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Original Research

Scenario-Based Assessment of Life-Cycle GHG Emissions from Grid-Connected Photovoltaic Systems under Different Electricity Mixes

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Abstract

This study evaluates the carbon-related performance of grid-connected photovoltaic (PV) systems under different electricity-generation mixes using a literature-based, scenario-oriented life-cycle GHG emissions assessment. A 1 MWp utility-scale crystalline-silicon PV reference system was defined with an annual electricity generation of 1,640 MWh, a 30-year lifetime, and an annual degradation rate of 0.5%, resulting in a projected cumulative electricity output of 45,793.99 MWh. The analysis considered three benchmark electricity-mix scenarios: a high-carbon grid, a transitioning grid, and a low-carbon benchmark grid. The gross life-cycle GHG burden of the PV system was interpreted using a literature-based range of 10-36 g CO_2e/kWh, with 19 g CO_2e/kWh adopted as the median reference case. Results show that scenario-estimated avoided emissions and net GHG benefits are highest in carbon-intensive electricity systems and decrease progressively as grid carbon intensity declines. Nevertheless, the net GHG benefit remains positive across all benchmark scenarios and across the tested PV emission-factor range. The findings indicate that PV deployment provides the greatest immediate GHG mitigation in fossil-intensive grids, while long-term improvements depend on cleaner manufacturing, low-carbon supply chains, circular economy strategies, and responsible end-of-life management. Because the analysis relies on literature-derived PV emission factors and average grid carbon-intensity benchmarks, the results should be interpreted as comparative scenario estimates rather than as outputs from a full process-based LCA model.

Keywords

Photovoltaic systems; life-cycle GHG emissions; electricity mix; grid-connected PV; avoided emissions; net GHG benefit; carbon-related performance; scenario assessment; utility-scale solar

1. Introduction

Photovoltaic (PV) technology has become one of the most important pillars of the transition toward low-carbon electricity systems. Its deployment has accelerated markedly in recent years, with global cumulative installed PV capacity exceeding 2.2 TW by the end of 2024 and more than 600 GW added in that year alone [1]. This growth confirms that PV is among the fastest-growing electricity generation technologies worldwide and highlights its increasing importance for decarbonization, energy diversification, and long-term resilience to fossil-fuel market volatility [2]. However, the rapid expansion of PV capacity also requires a careful assessment of its carbon-related performance across different electricity-generation contexts, particularly because the benefits of PV deployment depend not only on the technology itself, but also on manufacturing conditions, system performance, and the carbon intensity of the electricity that PV generation displaces.

From an environmental perspective, PV systems exhibit one of the lowest life-cycle greenhouse gas (GHG) profiles among commercial electricity generation options. Recent assessments of utility-scale solar report cradle-to-grave emissions of approximately 10-36 g CO_2e/kWh, which are substantially lower than the life-cycle emissions associated with fossil-based generation [3, 4]. At the same time, the global PV market is overwhelmingly dominated by crystalline silicon technology, which represented about 98% of total module production in 2024. This technological dominance makes crystalline-silicon systems the most representative basis for contemporary environmental assessment of grid-connected PV installations [5]. However, the carbon performance of photovoltaic systems cannot be inferred solely from operational emissions.

Although PV electricity is generated without direct emissions at the point of use, its overall footprint is shaped by raw material extraction, silicon purification, wafer and cell manufacturing, module assembly, transportation, installation, operation, maintenance, and end-of-life treatment. For this reason, a life-cycle perspective is necessary to interpret PV-related GHG emissions more accurately. Nevertheless, the present study does not develop a full process-based LCA with an original life-cycle inventory, process modeling, allocation rules, or database-specific modeling. Instead, it is framed as a literature-based, scenario-oriented assessment of life-cycle GHG emissions and avoided emissions from grid-connected PV systems. This clarification is important because the numerical evaluation relies on selected emission factors and grid carbon-intensity values reported in the literature, rather than on a newly constructed inventory model [6].

A particularly critical variable in this context is the electricity generation mix. The electricity mix affects PV systems in two distinct but interconnected ways. First, it influences the embodied impacts of manufacturing, especially in electricity-intensive stages such as silicon purification and cell production. In this sense, PV systems carry an initial environmental carbon debt, the magnitude of which depends strongly on the carbon intensity of the manufacturing supply chain. Recent studies show that China's PV production accounts for a very large share of the global PV carbon footprint, illustrating how manufacturing geography can materially alter life-cycle outcomes. Second, the electricity mix also determines the environmental significance of PV deployment during operation, since the benefit of solar electricity depends on the type of grid electricity displaced. Consequently, the same PV system may exhibit different GHG relevance depending on whether it offsets coal-dominated, gas-dominated, or already low-carbon electricity systems [7, 8]. In this study, the electricity mix is therefore treated as a key scenario variable for comparing how PV life-cycle emissions and avoided emissions change across different grid contexts.

This issue is closely linked to the global restructuring of PV supply chains. Differences in national grid carbon intensity imply that relocating PV manufacturing from more carbon-intensive electricity systems to lower-carbon industrial regions could significantly modify life-cycle results. Fraunhofer analyses also show that the energy payback time (EPBT) of PV systems varies with manufacturing and installation context; for example, systems manufactured in Europe and installed in Northern Europe require approximately 1.1 years to recover the energy invested, while irradiation and regional grid conditions can further shorten or lengthen this period [7, 9, 10]. Although EPBT is not necessarily the primary endpoint of every LCA study, it remains an important complementary metric because it captures how rapidly a PV system repays the energy required for its production and deployment [11]. Accordingly, EPBT is considered here as a complementary indicator that supports the interpretation of life-cycle emission results, especially when comparing different manufacturing locations, installation contexts, and grid conditions.

Another increasingly important dimension is circularity and end-of-life management**.** The very scale that now makes PV strategically significant also implies a growing future stream of retired modules. Joint IRENA-IEA PVPS projections estimate that cumulative PV panel waste could reach 78 million tonnes globally by 2050, which elevates end-of-life treatment from a marginal issue to a central component of long-term PV sustainability planning [12, 13]. This makes a life-cycle perspective especially relevant, since future deployment strategies must be evaluated not only in terms of current emissions reductions, but also considering material recovery, recycling infrastructure, and circular-economy opportunities. However, because this study focuses primarily on GHG emissions and avoided emissions, broader environmental categories such as mineral resource depletion, land use, toxicity, water use, and detailed end-of-life impacts are treated as relevant limitations and future research needs rather than as fully modeled impact categories.

