Assessing the Environmental Impacts of Renewable Energy Sources: A Life Cycle Perspective Using Solar Panel Models and Case Studies

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Introduction

The decarbonisation of the energy sector requires not only a rapid expansion of renewable electricity generation but also a careful assessment of the environmental impacts associated with these technologies. Photovoltaic (PV) modules are among the key enablers of the energy transition. While their operational phase is virtually emission-free, the processes of raw material extraction, manufacturing, transport, installation, and end-of-life treatment involve resource use and emissions that must be addressed in order to provide a complete picture of their sustainability.

Life Cycle Assessment (LCA) offers a systematic framework to quantify these impacts across the full life cycle of a product, from cradle to grave. This article presents the results of a collaborative study carried out by STH Consulting and VSB–Technical University of Ostrava. The analysis is based on a representative dataset of photovoltaic modules, derived from Environmental Product Declarations (EPDs) of multiple manufacturers. The objective is to derive aggregated emission factors and practical conversion tools that can be used both for applied decision-making in industry.

The study follows the main life cycle phases defined by EN 15804: A1–A3 (raw material supply, transport, and manufacturing), A4 (transport to site), A5 (installation), B1–B7 (operation), and C–D (end-of-life and benefits beyond the system boundary). By combining aggregated results with scenario-based calculations, the study provides both robust average indicators and flexible methods to adapt results to specific cases. In addition, practical tools such as conversion factors between weight and power, transport calculators, and payback time indicators are introduced to support consistent and transparent assessments.

1 Dataset and Conversion Factors

The dataset underlying this assessment consisted of a series of photovoltaic modules from different manufacturers, for which Environmental Product Declarations (EPDs) were available and are listed in the reference section (3S Swiss Solar Solutions AG, 2024; Abora Energy, 2022; First Solar, 2023; LONGi Green Energy Technology Co., Ltd., 2023; Midsummer AB, 2022a, 2022b, 2022c; Qinghai Huanghe Hydropower Development CO., Ltd. Xining Solar Power Branch, 2023; Risen Energy Co., Ltd., 2022; SunPower, 2021; Viridian Solar Ltd., 2023; Win Win Precision Technology Co., Ltd., 2024). These documents provided the basis for deriving the material composition, weight, and emission intensity of the reference module.

In order to enable a consistent comparison of results, a conversion ratio between the functional units of 1 Wp and 1 kg of module weight was established. A strong correlation ($r = 0.96$) between module weight and power output confirmed that both parameters are closely dependent. On this basis, the median ratio of all considered models was calculated, resulting in a value of 19.7 Wp/kg. This factor can be applied to convert data between weight- and power-based functional units, ensuring comparability and consistency across different models and case studies.

2 Production Phase

A1–A3: Raw Material Supply, Transport, and Manufacturing

Phases A1–A3 represent the upstream environmental impacts of photovoltaic modules, covering raw material extraction and processing (A1), transport of materials (A2), and manufacturing processes (A3).

Based on the Environmental Product Declarations (EPDs) of the analyzed models, an aggregated representative reference module was defined with a weight of approximately 21 kg. The corresponding material composition is presented in Table 1. This representative composition can be applied as a default model in cases where specific product data are unavailable, ensuring comparability and providing a practical baseline for further assessments.

For those models where the EPDs reported phases A1, A2, and A3 separately, the relative contributions of each phase were determined. The resulting average distribution was established as 89% for A1, 4% for A2, and 7% for A3. This distribution was applied to aggregated values in cases where the EPDs reported only a single combined value for A1–A3, which is a common practice. This approach enables the estimation of the emission intensity of individual sub-phases, even where disaggregated data are not available.

In addition, coefficients of installation-related emission load were aggregated from the available models, resulting in values of 0.02 kg CO_2 per Wp and 0.39 kg CO_2 per kg of panel weight. These coefficients allow for scalable es-

Table 1: Average material composition of the representative solar panel

Material	Share (%)
Glass	49.0
Plastics	26.0
Aluminium	8.0
Steel and iron	7.0
Electronics	6.5
Rubber	0.5
Others	3.0

timations of installation emissions depending on the size and configuration of photovoltaic systems.

