive manufacturing processes and the extraction of raw materials such as silicon, silver, aluminium, and glass. In contrast, the operational phase of the solar power plant is characterised by minimal environmental burdens, with negligible direct emissions of greenhouse gases, air pollutants, or water contaminants.

The system demonstrates a favourable Energy Payback Time (EPBT) of approximately 1 year and 5 months, meaning the energy used in its production is offset relatively quickly. Furthermore, the Energy Return on Investment (EROI) is estimated at 14:1 when considering only the non-renewable primary energy demand, indicating a strong net energy gain over the system's 30-year lifespan. This is particularly notable given Denmark's moderate solar irradiance, underscoring the efficiency and viability of solar PV in the region.

End-of-life considerations reveal that many components - especially glass and metals - are recyclable leading to a recyclability rate of the park of 86%. However, the environmental sustainability of the system can be further improved through advancements in recycling infrastructure and processes, particularly for silicon and silver recovery since the circularity and linear flow of the solar park is only 0.49 and 0.56 respectively.

From a climate perspective, the solar power plant will reduce greenhouse gas emissions compared to fossil fuel-based energy system in Norddjurs Municipality. The system facilitates the electrification of energy sectors, such as heating and transport, by providing clean electricity.

7.1. Limitations and Recommendations for Future BeGreen LCAs on Solar PV Systems

To strengthen the accuracy, relevance, and strategic value of BeGreen's future life cycle assessments (LCAs) of solar photovoltaic (PV) systems, the following limitations identified in the current study are grouped into three key areas, each with targeted recommendations for improvement in future reporting and decision-making

7.1.1. Data Quality and Methodological Transparency

Current Limitations:

- The use of older life cycle inventory (LCI) datasets may not reflect recent developments in PV manufacturing, especially in key production regions such as China
- The selection of environmental impact indicators and databases limits the comparability of BeGreen's results with other studies and may constrain the scope of conclusions
- End-of-life assumptions, including the cut-off approach and definitions of the end-of-waste state, influence allocation outcomes and may not align with evolving industry practices

Recommendations for BeGreen:

- Future LCA reports should incorporate the latest LCI datasets, including updates from the IEA-PVPS database, to better reflect current technologies and supply chain realities

- Clearly document the choice of databases and impact indicators to improve transparency and facilitate benchmarking with external studies
- Revisit allocation methods and end-of-life assumptions to ensure alignment with emerging standards and circular economy principles

2. End-of-Life Scenarios and Circularity Integration

Current Limitations:

- Recycling rates and grid compositions used in the current LCA reflect present-day conditions, limiting the relevance of long-term projections
- The study lacks detailed data on recycling technologies for key PV materials such as silicon, silver, and rare metals
- End-of-life treatment routes are not explored in sufficient depth, reducing the ability to assess future environmental benefits

Recommendations for BeGreen:

- Integrate more region-specific and technology-specific data on recycling processes to improve scenario realism
- Expand the scope of end-of-life scenarios to include multiple treatment pathways and future recycling infrastructure developments
- Encourage suppliers and partners to adopt circular design principles that support modularity, disassembly, and material recovery
- Support industry initiatives and partnerships aimed at advancing recycling technologies and infrastructure for PV systems

3. System Boundaries and Emerging Technologies

Current Limitations:

- The current LCA lacks geographical specificity, which may overlook regional differences in energy mixes, upstream processes, and regulatory frameworks
- Sensitivity and uncertainty analyses are limited, reducing the robustness of the findings
- The role of battery energy storage systems (BESS) and smart grid technologies is not considered, despite their growing importance in PV system integration

Recommendations for BeGreen:

- Conduct regionalised LCAs using geographically tailored data to better reflect local conditions and policy environments
- Broaden sensitivity and uncertainty analyses to strengthen the credibility of results and support risk-informed decision-making
- Include BESS and smart grid components in future assessments to capture their contributions to system reliability, flexibility, and environmental performance

By addressing these limitations in future LCA reports, BeGreen can enhance its environmental reporting, support strategic planning, and contribute to industry leadership in sustainable solar PV deployment.