Simultaneously, environmental assessment of PV systems should be conducted at the system level, rather than being limited to cell or module characteristics alone. Earlier PV LCA literature often focused primarily on cell technologies or module production. In contrast, complete grid-connected plants also depend on balance-of-system components, inverter configuration, structural supports, site conditions, and operational energy yield. This distinction is crucial because differences in plant design and the surrounding electricity context can significantly influence total carbon-related performance. More recent reviews have also emphasized that differences in system boundaries, functional units, data quality, and regional inventories continue to generate variability across PV LCA studies, underscoring the need for transparent and scenario-based comparisons. Therefore, the contribution of this study is not the general claim that PV systems reduce emissions, which is already well established, but rather the transparent comparison of how life-cycle GHG emissions and avoided emissions vary under different electricity mixes, manufacturing contexts, and system assumptions.

As PV penetration increases in modern power systems, broader grid-integration issues also become relevant. IEEE 1547-2018 establishes technical requirements for interconnection and interoperability of distributed energy resources, including functions related to reactive power capability, voltage and power control, abnormal operating response, and associated interface performance. Although these aspects are not treated here as primary analytical variables, they provide relevant technical context for understanding the operational environment in which grid-connected PV systems are deployed. In the present study, the system boundary is limited to grid-connected PV generation without battery energy storage to preserve clarity in the environmental interpretation of the photovoltaic system itself [14]. This delimitation avoids adding the material, operational, and end-of-life burdens associated with storage technologies. It allows the analysis to focus specifically on PV generation, degradation-adjusted electricity output, grid carbon intensity, and avoided emissions. As shown in Table 1, previous literature has established that PV systems generally present lower life-cycle GHG emissions than fossil-based electricity generation. However, existing studies often address emission benchmarks, manufacturing geography, EPBT, grid context, and end-of-life considerations separately.

Table 1 Positioning of the present study within previous PV life-cycle emissions literature.

Literature focus	What previous studies show	Gap addressed by this study	Key references
PV life-cycle GHG emissions	PV systems have substantially lower life-cycle GHG emissions than fossil-based electricity generation.	Although emission benchmarks are well established, fewer studies compare how life-cycle GHG emissions and avoided emissions vary across different electricity-generation mixes using a transparent scenario-based approach.	[3, 4]
Technology and manufacturing context	Crystalline-silicon PV dominates global module production, and manufacturing location affects embodied emissions through electricity carbon intensity.	This study links PV technology representativeness and manufacturing context with deployment-grid conditions to interpret how PV benefits change across scenarios.	[5, 7, 8]
Energy recovery and system performance	EPBT varies according to manufacturing location, installation region, irradiation, and system performance.	This study uses EPBT as a complementary indicator, while focusing primarily on life-cycle GHG emissions and avoided emissions under different grid mixes.	[9-11]
End-of-life and circularity	PV waste growth makes recycling, material recovery, and circular economy strategies increasingly important.	This study incorporates circularity as a strategic consideration, while recognizing that detailed end-of-life impacts are not fully modeled.	[12, 13]
Present study	The general conclusion that PV reduces emissions compared with fossil-based electricity is already well established.	The contribution of this study is a literature-based, scenario-oriented assessment showing how life-cycle GHG emissions and avoided emissions from grid-connected PV systems vary according to electricity-generation mix, manufacturing context, degradation-adjusted generation, and selected system assumptions.	This study

Source: Prepared by the authors.

Table 1 summarizes the main areas addressed in previous PV life-cycle research and the gap considered in the present study. The novelty of this work lies in integrating these dimensions into a literature-based, scenario-oriented assessment that compares life-cycle GHG emissions and avoided emissions from grid-connected PV systems under different electricity-generation mixes.

Using a literature-based, scenario-oriented life-cycle GHG emissions framework, this study evaluates the carbon-related performance of grid-connected photovoltaic systems under different electricity-generation mixes. The analysis examines how variations in electricity supply conditions, manufacturing context, and displaced grid electricity shape PV-related emissions and avoided emissions. The study also recognizes that average grid carbon-intensity values provide a simplified representation of avoided emissions and that future grid decarbonization may modify long-term results. These aspects are therefore addressed as important methodological considerations for interpreting the scenarios. By addressing the interaction between PV system configuration, manufacturing context, displaced grid electricity, and end-of-life considerations, the study provides decision-relevant insights for sustainable PV deployment, low-carbon manufacturing, long-term circularity planning, and energy-system design in increasingly decarbonized electricity systems [15].

2. Materials and Methods

2.1 Goal and Scope

2.1.1 Study Design

This study employed a literature-based, scenario-oriented life-cycle GHG emissions assessment to evaluate the carbon-related performance of grid-connected photovoltaic (PV) systems under different electricity-generation mixes. The analysis was based on publicly accessible technical and environmental datasets to ensure transparency, reproducibility, and comparability. The study did not develop a full process-based life cycle assessment (LCA) with an original life-cycle inventory, process-specific modeling, allocation rules, or database-specific modeling. Instead, it used selected life-cycle PV emission factors from the literature, annual PV electricity generation estimates, and grid carbon-intensity values to construct comparative scenarios. The analysis focused on GHG emissions and avoided emissions, while grid integration was considered only as general contextual elements [16].

This study was not designed as a systematic literature review. Instead, literature-derived values were selected to support a transparent scenario-based assessment of life-cycle GHG emissions from grid-connected PV systems. The sources were selected based on their relevance to utility-scale photovoltaic systems, public availability, methodological transparency, recent publication date, consistency with life-cycle GHG assessment practices, and applicability to the technical assumptions of the 1 MWp reference system. Priority was given to peer-reviewed studies, international technical reports, and publicly available datasets from recognized institutions such as NREL, IEA PVPS, Fraunhofer ISE, PVGIS, and Ember. Therefore, the numerical assessment should be interpreted as a literature-based, publicly supported scenario comparison, rather than as a systematic literature review or a full process-based life-cycle inventory model.

2.1.2 Functional Unit and System Boundaries

The functional unit was defined as 1 kWh of AC electricity delivered to the grid. The assessment followed a life-cycle perspective and considered the main stages commonly associated with grid-connected PV systems: raw material extraction, manufacturing, transportation, installation, operation and maintenance, and end-of-life treatment. These stages were represented through life-cycle GHG emission factors reported in the literature, rather than through a newly constructed process-based inventory. Battery energy storage was excluded from the system boundary to preserve the focus on grid-connected PV generation and avoid adding the additional material, operational, and end-of-life burdens associated with storage technologies [4, 12].