A4: Transport

Phase A4 covers the environmental impacts associated with the transport of photovoltaic modules from the production site to the place of installation. Transport emissions depend on three key parameters: the transported weight of the module, the transport distance, and the type of transport mode. In this study, specific emission factors for road, sea, and rail transport were derived from Environmental Product Declarations (EPDs) and supporting literature, and used to model transport-related greenhouse gas emissions.

The calculation was designed to be applicable both to individual modules and to larger system comparisons. Depending on data availability, either the panel weight W (in kilograms) or the rated power P (in Wp) is taken as input. A conversion factor $k = 19.7$ Wp/kg, determined from the dataset, allows switching between weight and power. If neither W nor P are available, the reference module weight is applied as the default.

Transport distances are entered by mode ($d_{\text{road}}, d_{\text{sea}}, d_{\text{rail}}$). Where distances are unknown, scenario-based assumptions are used (e.g., distinguishing between national, regional, or global supply chains). These scenarios are defined by representative average distances collected from case studies in the dataset.

Calculation principle. Emission factors EF for the different modes are expressed in g CO_2e/tkm. Therefore, the panel weight W must first be converted into tonnes:

$$W_{\text{t}} = \frac{W\,[\text{kg}]}{1000}$$

Emissions per transport mode are then calculated as:

$$E_{\text{mode,g}} = W_{\text{t}} \cdot EF_{\text{mode}} \cdot d_{\text{mode}}$$

where $E_{\text{mode,g}}$ is the emission in grams CO_2e. To obtain the result in kilograms:

$$E_{\text{mode,kg}} = \frac{E_{\text{mode,g}}}{1000}$$

The total transport emissions per panel are then:

$$E_{\text{A4,panel}} = E_{\text{road}} + E_{\text{sea}} + E_{\text{rail}}$$

For reporting in functional units, the following conversions are applied:

$$E_{\text{A4, per Wp}} = \frac{E_{\text{A4,panel}}}{P}, \qquad E_{\text{A4, per kg}} = \frac{E_{\text{A4,panel}}}{W}$$

The logic of the transport calculation, including input requirements, conversions, and the handling of missing data, is summarized in Figure 1.