Annex A: Data source description, uncertiaty and signficance for each unit process

	Source	Year of relevance	Uncertainty	Significance to study results
PV modules				
Metallurgical grade silicon	PVPS	2020	Low	Very high
Polysilicon purification	PVPS	2020	Low	Very high
Ingot casting	PVPS	2020	Low	Very high
Wafer Slicing	PVPS	2020	Low	Very high
Cell manufacturing	PVPS	2020	Low	Very high
Module assembly	PVPS	2020	Low	Very high
Balance Of System (BOS)				
Mounting structure	Measured	2024	Low	Medium
Inverters	Measured	2024	Low	Medium
Cabling	Measured	2024	Low	Medium
HV transformer	Calculated	2024	Medium	Medium
MV transformer	Calculated	2024	Low	Medium
Fencing	Calculated	2024	Low	Low
Construction				
Assembly of the park	Measured	2024	Low	Low
O&M				
Replacements of parts	Estimated	2024	Medium	Medium
End-of-life				
Metal recycling	Estimated	2024	Medium	Low
Incineration for energy recovery	Estimated	2024	Medium	Low
Landfilling	Estimated	2024	Medium	Low

Annex B: Data quality assessment for key study inputs (Quality level ranked from 1-5 (very good to poor) based on ILCD handbook[27])

Parameter	General description LCI dataset used (where applicable)	Technological representativeness (Quality level)	Time-related representativeness (Quality level)	Geographical representativeness (Quality level)	Completeness (Quality level)	Precision/uncertainty (Quality level)	Methodological appropriateness and consistency
Galvanised steel (Mounting system, fencing, transformers)	RER: Steel hot dip galvanised	This dataset includes raw material extraction (e.g. coal, iron, ore, etc.) and processing, e.g. scrap, coke making, sinter, blast furnace, basic oxygen furnace, hot strip mill, annealing and tempering, galvanising. Details on the steel product manufacturing route can be found in Appendix 1 of the 2017 worldsteel LCA Methodology Report. The steelmaking processes are shown in the flow diagram. Inputs included in the Life Cycle Inventory relate to all raw material inputs, including steel scrap, energy, water, and transport. Outputs include steel and other co-products, emissions to air, water and land. Further information is given in the 2017 worldsteel LCA Methodology Report. (Very good: 1)	Based on annual data from a 12 month period between 2017 and 2021 provided by each participating site from which an annual average is calculated. (Very good: 1)	Data set is based on weighted average site-specific data (gate-to-gate) of European steel producers. Electricity grid mix is country-specific.. (Good: 2)	There is no deviation from data cut-off and completeness principles (Very good: 1)	No uncertainty adjustments have been applied (Very good: 1)	No deviations from the LCI method principle (Good: 2)
Glass (PV module)	RER: Float flat glass	The float flat glass process is mainly based on the best available techniques reference document for the manufacture of glass by the industrial emission directive 2010/75/EU and completed with additional literature data to define the flat float glass production in detail. The main material composition as well as the main emissions have been considered. In the	2024 annual average (Very good: 1)	The data set represents the European specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics. (Fair: 3)	Coverage of at least 99% of mass and energy of the input and output flows as well as the environmental relevance. No inputs or outputs were knowingly excluded from the scope of analysis. For further details please see the document "Sphera LCA Databases Modelling Principles". (Good: 2)	No uncertainty adjustments have been applied (Good: 2)	No deviations from the LCI method principle (Good: 2)

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[27] ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf

		float glass process quartz sand and glass for recovery are melted with additional materials e.g. dolomite, kaolin, limestone, potassium carbonate, soda and sodium sulphate. (Good: 2)					
Aluminium (cabling)	RER: Aluminium ingot mix - production mix	This dataset represents European primary aluminium ingot. The ingot is produced in Europe while Bauxite and refined Alumina are mainly imported (global average). The foreground data of Aluminium production steps (Bauxite, Alumina, Electrolysis, Anode and paste production and casting) are based on 2019 IAI data. (Good: 2)	2024 annual average (Very good: 1)	The data set is based on European averages calculated from site-specific data of the European aluminium industry covering bauxite mining, alumina production, primary aluminium production and process scrap remelting. Country-specific electricity grid mix has been used. Bauxite mining is a global average. Alumina and primary aluminium production are based on a mixture of local production and imports. (Good: 2)	Coverage of at least 99% of mass and energy of the input and output flows as well as the environmental relevance. No inputs or outputs were knowingly excluded from the scope of analysis. For further details please see the document "Sphera LCA Databases Modelling Principles". (Good: 2)	No uncertainty adjustments have been applied (Good: 2)	No deviations from the LCI method principle (Good: 2)
Aluminium (PV module)	CN: Aluminium extrusion profile (PV module)	Aluminium semi-finished sheet product, including primary production, transformation and recycling. Aluminium profiles are produced by an extrusion process. The starting material is aluminium billets (typically of cylindrical shape), which are pressed through a dye into the desired shape at the temperatures of 400-500 ° C.	2024 annual average	Electricity is modelled according to the individual country-specific situations. The national emission and efficiency standards of the power plants are modelled as well as the share of electricity plants and combined heat and power plants (CHP). The country-specific energy carrier supply (share of imports and / or domestic supply) including the country-specific energy carrier properties (e.g. element and energy content) are accounted for. The exploration, mining/production, processing and transport processes of the energy carrier supply chains are modelled according to the specific situation of each electricity producing country.	Coverage of at least 99% of mass and energy of the input and output flows as well as the environmental relevance. No inputs or outputs were knowingly excluded from the scope of analysis. For further details please see the document "Sphera LCA Databases Modelling Principles".	No uncertainty adjustments have been applied (Good: 2)	No deviations from the LCI method principle (Good: 2)