2.2 Data Sources and Scenario Definition

2.2.1 Public Data Sources

The analysis was developed using publicly accessible databases and technical reports. Annual photovoltaic electricity generation was estimated using PVGIS. Life-cycle greenhouse gas emission factors for photovoltaic electricity were obtained from public NREL reports. Carbon intensity values for different electricity mixes were taken from publicly available electricity datasets. These sources were selected because they provide transparent and reproducible information suitable for a comparative theoretical assessment [4].

2.2.2 Definition of Electricity Mix Scenarios

Three comparative electricity-mix scenarios were considered in the present study:

- A carbon-intensive electricity mix.
- An intermediate electricity mix.
- A low-carbon electricity mix.

These scenarios were used to evaluate how the carbon relevance of photovoltaic electricity changes depending on the carbon intensity of the surrounding grid [17, 18]. The scenarios were defined as comparative analytical benchmarks, rather than as representations of a single national electricity system. Therefore, the results should be interpreted as scenario-based comparative estimates. The present study uses average grid carbon-intensity values as comparative benchmarks. This approach was selected to preserve transparency, reproducibility, and compatibility with publicly available datasets. However, average emission factors do not necessarily represent the marginal generators displaced by PV electricity. Marginal emission factors may provide a more precise estimate of avoided emissions in consequential assessments, particularly when the displaced generation source varies by time of day, season, demand profile, and dispatch conditions. Accordingly, the avoided-emissions results should be interpreted as comparative-scenario estimates, not as definitive consequential displacement estimates.

2.3 Calculation Procedure

2.3.1 Lifetime Electricity Generation

The total electricity generated during the system lifetime was estimated using annual electricity production data, the assumed operational lifetime of the photovoltaic system, and the annual degradation rate. Since PV output decreases progressively over time, the calculation was performed as follows:

$$E_{life} = E_{annual} \times \frac{[1-(1-d)^N]}{d} \tag{1}$$

where E_{life} is the lifetime electricity generation, E_{annual} is the first-year annual electricity output, d is the annual degradation rate, and N is the system lifetime in years. The degradation rate was expressed as a decimal; for example, 0.5% per year corresponds to 0.005.

2.3.2 Gross Life-Cycle Greenhouse Gas Emissions

The total life-cycle greenhouse gas emissions of the photovoltaic system were estimated from the literature-based emission factor for PV electricity:

$$GHG_{PV,total} = EF_{PV} \times E_{life} \tag{2}$$

where $GHG_{PV,total}$ is the total greenhouse gas emissions associated with the PV system over its lifetime, EF_{PV} is the life-cycle greenhouse gas emission factor of the PV system, and E_{life} is the lifetime electricity generation [19, 20].

2.3.3 Avoided Emissions under Different Electricity Mixes

To compare the environmental benefit of photovoltaic electricity under different grid conditions, the avoided emissions were estimated as:

$$GHG_{avoided} = EF_{grid} \times E_{life} \tag{3}$$

where $GHG_{avoided}$ is the amount of greenhouse gas emissions avoided by the PV system, EF_{grid} is the carbon intensity of the electricity mix considered, and E_{life} is the lifetime electricity generation.

The GHG mitigation benefit was calculated as:

$$GHG_{net\ benefit} = GHG_{avoided} - GHG_{PV,total} \tag{4}$$

A positive value indicates that the photovoltaic system emits fewer emissions than it generates over its life cycle [16].

2.3.4 Comparative Reduction Indicator

To facilitate interpretation, the percentage reduction in greenhouse gas emissions achieved by photovoltaic electricity relative to each electricity mix was calculated as:

$$Reduction(\%) = \left(\frac{EF_{grid} - EF_{PV}}{EF_{grid}}\right) \times 100 \quad (5)$$

where EF_{grid} is the carbon intensity of the compared electricity mix and EF_{PV} is the life-cycle greenhouse gas intensity of the photovoltaic system.

2.4 Interpretation and Limitations

2.4.1 Interpretation of Results

The results were interpreted as a comparative scenario-based assessment using publicly available data and literature-derived parameters. The main purpose was to determine how the carbon-related environmental performance of grid-connected photovoltaic systems changes under different electricity-generation mixes and to identify the extent to which grid carbon intensity influences the relative advantage of photovoltaic electricity [8]. Therefore, the results should be understood as comparative estimates rather than as outputs from a full process-based life-cycle inventory model.

2.4.2 Study Limitations

This study does not represent a full industrial process-based LCA with proprietary inventories. Instead, it provides a simplified but transparent comparative approach based on publicly accessible information. Power quality, voltage regulation, and interoperability were acknowledged as relevant contextual issues for grid-connected photovoltaic systems, but they were not modelled as primary variables.

3. Results

3.1 Reference PV System and Electricity Mix Scenarios

3.1.1 Reference PV System Characteristics

To ensure that the comparative assessment reflects the current technological mainstream of utility-scale photovoltaic deployment, a representative grid-connected crystalline-silicon PV system was selected as the reference case. This choice was made to balance technological relevance with methodological clarity. Rather than defining a highly specialized or site-specific configuration, the reference system was designed to represent a contemporary commercial installation suitable for a literature-based, scenario-oriented life-cycle GHG emissions assessment. This approach is particularly appropriate for the present study, whose primary objective is to compare the carbon-related performance of PV electricity under different electricity-generation mixes, rather than to optimize a specific plant design. Crystalline-silicon technology remains overwhelmingly dominant in the global PV market. At the same time, recent commercial trends indicate a strong transition toward high-efficiency TOPCon-based modules within the broader monocrystalline silicon segment.

The reference system was defined as a 1 MWp utility-scale plant connected to the medium-voltage grid [21]. This nominal capacity was selected as a scalable benchmark that is sufficiently large to represent grid-connected utility applications while remaining simple enough for transparent scenario-based analysis. In accordance with the methodological logic recommended by IEA PVPS Task 12, the system is interpreted in terms of AC electricity delivered to the grid, and the main technical assumptions were chosen to be representative rather than site-specific. Accordingly, the adopted irradiation, performance ratio, lifetime, and degradation rate correspond to realistic contemporary values commonly used in photovoltaic environmental assessment studies [4, 13, 22, 23].

A representative solar-belt irradiation level was assumed to define a credible high-yield operational context without tying the analysis to a single measured installation. The annual electricity generation of the reference system was estimated from the selected irradiation and performance assumptions and is therefore intended as a technically reasonable benchmark for comparative environmental calculations. The operational lifetime was set to 30 years, and the annual degradation rate to 0.5%/year, which is a conservative and commonly used assumption for a generic utility-scale PV system. This value remains consistent with recent utility-scale PV literature while avoiding unnecessary dependence on model-specific manufacturer warranties [24-26]. The technical assumptions summarized in Table 2 combine literature-based parameters, representative engineering assumptions, and calculated values adopted for the present comparative assessment. Technology-related values were aligned with recent reporting on commercial PV modules. In contrast, the broader life-cycle framework and reporting logic were informed by IEA PVPS Task 12 guidance and recent utility-scale solar LCA references [13].