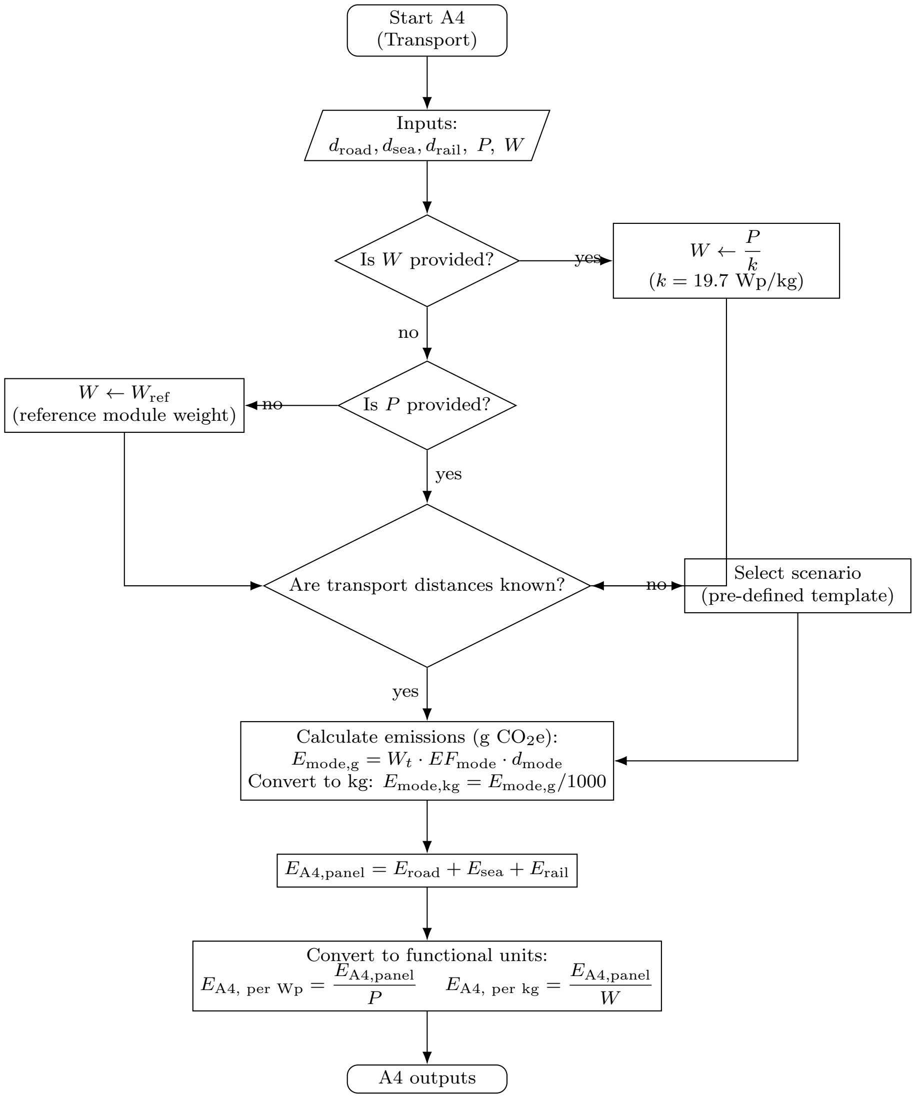

Figure 1: Algorithm for calculating transport emissions in Phase A4. Emission factors EF are expressed in g CO_2e/tkm; panel mass W is converted to tonnes (W_t) prior to calculation.

Illustrative Example for the Reference Module

Inputs. Reference module: $P = 420$ Wp, conversion factor $k = 19.7$ Wp/kg $\Rightarrow W = \frac{P}{k} \approx 21.32$ kg. Converted to tonnes: $W_t = 0.02132$ t.

Transport distances (illustrative): $d_{\text{road}} = 120$ km, $d_{\text{rail}} = 400$ km, $d_{\text{sea}} = 7800$ km.

Mode-specific emission factors (in g CO_2e/tkm): Road (average): 155, Rail: 15, Sea: 7.

Mode-wise emissions.

$$\begin{aligned} E_{\text{road}} &= 0.02132 \cdot 155 \cdot 120 = 397\,\text{g} \approx 0.397\,\text{kg}, \\ E_{\text{rail}} &= 0.02132 \cdot 15 \cdot 400 = 128\,\text{g} \approx 0.128\,\text{kg}, \\ E_{\text{sea}} &= 0.02132 \cdot 7 \cdot 7800 = 1162\,\text{g} \approx 1.162\,\text{kg}. \end{aligned}$$

Total per panel and functional units.

$$\begin{aligned} E_{\text{A4,panel}} &\approx 1.687 \text{ kg } CO_2\text{e/panel}, \\ E_{\text{A4, per Wp}} &= \frac{1.687}{420} \approx 0.0040 \text{ kg } CO_2\text{e/Wp}, \\ E_{\text{A4, per kg}} &= \frac{1.687}{21.32} \approx 0.079 \text{ kg } CO_2\text{e/kg}. \end{aligned}$$

Table 2: Mode-wise breakdown of A4 transport emissions for the reference module (using average road factor 155 g CO_2/tkm)

Transport mode	kg CO_2e / panel	Share (%)
Road (avg. 155 g/tkm)	0.397	23.5
Rail	0.128	7.6
Sea	1.162	68.9
Total	1.687	100.0

This example demonstrates that, for long-distance transport chains, sea freight is the dominant contributor to transport-related emissions, while road and rail transport play a smaller but non-negligible role.

A1–A5: Overall Production Footprint

The production phase (A1–A5) covers all processes from raw material supply (A1), transport of input materials (A2), manufacturing (A3), transport to the construction site (A4), and installation (A5). This stage therefore represents the complete upstream and construction-related burden of photovoltaic modules prior to their operational lifetime.

For the aggregation of emission values across the analyzed models, the statistical median was applied in order to minimize the influence of extreme values and to derive a robust central tendency. The reference module for this assessment was defined with a nominal power of 420 Wp.