Copper (cabling)	GLO: Copper mix (99.999% from electrolysis)	Three copper production routes were modelled for the global copper mix: electrolyte copper 99,99% world -mix. Outokumpu was modelled for Chile, ISA smelt for Australia and the Mitsubishi process for Indonesia. The Australian route was modelled on data based from the largest Australian copper producing company. (Good: 2)	2024 annual average (Very good: 1)	The mix is based on primary copper production in Chile, with production in Australia and Indonesia also included, but with a smaller production mix. The data set represents the global situation, focusing on the main technologies, and the region specific characteristics. (Good: 2)	Coverage of at least 99% of mass and energy of the input and output flows as well as the environmental relevance. No inputs or outputs were knowingly excluded from the scope of analysis. For further details please see the document "Sphera LCA Databases Modelling Principles". (Good: 2)	No uncertainty adjustments have been applied (Good: 2)	No deviations from the LCI method principle (Good: 2)
Silica sand (PV module)	DE Silica sand (flour)	Quartz (silica) is one of the most common minerals in the Earth's continental crust. It belongs to the hexagonal crystal system, and is made up of silicon, (SiO2). Quartz has a density is 2.65 g/cm. Silica sand is mined together with kaolin and feldspar using bucket excavators or bucket chain dredgers. The material is treated in a multi- step process. The material is grinded into smaller particle size, separation from impurities occurs by using separation methods like flotation, magnetic separation, chemical treatment (e.g. with acid), sieving and washing. (Good: 2)	2024 annual average (Very good: 1)	The data set represents the German situation, focusing on the main technologies, the region specific characteristics and / or import statistics. (Good: 2)	Coverage of at least 99% of mass and energy of the input and output flows as well as the environmental relevance. No inputs or outputs were knowingly excluded from the scope of analysis. For further details please see the document "Sphera LCA Databases Modelling Principles". (Good: 2)	No uncertainty adjustments have been applied (Good: 2)	No deviations from the LCI method principle (Good: 2)
Chinese electricity grid mix (PV module)	CN: Electricity grid mix	Foreground system: The national or regional specific electricity consumption mix is provided by the conversion of the different energy carriers to electricity and imports from neighbouring countries. Background system: Electricity: Electricity is modelled according to the individual country-specific situations. (Good: 2)	2021 annual average (Very good: 1)	The data set represents the average national or region specific electricity mix including main activity producers and autoproducers as well as electricity imports. (Good: 2)	Coverage of at least 99% of mass and energy of the input and output flows as well as the environmental relevance. No inputs or outputs were knowingly excluded from the scope of analysis. For further details please see the document "Sphera LCA Databases Modelling Principles". (Good: 2)	No uncertainty adjustments have been applied (Good: 2)	No deviations from the LCI method principle (Good: 2)
Silicon steel (MV & HV transformers)	RER: steel production, 3.2% silicon alloy, for grain oriented electrical steel (ecoinvent)	The production of this alloy follows the typical path of the secondary metallurgy: alloying elements are added to the ladle to reach the desired composition. For this specific alloy, considering the high reactivity of ferrosilicon, the addition of the alloying elements is performed under vacuum.	2024	The activity is considered to be valid for the European geography, since the processing is considered to be performed in Europe.	The exchanges were calculated combining expert opinions and literature.	The dataset is based on experts opinion and literature.	Unknown
Concrete (Foundations for	Concrete C20/25 (Ready-mix	Foreground system: Concretes and mortars are a mixture of cement, water and aggregates (e.g.	2024 annual average	The data set represents the country/ region specific situation in Europe by	Coverage of at least 99% of mass and energy of the input and output flows as well as the	No uncertainty adjustments	No deviations from the LCI