Table 2 Technical assumptions of the reference grid-connected PV system.

Parameter	Value	Unit
Installed capacity	1,000 (1 MWp)	kWp
Module technology	High-efficiency monocrystalline silicon, TOPCon-based mainstream commercial modules	-
Module efficiency	22.0-22.7	%
Reference location	Representative high-yield solar-belt site	-
Annual irradiation	2000	kWh/m^2/year
Performance ratio (PR)	0.82	-
Annual electricity generation	1640	MWh/year
System lifetime	30	years
Annual degradation rate	0.5	%/year
Inverter architecture	String inverters	-
Inverter efficiency	98.5	%
Grid connection type	Medium-voltage, grid-connected utility-scale	-
Mounting structure	Galvanized steel support structure	-

Note: The values reported in this table represent technical assumptions for the reference system used in the scenario-based assessment. They are not derived from a newly constructed process-based life-cycle inventory. The authors calculated annual electricity generation from installed capacity, annual irradiation, and performance ratio.

Source: Prepared by the authors based on IEA PVPS, NREL, Fraunhofer ISE, PVGIS, and IEA PVPS Task 12 methodological guidance [4, 5, 9, 19, 25, 26].

3.1.2 Electricity Mix Carbon-Intensity Benchmarks

The high-carbon grid scenario was assigned a carbon intensity of 708 g CO_2e/kWh, representing coal-dominated electricity systems in which PV deployment is expected to deliver the largest immediate GHG mitigation benefit. The transitioning grid scenario was defined at 384 g CO_2e/kWh, representing mixed electricity systems with substantial fossil generation but increasing shares of renewables and other low-carbon sources. The low-carbon benchmark scenario was assigned 213 g CO_2e/kWh, reflecting comparatively decarbonized present-day electricity systems such as the recent EU average [27, 28]. The electricity-mix scenarios used in the comparative assessment are summarized in Table 3.

Table 3 Electricity-mix scenarios and analytical role in the present study.

Scenario	**Dominant source**	**Carbon intensity (g CO_2e/kWh)**	**Strategic analytical role**
High-carbon grid	Coal-dominated electricity system	708	Baseline for maximum avoided-emissions potential
Transitioning grid	Mixed fossil-based grid with growing low-carbon contribution	384	Evaluation of PV performance under mainstream transition conditions
Current low-carbon grid	Comparatively decarbonized electricity system	213	Assessment of PV relevance where grid emissions are already substantially reduced

Note: Scenario values were used as comparative analytical benchmarks. They represent average grid carbon intensity rather than marginal displacement factors and are applied here as static reference cases for scenario-based interpretation.

Source: Prepared by the authors based on recent public electricity-sector reporting [27-29].

These values were used as literature- and publicly available data-based scenario inputs, not as outputs from a newly constructed process-based life-cycle inventory model. As noted in the methodological section, the scenarios are based on average grid carbon-intensity values. They should therefore be interpreted as comparative benchmarks, rather than as full consequential displacement factors. A further limitation of the scenario framework is its static character. Because PV systems typically operate for several decades, future grid decarbonization may reduce the avoided emissions associated with photovoltaic generation over time. For this reason, the selected scenarios should be understood as fixed analytical benchmarks for comparative interpretation rather than as dynamic lifetime projections**.** The marked contrast among the selected scenarios is illustrated in Figure 1.

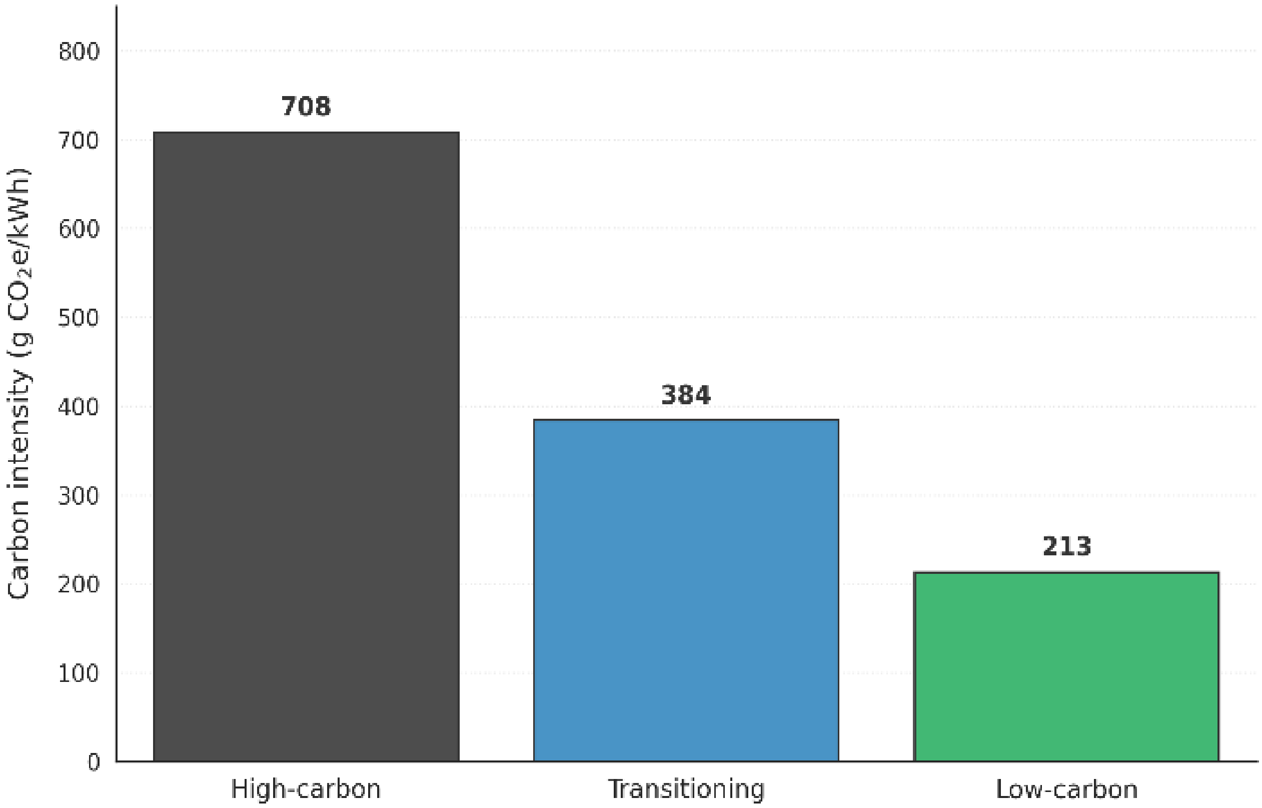

Figure 1 Carbon intensity of the selected electricity-mix scenarios. Source: Prepared by the authors.