Based on the available dataset, the emission intensity of the production phase was determined as 0.36 kg CO_2e per Wp. For the reference module of 420 Wp, this corresponds to a total cradle-to-installation footprint of approximately 149.7 kg CO_2e.

It should be noted that phase A5 (installation) was simplified to zero. This approach follows established LCA practice, as the installation process generally contributes less than 1% to the overall life cycle impacts, primarily consisting of packaging waste and minor on-site energy use. The negligible contribution of this phase justifies its exclusion without affecting the robustness of the overall results. (Sustainable Minds, 2018)

Operation Phase

The operational phase of photovoltaic modules (B1–B7) was simplified to zero, as the direct environmental impacts during use are negligible. Solar panels do not generate emissions while producing electricity, and maintenance requirements are minimal, typically limited to occasional cleaning with water or the replacement of auxiliary components. In line with EN 15804 and established LCA practice, such contributions generally fall below the 1% cut-off threshold and are therefore excluded from the quantified life cycle inventory. Instead, the operational phase is primarily relevant for calculating performance indicators such as Energy Payback Time or CO_2 Payback Time, which express the time required for the system to offset the environmental burden of its production phase (Circular Ecology, n.d.; Frischknecht et al., 2015)

Operational Phase Indicators: Energy and CO_2 Payback Times

Although the operational phase of photovoltaic modules was simplified to zero in terms of direct environmental burdens, it remains relevant for performance indicators that express how quickly the production-related impacts are offset during use. Two key indicators were therefore calculated: the Energy Payback Time (EPBT) and the CO_2 Payback Time (CPBT).

Energy Payback Time (EPBT). EPBT expresses the number of years required for a photovoltaic module to generate the same amount of energy that was invested into its production. It is calculated as:

$$EPBT = \frac{E_{\text{inv}}}{E_{\text{ann}}}$$

where E_{inv} is the total primary energy invested in the module production (phases A1–A3), and E_{ann} is the average annual electricity output of the module over its reference service life. The electricity output in the first year of operation was determined using the following expression:

$$E_1 = S_{\text{rad}} \times A \times y \times PR \times (1 - \text{deg})$$

with S_{rad} as site-specific solar irradiation, A the module area, y the module yield (Wp/m^2), PR the performance ratio, and deg the annual degradation rate. The reference service life was assumed to be 25 years, and total electricity production was obtained by summing degraded annual outputs across the lifetime.

CO_2 Payback Time (CPBT). CPBT expresses the number of years required for a module to compensate, through avoided grid emissions, the greenhouse gas emissions associated with its production. It is calculated as:

$$CPBT = \frac{GWP_{\mathrm{A1–A5}}}{E_{\mathrm{ann}} \times EF_{\mathrm{el}}}$$

where $GWP_{\mathrm{A1–A5}}$ is the global warming potential of the production phase, E_{ann} is the average annual electricity output of the module, and EF_{el} is the emission factor of the displaced grid electricity. For this purpose, the EU average grid emission factor of 213.3 g CO_2e/kWh was applied.

Results. For those models where the necessary parameters were available in the EPDs, EPBT and CPBT values were calculated following the above methodology. The aggregated values are shown in Table 3.

Table 3: Aggregated results of Energy and CO_2 Payback Times

	EPBT (years)	CPBT (years)
Median value	2.19	2.02

These results indicate that photovoltaic modules typically offset both their embodied energy and carbon footprint within approximately two years of operation, while continuing to provide net positive environmental benefits over their 25-year lifetime.

End-of-life Phase

According to the WEEE Directive 2012/19/EU, specifically Article 11 and Annex V, products in category 4 – including photovoltaic panels – are required to achieve at least 85% recovery of their total weight and at least 80% preparation for reuse and recycling. In practice, this means that from every 100 kg of panel material, a minimum of 85 kg must be directed into recovery processes, while the remaining 15 kg constitute residual waste streams. These residues typically consist of materials such as encapsulant foils (EVA) and mixed plastics, which are disposed of either through landfilling or incineration.