transformers)	concrete) (EN15804 A1-A3)	sand, gravel, flint, blast furnace slag) and, when necessary, additives such as condensers, retarding agents or air-entraining agents. Cement and water form the cement paste binds the grains of stone forming a hard stone. The concrete's properties can be altered by using different structutres and grains of stone.		focusing on the main technologies and the legislative conditions of the region.	environmental relevance. No inputs or outputs were knowingly excluded from the scope of analysis. For further details please see the document "Sphera LCA Databases Modelling Principles".	have been applied	method principle
Aluminium remelting (PV module, cabling)	RER+EFTA: Aluminium refining, excluding alumina credit: casting alloy ingot from scrap (2021)	This process considers the recovery of aluminium scrap in Europe for producing casting alloy ingot and deox. This dataset includes the use of rotary, reverbatory processes, including salt slag and dross treatment. The Aluminium Environmental Profile Report is used as a reference in this dataset. A second version of the November 2024 report was published in May 2025.	2021 annual average	The data set represents the European specific situation, focusing on the main technologies and the legislative boundary conditions. The following countries are included: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and UK	See the 2025 European Aluminium Environmental Profile Report (v2.0): https://european-aluminium.eu/blog/environmental-profile-reports/	If any see 2025 European Aluminium Environmental Profile Report (v2.0): https://european-aluminium.eu/blog/environmental-profile-reports/	If any see the 2025 European Aluminium Environmental Profile Report (v2.0): https://european-aluminium.eu/blog/environmental-profile-reports/
Steel recycling	CN: Electric arc furnace steelmaking (No water) ILCD	This dataset represents the electric arc furnace (EAF) steelmaking process, which is employed in the production of crude steel using a combination of pig iron and scrap steel. The process is typically used in steel mills for manufacturing structural steel products, tools, machinery, and vehicles.	Unknown	China	Data provider: Tiangong LCI Data Working Group	Unknown	Unknown
Copper recycling	RER: Treatment of copper scrap by electrolytic refining (ecoinvent)	This dataset represents the production of 1 kg of copper cathodes, by electrolytic refining, in 2003. It is designed for the use of the metal as part of the consumption mix 'copper, at regional storage'.	2024	This module is valid for one single very big plant, which is taken as proxy for the RER.	Representativeness: 15.3%. Data was obtained from one single very big plant in Germany, and it is taken as proxy for the RER.	Sampling procedure: literature	Unknown

Annex C: Data sets used for PV module manufacturing process steps (all datasets from Sphera Managed LCA Content unless specified)

Step 1: Metallurgical silicon

Inputs	**Inventory data**	**Dataset/elementary flow applied**
Technosphere	electricity, medium voltage, at grid	CN: Electricity grid mix
	wood chips, production mix, wet, measured as dry mass, at forest road & at sawmill	US: Wood chips pine (10% water content)
	hard coal coke, at plant	DE: Metallurgical coke
	graphite, at plant	RoW: Graphite production (ecoinvent)
	charcoal, at plant	GLO: Charcoal production (ecoinvent)
	petroleum coke, at refinery	RER: Petroleum coke
	silica sand, at plant	DE: Silica sand (flour)
	oxygen, liquid, at plant	DE: Oxygen (liquid)
	disposal, slag from MG silicon production, 0% water, to inert material landfill	RoW: inert material landfill construction (ecoinvent)
	silicone plant	Excluded (meets cut-off criteria)
	transport, transoceanic freight ship	RER: Container ship (EN15804 A4)
	transport, freight, lorry, fleet average	RER: Rail transport incl. fuel, average
	transport, freight, rail	CN: Transport truck-trailer (40 t total cap., 24.7t payload)
Outputs		
Emissions air, low population density	Heat, waste	Heat, waste
	Arsenic	Arsenic
	Aluminium	Aluminium
	Antimony	Antimony
	Boron	Boron
	Cadmium	Cadmium
	Calcium	Calcium
	Carbon monoxide, biogenic	Carbon monoxide, biogenic
	Carbon monoxide, fossil	Carbon monoxide, fossil
	Carbon dioxide, biogenic	Carbon dioxide, biogenic
	Carbon dioxide, fossil	Carbon dioxide, fossil
	Chromium	Chromium
	Chlorine	Chlorine
	Cyanide	Cyanide
	Fluorine	Fluorine
	Hydrogen sulfide	Hydrogen sulfide
	Hydrogen fluoride	Hydrogen fluoride
	Iron	Iron
	Lead	Lead