Figure 1 illustrates the marked contrast in carbon intensity across the selected electricity-mix scenarios. The high-carbon grid presents the highest emission factor, whereas the low-carbon benchmark grid shows a substantially reduced carbon intensity. This contrast provides the comparative basis for evaluating the relative GHG mitigation benefit of photovoltaic electricity under different grid conditions.

3.2 Lifetime Electricity Generation of the PV System

3.2.1 Annual and Lifetime Electricity Output

The lifetime electricity output of the reference grid-connected PV system was estimated from the Year-1 electricity generation defined in Table 2 and the annual degradation rate adopted for the reference case. Based on an initial annual electricity generation of 1,640 MWh/year and a constant degradation rate of 0.5% per year, the reference system is projected to generate approximately 45,794 MWh over a 30-year operating lifetime.

The projected electricity output shows a gradual decline in annual generation over time due to the cumulative effect of the assumed degradation rate. Annual electricity production decreases from 1,640 MWh in the first year to 1,418 MWh in the thirtieth year, corresponding to an overall reduction of approximately 13.5% relative to the initial annual generation. Despite this progressive decline, total electricity production accumulated over time continues to increase throughout the system lifetime, exceeding 31,000 MWh by Year 20 and reaching nearly 45,800 MWh by Year 30.

The corresponding average annual electricity generation over the full lifetime is approximately 1,526 MWh/year.

These projections are particularly relevant for the present literature-based, scenario-oriented life-cycle GHG emissions assessment, because lifetime electricity generation constitutes the normalization basis for the emission-intensity indicators expressed per unit of electricity delivered to the grid. In this sense, greater cumulative electricity production improves the relative carbon-related performance of the photovoltaic system by distributing its literature-derived life-cycle emissions over a larger amount of lifetime electricity output. Table 4 summarizes the estimated annual and cumulative electricity generation over the system lifetime, while Figure 2 illustrates the evolution of annual and cumulative generation over the assumed 30-year operating period of the reference PV system [4, 29].

Table 4 Estimated electricity generation over the system lifetime.

Year	Annual generation (MWh/year)	Cumulative electricity generation (MWh)
1	1640	1640
5	1607.45	8118.41
10	1567.66	16035.88
20	1491.02	31287.76
30	1418.12	45793.99

Source: Prepared by the authors based on the technical assumptions defined in Table 2 and informed by recent PV LCA methodological guidance and utility-scale benchmark literature [5, 12, 13].

Note: Annual electricity generation was estimated from the Year-1 electricity output of the reference PV system assuming a constant annual degradation rate of 0.5%. Cumulative electricity generation refers to the total electricity produced from Year 1 up to the selected year. The authors calculated values.

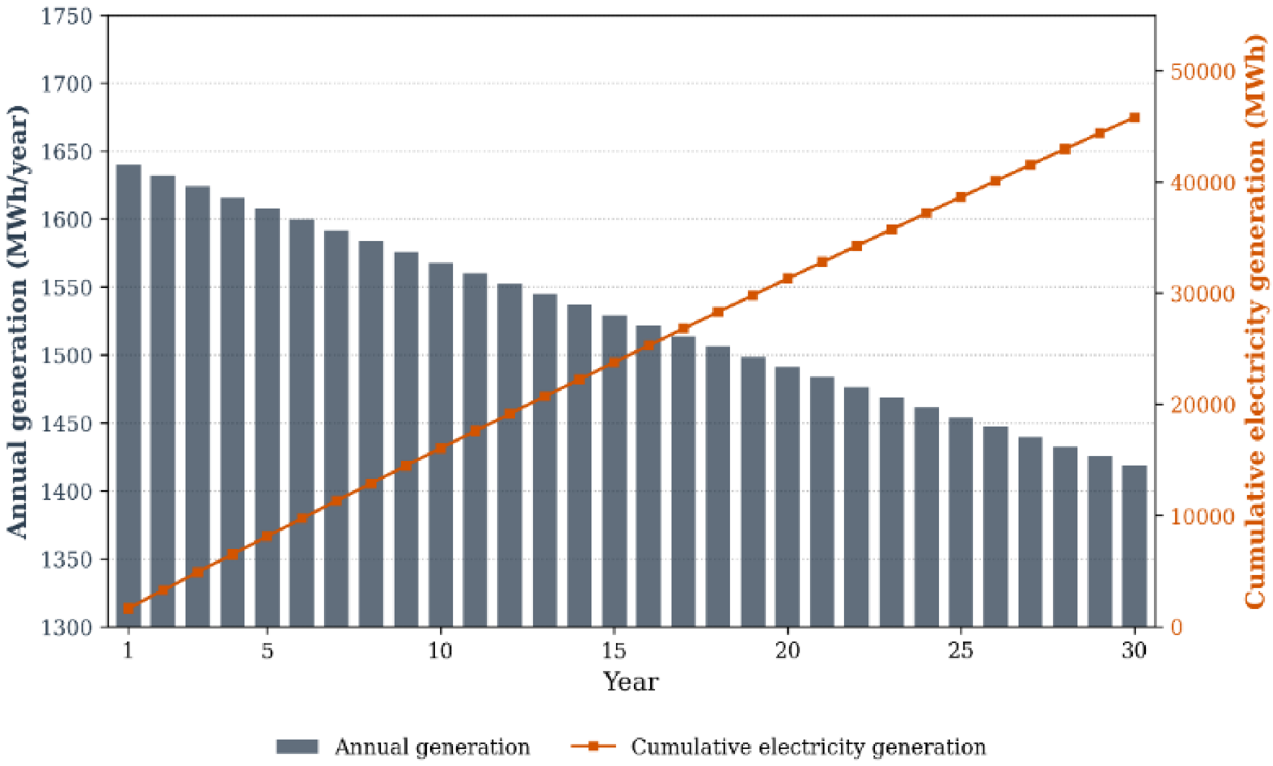

Figure 2 Estimated annual and cumulative lifetime electricity generation of the reference PV system over a 30-year operating period. Source: Prepared by the authors based on the technical assumptions defined in Table 2 and the assumed annual degradation rate of 0.5%.