End-of-life emissions were calculated using the following expression:

$$E_{\mathrm{recycling}} = \left(\frac{C2}{1\,\mathrm{km}} \times \text{Transport distance [km]} \right) + C3 + C4 + D$$

where $C2$ represents transport-related emissions, $C3$ the impacts from waste processing, $C4$ the emissions from disposal, and D the credits from material recovery. Transport distances were aggregated based on case studies provided in the source documents, while the default assumption according to the PCR is 50 km of road transport. The calculated results were then expressed either per unit weight of the module or per nominal power output (Wp).

In addition to standard recovery scenarios, advanced recycling technologies such as the *Full Recycling End-of-Life Procedure (FRELP)* have been developed, for example within EU projects such as PV CYCLE. The aim of this process is to separate and recycle the majority of valuable panel components, including glass, aluminium, silicon, copper, and silver. Reported recovery rates for this method reach 90–95% of the module mass, although not all recovered fractions can be reused in their original material quality.

Phase D represents an indirect effect of the product, reflecting the potential environmental benefits that arise in the future when recycled materials substitute the production of primary raw materials.

The aggregated result for the end-of-life phase was determined as -0.051 kg CO_2e per Wp. This negative value indicates that the environmental credits obtained from material recovery and recycling outweigh the residual burdens of treatment and disposal, leading to a net environmental benefit in this life cycle stage.

Table 4: End-of-life balance of photovoltaic panels (Phase D)

Parameter	Value
Recovery rate (WEEE requirement)	85%
Recycling rate (WEEE requirement)	80%
Residual waste (landfill/incineration)	15%
Advanced method (FRELP)	90–95% recovery
Aggregated result (kg CO_2e per Wp)	-0.051

For the reference module defined in this study with a nominal power of 420 Wp, the aggregated coefficient of -0.051 kg CO_2e/Wp corresponds to a total of approximately -21.4 kg CO_2e. This means that, at the end-of-life stage, the recycling and recovery processes of the reference module would return more than twenty kilograms of CO_2e savings compared to the burdens associated with disposal.

Conclusion

This collaborative study by STH Consulting and VSB–Technical University of Ostrava presented a comprehensive life cycle assessment of photovoltaic modules, combining information from multiple Environmental Product Declarations into a harmonised dataset. A representative reference module with a power of 420 Wp and a weight of approximately 21 kg was defined, enabling consistent comparisons across different models and use cases.

The results confirm that the majority of greenhouse gas emissions are concentrated in the production phase (A1–A3), while transport (A4) and installation (A5) contribute relatively little to the overall footprint. The operation phase (B1–B7) was simplified to zero in line with established LCA practice, with additional insights provided by performance indicators such as Energy Payback Time (EPBT) and CO_2 Payback Time (CPBT). Both indicators showed that PV modules offset their embodied energy and carbon footprint within approximately two years of operation. The end-of-life phase (C–D) demonstrated a net environmental benefit, with credits from material recovery exceeding the burdens of recycling and disposal.

Overall, the study highlights that photovoltaic technology delivers a very favourable environmental balance: after a short payback period, modules provide decades of emission-free electricity generation. By publishing aggregated values and practical calculation methods, this work aims to support researchers, industry practitioners, and policymakers in applying LCA to renewable energy technologies in a transparent and consistent manner. Future research should focus on improving the granularity of recycling data, updating emission factors for transport and manufacturing as supply chains evolve, and extending the methodology to other renewable technologies for holistic energy system assessments.

Key findings at a glance:

- **Production phase (A1–A5):** 0.36 kg CO_2e/Wp, corresponding to approx. 150 kg CO_2e per reference module (420 Wp).
- **Installation (A5):** negligible, simplified to zero in line with cut-off criteria.
- **Operation phase (B1–B7):** direct impacts simplified to zero; instead evaluated via indicators.
- **EPBT (Energy Payback Time):** 2.19 years (median).
- **CPBT (CO_2 Payback Time):** 2.02 years (median).
- **End-of-life phase (C–D):** aggregated result –0.051 kg CO_2e/Wp, equivalent to about –21 kg CO_2e for the reference module, demonstrating net environmental benefits from recycling.

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