	Mercury	Mercury
	NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC, non-methane volatile organic compounds, unspecified origin
	Nitrogen oxides	Nitrogen oxides
	Particulates, > 10 um	Particulates, > 10 um
	Potassium	Potassium
	Silicon	Silicon
	Sodium	Sodium
	Sulfur dioxide	Sulfur dioxide
	Tin	Tin

Step 2: Polysilicon

Inputs	Inventory data	Dataset/elementary flow applied
	MG-silicon, at plant	Input from metallurgical silicon process
	hydrochloric acid, 30% in H2O, at plant	DE: Hydrochloric acid (32%)
	hydrogen, liquid, at plant	DE: Hydrogen (steam refrming natural gas)
	sodium hydroxide, 50% in H2O, production mix, at plant	DE: Sodium hydroxide mix (50%)
	transport, freight, lorry, fleet average	CN: Transport, truck-trailer (40t total cap., 24.7t payload)
	transport, freight, rail	RER: Rail transport incl. fuel, average
	electricity, medium voltage, at grid	CN: Electricity grid mix
	heat, at cogen 1MWe lean burn, allocation exergy	RoW: heat, non-market, at cogen 160kWe Jakobsberg, allocation exergy
	silicone plant	Excluded (meets cut-off criteria)
Outputs		
Emissions air, high population density	Heat, waste	Heat, waste
Emission water, river	AOX, Adsorbable Organic Halogen as Cl	AOX, Adsorbable Organic Halogen as Cl
	BOD5, Biological Oxygen Demand	BOD5, Biological Oxygen Demand
	COD, Chemical Oxygen Demand	COD, Chemical Oxygen Demand
	Chloride	Chloride
	Copper	Copper
	Nitrogen	Nitrogen
	Phosphate	Phosphate
	Sodium, ion	Sodium, ion
	Zinc	Zinc
	Iron	Iron
	DOC, Dissolved Organic Carbon	DOC, Dissolved Organic Carbon
	TOC, Total Organic Carbon	TOC, Total Organic Carbon

Step 3: Ingot

Inputs	Inventory data	Dataset/elementary flow applied
Technosphere	silicon, production mix, photovoltaics, at plant	Input from polysilicon process
Materials	argon, liquid, at plant	DE: Argon (liquid)
	hydrogen fluoride, at plant	RoW: hydrogen fluoride production (ecoinvnet)
	nitric acid, 50% in H2O, at plant	DE: Nitric acid (60%)
	sodium hydroxide, 50% in H2O, production mix, at plant	DE: sodium hydroxide mix (50%)
	ceramic tiles, at regional storage	RER: Glass cermic production
	lime, hydrated, packed, at plant	DE: Calcium hydroxide (Ca(OH)2; dry; slaked
	electricity, medium voltage, at grid	CN: Electricity grid mix
	natural gas, burned in industrial furnace low-NOx >100kW	CN: natural gas, burned in gas turbine
Resource, in water	water, deionised, water balance according to MoeK 2013, at plant	CN: Water (deionised)
	Water, cooling, unspecified natural origin, CN	Excluded (meets cut-off criteria)
Transport	transport, freight, lorry, fleet average	CN: Transport, truck-trailer (40t total cap., 24.7t payload)
	transport, freight, rail	RER: Rail transport incl. fuel, average
Infrastructure	silicone plant	Excluded (meets cut-off criteria)
Disposal	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	RoW: inert material landfill construction (ecoinvent)
	treatment, sewage, to wastewater treatment, class 2	Municipal wastewater treatment (mix)
Outputs		
Emission, air	Heat, waste	Heat, waste
	Water, CN	Water, CN
	Nitrogen oxides	Nitrogen oxides
Emission water, river	Hydroxide	Hydroxide
	BOD5, Biological Oxygen Demand	BOD5, Biological Oxygen Demand
	COD, Chemical Oxygen Demand	COD, Chemical Oxygen Demand
	DOC, Dissolved Organic Carbon	DOC, Dissolved Organic Carbon
	TOC, Total Organic Carbon	TOC, Total Organic Carbon
	Nitrate	Nitrate