Figure 2 shows the expected decline in annual electricity generation due to long-term module degradation, together with the steady increase in cumulative lifetime electricity output. Although annual production gradually decreases, cumulative generation continues to rise throughout the full operating life of the system, confirming the long-term energy contribution of the reference PV installation and its importance fornormalizing life-cycle environmental impacts.

3.3 Gross Life-Cycle Environmental Profile of the PV System

3.3.1 Gross Life-Cycle Greenhouse Gas Emissions and Stage Contributions

The gross life-cycle greenhouse gas (GHG) profile of the reference grid-connected PV system was interpreted using a literature-based range of life-cycle carbon intensities reported for contemporary utility-scale solar systems. Recent NREL results indicate that utility-scale PV can exhibit life-cycle GHG emissions between 10 and 36 g CO_2e/kWh, depending on manufacturing supply chain, installation location, and end-of-life treatment. Within this range, a median reference value of 19 g CO_2e/kWh was adopted for the present comparative assessment, as it is consistent with the benchmark utility-scale case reported by NREL for an average imported supply chain with partial end-of-life recycling. This range confirms that photovoltaic electricity remains a low-carbon generation option even before avoided grid emissions are considered. However, the spread between the low and high estimates indicates that manufacturing context and end-of-life assumptions still play an important role in determining the gross GHG profile of the PV system [4, 30]. In particular, the high end of the range is associated with carbon-intensive manufacturing and less favorable end-of-life treatment, whereas the low end reflects cleaner supply chains and higher material recovery.

The literature-based range adopted for the present study is shown in Figure 3. To support interpretation of the gross GHG profile, the total life-cycle GHG burden of the reference PV system was decomposed into representative stage-level contributions using the median value of 19 g CO_2e/kWh as the reference case. This breakdown should not be interpreted as the result of a newly constructed process-based life-cycle inventory. Instead, it is presented as a literature-informed interpretive distribution designed to identify the main GHG hotspots reported in recent PV life-cycle studies. The purpose of this stage-level profile is therefore to support qualitative hotspot interpretation, particularly regarding the relative importance of raw material supply and manufacturing, rather than to provide inventory-derived percentage contributions for a specific industrial supply chain.

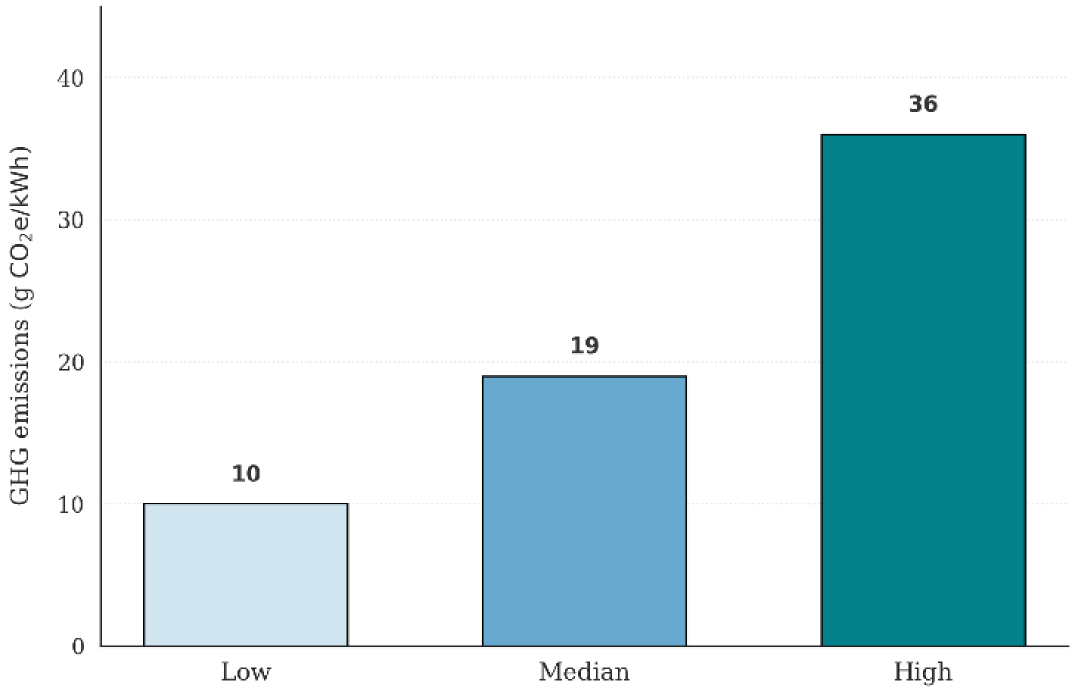

Figure 3 Literature-based range of gross life-cycle greenhouse gas emissions for the reference grid-connected photovoltaic system. Source: Prepared by the authors based on the life-cycle GHG values reported by NREL [4].

Recent studies report that manufacturing is commonly the dominant stage in PV life-cycle GHG emissions, with module manufacturing often accounting for most of the total impacts and, in some cases, more than 60-80% of the system-level GHG burden. Based on this interpretive synthesis, the median gross life-cycle GHG burden was apportioned across six stages: raw materials, manufacturing, transport, installation, operation and maintenance, and end-of-life. The resulting distribution should therefore be understood as a representative literature-informed profile, not as a precise inventory-calculated result. The largest contribution was assigned to manufacturing, followed by raw material supply, while the remaining stages together account for a comparatively smaller fraction of the total. The representative stage contribution profile used in the present study is presented in Figure 4. Taken together, Figure 3 and Figure 4 show that the gross GHG profile of the reference PV system remains comparatively low in absolute terms, but is strongly shaped by upstream processes, particularly manufacturing and raw material supply. By contrast, transport, installation, operation and maintenance, and end-of-life contribute relatively minor shares to the representative GHG profile. This pattern suggests that the greatest opportunities for further emissions reduction lie in cleaner manufacturing electricity, improved material efficiency, lower-carbon logistics, and stronger circular end-of-life pathways [31-33].

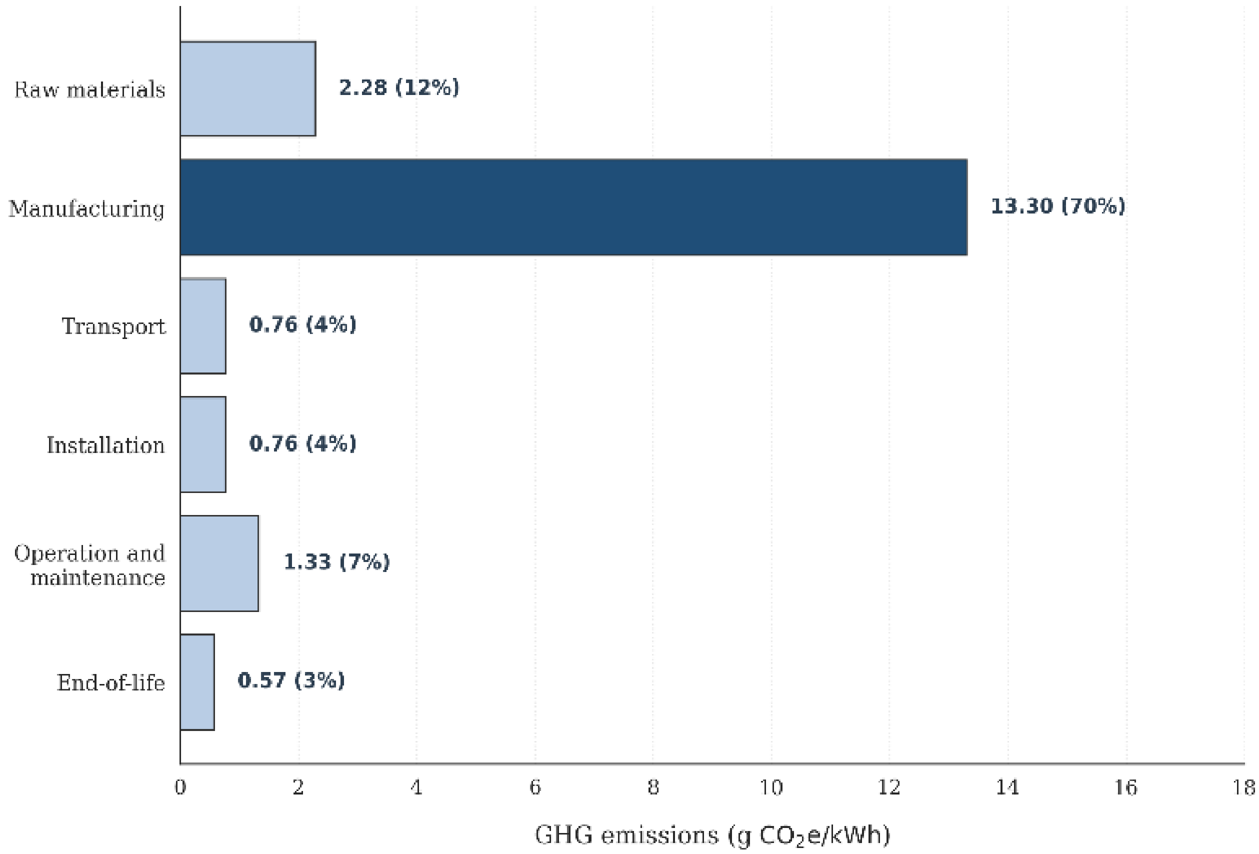

Figure 4 Representative literature-informed contribution of life-cycle stages to the gross greenhouse gas burden of the reference grid-connected photovoltaic system, based on the median literature case of 19 g CO_2e/kWh. Note: Stage contributions are representative literature-informed estimates and should not be interpreted as results from an original process-based life-cycle inventory. The distribution is used for hotspot interpretation, particularly to illustrate the relative importance of manufacturing and raw material supply in PV life-cycle GHG emissions. Source: Prepared by the authors based on the life-cycle GHG values reported by NREL and supporting PV life-cycle literature [4, 31-33].

3.4 Avoided Emissions and Net GHG Benefit under Different Electricity Mixes

To evaluate the carbon-related mitigation value of the reference grid-connected PV system, the lifetime electricity output estimated in Section 3.2 was combined with the electricity-mix carbon intensities defined in Section 3.1.2. Using a projected lifetime generation of 45,793.99 MWh, total avoided greenhouse gas emissions were estimated for the three comparative benchmark scenarios.

The results show a strong dependence on grid carbon intensity. Under the high-carbon grid scenario, the PV system avoids approximately 32.42 kt CO_2e over its operating lifetime. Under the transitioning grid scenario, avoided emissions decrease to 17.58 kt CO_2e, whereas under the low-carbon benchmark scenario they are reduced to 9.75 kt CO_2e [27, 28, 34].

These results confirm that the scenario-estimated climate benefit of photovoltaic deployment is greatest in carbon-intensive electricity systems, where the displacement of fossil-based generation yields the highest avoided emissions. Because the calculation is based on average grid carbon-intensity values, these results should be interpreted as comparative scenario estimates rather than as full consequential displacement estimates. The scenario comparison is presented in Figure 5.