Step 4: Wafer

Inputs	Inventory data	Dataset/elementary flow applied
Technosphere	CZ single crystalline silicon, photovoltaics, at plant	Input from ingot process
	flat glass, uncoated, at plant	RER: Float flat glass
	sodium hydroxide, 50% in H2O, production mix, at plant	DE: Sodium hydroxide mix (50%)
	hydrochloric acid, 30% in H2O, at plant	DE: Hydrochloric acid (32%)
	acetic acid, 98% in H2O, at plant	DE: Acetic acid from methanol (low pressure carbonylation) (Monsanto process)
	dipropylene glycol monomethyl ether, at plant	RoW: Dipropylene glycol monomethyl ether production (ecoinvent)
	alkylbenzene sulfonate, linear, petrochemical, at plant	RoW: Alkylbenzene sulfonate production, linear, petrochemical (ecoinvent)
	acrylic binder, 34% in H2O, at plant	RoW: Acrylic binder production, wit water, in 54% solution state (ecoinvnet)
	brass, at plant	RoW: Brass production (ecoinvnet)
	chromium steel 18/8, at plant	RER: Stainless steel Quarto plate (304)
	wire drawing, steel	RoW: wire drawing, copper
	electricity, medium voltage, at grid	CN: Electricity grid mix
	natural gas, burned in industrial furnace low-NOx >100kW	CN: natural gas, burned in gas turbine
Water	water, deionised, water balance according to MoeK 2013, at plant	CN: Water (deionised)
Disposal	disposal, waste, silicon wafer production, 0% water, to underground deposit	RoW: inert material landfill construction (ecoinvent)
	treatment, sewage, to wastewater treatment, class 2	Municipal wastewater treatment (mix)
Transport	transport, freight, lorry, fleet average	CN: Transport, truck-trailer (40t total cap., 24.7t payload)
	transport, freight, rail	RER: Rail transport incl. fuel, average
Infrastructure	wafer factory	Excluded (meets cut-off criteria)
Outputs		
Emission air	Heat, waste	Heat, waste
	Water, CN	Water, CN
Emission water, river	BOD5, Biological Oxygen Demand	BOD5, Biological Oxygen Demand
	COD, Chemical Oxygen Demand	COD, Chemical Oxygen Demand
	TOC, Total Organic Carbon	TOC, Total Organic Carbon

Step 5: Cell

Inputs	Inventory data	Dataset/elementary flow applied
Wafers	single-Si wafer, photovoltaics, at plant	Input from wafer process
Materials	metallization paste, front side, at plant	RoW: Metallization paste production, front side (ecoinvnet)
	metallization paste, back side, at plant	RoW: Metallization paste production, back side (ecoinvnet)
	metallization paste, back side, aluminium, at plant	RoW: Metallization paste production, back side, aluminium (ecoinvnet)
	ammonia, liquid, at regional storehouse	DE: Ammonia (NH3) without CO2 recovery (carbon dioxide emissions to air)
	phosphoryl chloride, at plant	RoW: Phosphorous chloride production (ecoinvnet)
	isopropanol, at plant	DE: Isopropanol
	hydrochloric acid, 30% in H2O, at plant	DE: Hydrochloric acid (32%)
	hydrogen fluoride, at plant	RoW: Hydrogen fluoride production (ecoinvnet)
	sodium hydroxide, 50% in H2O, production mix, at plant	DE: Sodium hydroxide mix (50%)
	lime, hydrated, packed, at plant	DE: Calcium hydroxide (Ca(OH)2; dry; slaked
	refrigerant R134a, at plant	RoW: Refrigerant R134a production (ecoinvent)
	nitrogen, liquid, at plant	CN: Nitrogen (liquid)
	silane, at plant	Excluded (meets cut-off criteria)
	tap water, water balance according to MoeK 2013, at user	CN: Tap water from surface water
	electricity, medium voltage, at grid	CN: Electricity grid mix
	natural gas, burned in industrial furnace low-NOx >100kW	CN: natural gas, burned in gas turbine
	photovoltaic cell factory	Excluded (meets cut-off criteria)
	transport, freight, lorry, fleet average	CN: Transport, truck-trailer (40t total cap., 24.7t payload)
	transport, freight, rail	RER: Rail transport incl. fuel, average
	treatment, PV cell production effluent, to wastewater treatment, class 3	Municipal wastewater treatment (mix)
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	RoW: inert material landfill construction (ecoinvent)
	disposal, solvents mixture, 16.5% water, to hazardous waste incineration	RoW: treatment of hazardous waste, hazardous waste incineration (ecoinvent)
Emission air, high population density	Heat, waste	Heat, waste
	Water, CN	Water, CN
	Aluminium	Aluminium
	Hydrogen fluoride	Hydrogen fluoride
	Lead	Lead
	Silicon	Silicon
	Silver	Silver
	Tin	Tin
	Ammonia	Ammonia
	Carbon dioxide, fossil	Carbon dioxide, fossil
	Chlorine	Chlorine
	Hydrogen	Hydrogen

	2-Propanol	2-Propanol
	Acetaldehyde	Acetaldehyde
	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a
	NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC, non-methane volatile organic compounds, unspecified origin

Step 6: Panel

Inputs	Inventory data	Dataset/elementary flow applied
Materials	photovoltaic cell, single-Si, at plant	Input from cell production
	aluminium alloy, AlMg3, at plant	CN: Aluminium extrusion profile
	copper, at regional storage	GLO: Copper mix (99.999% from electrolysis)
	wire drawing, copper	RoW: wire drawing, copper
	diode, unspecified, at plant	GLO: Diode production, glass, for surface-mounting (ecoinvnet)
	silicone product, at plant	RER: Silicone sealing compound (EN15804 A1-A3)
	tin, at regional storage	RoW: Tin production (ecoinvnetn)
	lead, at regional storage	DE: Lead (99.995%)
	solar glass, low-iron, at regional storage	RER: Float flat glass
	tempering, flat glass	GLO: tempering, flat glass (ecoinvent)
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RoW: Glass fibre reinforced plastic production
	polyethylene terephthalate, granulate, amorphous, at plant	DE: Polyethylene terepthalatae granulate (PET via DMT)
	polyethylene, HDPE, granulate, at plant	RER: Polyethylene, HDPE, granulate
	ethylvinylacetate, foil, at plant	RoW: ethylvinylacetate production, foil (ecoinvent)
	polyvinylfluoride film, at plant	RoW: Polyvinylfluoride, film production (ecoinvent)
	tap water, water balance according to MoeK 2013, at user	CN: Tap water from surface water
	hydrogen fluoride, at plant	RoW: Hydrogen fluoride production (ecoinvnet)
	1-propanol, at plant	RoW: 1-propanol production (ecoinvnet)
	isopropanol, at plant	DE: Isopropanol
	potassium hydroxide, at regional storage	RoW: Potassium hydroxide production (ecoinvet)
	soap, at plant	RoW: soap production (ecoinvent)
	corrugated board, mixed fibre, single wall, at plant	RoW: corrugated board box production (ecoinvent)
	EUR-flat pallet	RoW: EUR-flat pallet production (ecoinvent)
	electricity, medium voltage, at grid	CN: Electricity grid mix
	diesel, burned in building machine, average	GLO: diesel, burned in building machine (ecoinvent)
	photovoltaic panel factory	Excluded (meets cut-off criteria)
	transport, freight, lorry, fleet average	CN: Transport, truck-trailer (40t total cap., 24.7t payload)
	transport, freight, rail	RER: Rail transport incl. fuel, average
	disposal, municipal solid waste, 22.9% water, to municipal incineration	RER: Commercial waste in municipal waste incineration plant (0% H2O content)
	disposal, polyvinylfluoride, 0.2% water, to municipal incineration	RER: Commercial waste in municipal waste incineration plant (0% H2O content)
	disposal, plastics, mixture, 15.3% water, to municipal incineration	RER: Commercial waste in municipal waste incineration plant (0% H2O content)

	disposal, used mineral oil, 10% water, to hazardous waste incineration	RER: Commercial waste in municipal waste incineration plant (0% H2O content)
	treatment, sewage, from residence, to wastewater treatment, class 2	RER: Municipal wastewater treatment (mix)
Outputs		
Emissions air	Heat, waste	Heat, waste
	NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC, non-methane volatile organic compounds, unspecified origin
	Carbon dioxide, fossil	Carbon dioxide, fossil
	Water, CN	Water, CN

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