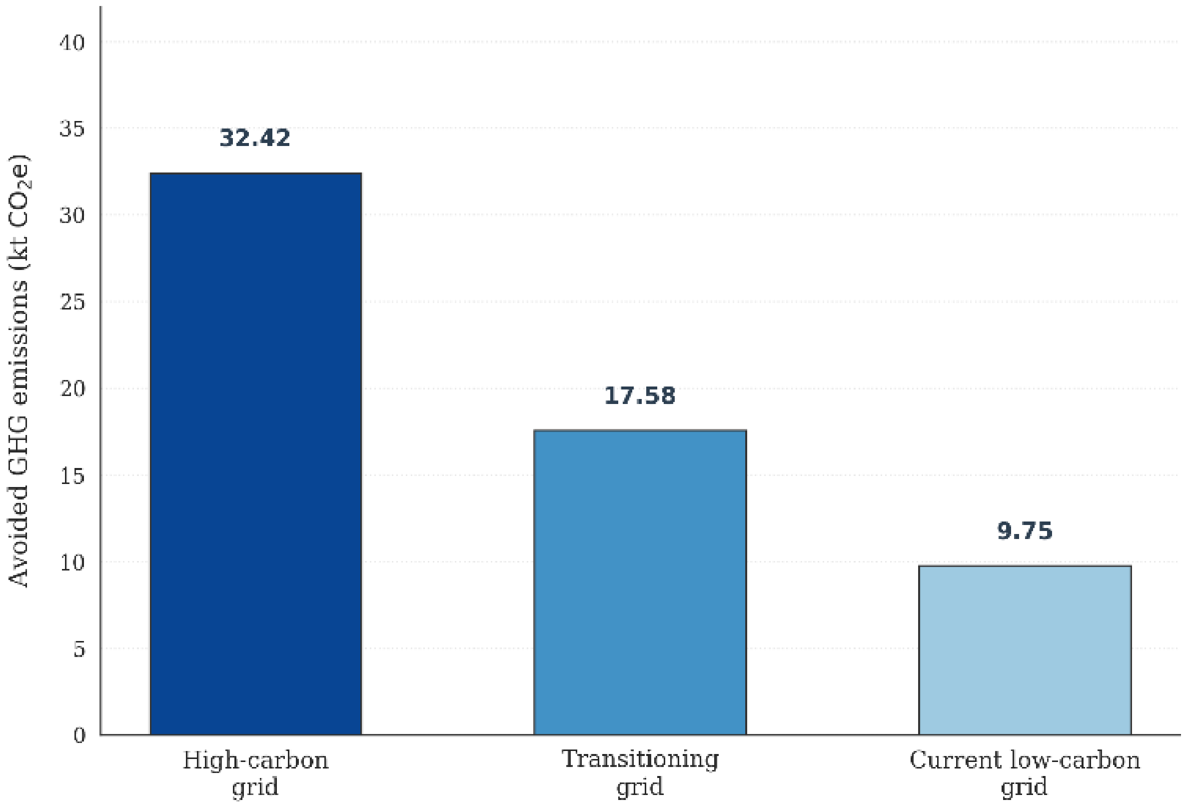

Figure 5 Estimated avoided greenhouse gas emissions of the reference grid-connected photovoltaic system under different electricity-mix scenarios over the 30-year operating lifetime. Source: Prepared by the authors based on the life-cycle GHG values reported by NREL.

To complement this comparison, the avoided emissions were evaluated against the literature-based gross life-cycle GHG burden of the PV system itself. Using the median literature-based value of 19 g CO_2e/kWh adopted in Section 3.3, the total gross life-cycle greenhouse gas emissions of the reference system amount to approximately 0.87 kt CO_2e over its 30-year operating lifetime. After subtracting this burden from the avoided emissions under each electricity-mix scenario, the resulting net GHG benefit remains strongly positive in all cases, reaching approximately 31.55 kt CO_2e under the high-carbon grid, 16.71 kt CO_2e under the transitioning grid, and 8.88 kt CO_2e under the low-carbon benchmark scenario [27, 28, 35]. These results demonstrate that the carbon-related value of photovoltaic electricity is clearly grid-dependent: the net benefit is strongest in carbon-intensive systems and progressively smaller in cleaner grids, although it remains positive in all scenarios considered. Thus, the comparison should be understood as a literature-based, scenario-oriented estimate of avoided and net GHG emissions, rather than as the output of a full process-based life-cycle inventory model. The relationship between gross emissions, avoided emissions, and net GHG benefit is shown in Figure 6.

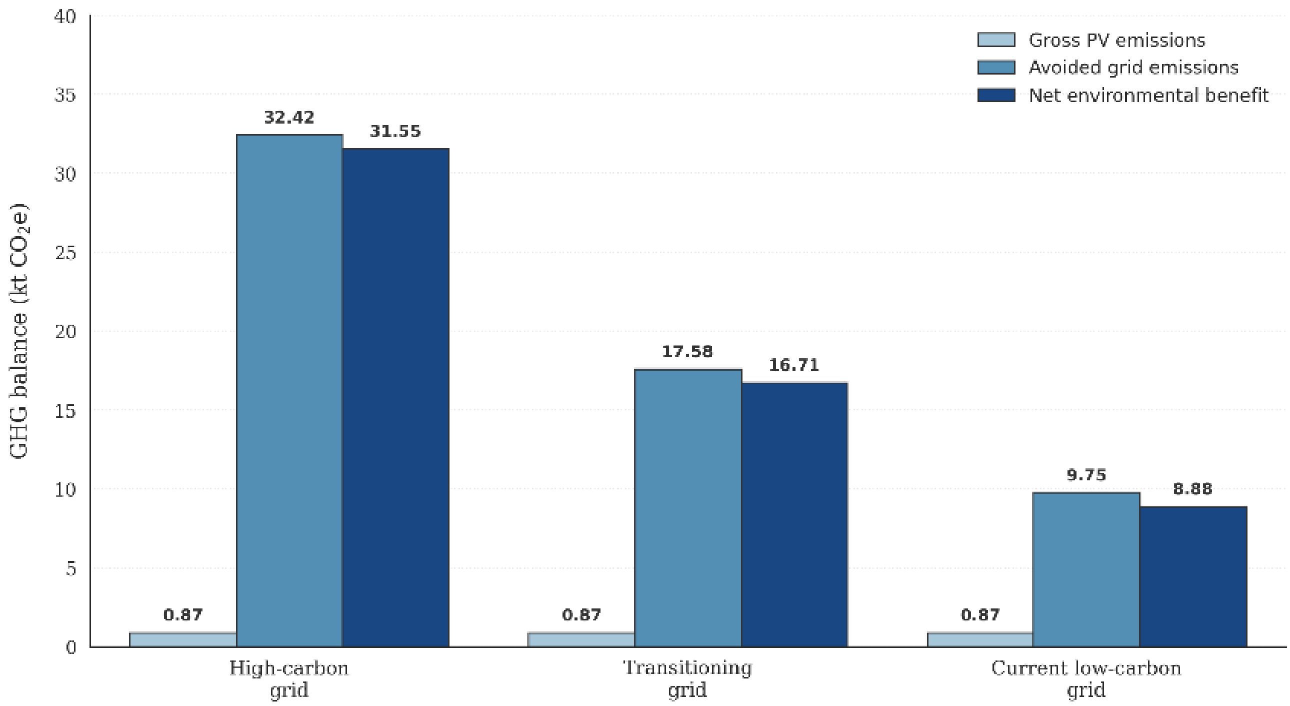

Figure 6 Gross life-cycle GHG emissions, avoided grid emissions, and net GHG benefit of the reference grid-connected photovoltaic system under different electricity-mix scenarios over the 30-year operating lifetime. Source: Prepared by the authors based on the life-cycle GHG values reported by NREL.

3.5 Comparative Environmental Advantage of PV Electricity across Electricity-Mix Scenarios

The comparative GHG advantage of photovoltaic electricity was further evaluated by expressing the gross life-cycle greenhouse gas burden of the reference system relative to the carbon intensity of each electricity-mix scenario. Using the median PV life-cycle emission factor of 19 g CO_2e/kWh, the percentage reduction in greenhouse gas emissions achieved by photovoltaic electricity was calculated for each benchmark grid. The results indicate that photovoltaic electricity reduces greenhouse gas intensity by approximately 97.3% relative to the high-carbon grid, 95.1% relative to the transitioning grid, and 91.1% relative to the low-carbon benchmark grid. These values indicate that photovoltaic systems retain a strong carbon-related advantage across all scenarios considered, even when integrated into comparatively cleaner electricity systems [4, 20, 36, 37].

At the same time, the magnitude of this advantage is not uniform. The results show that the relative GHG mitigation benefit of photovoltaic electricity is greatest in high-carbon systems, where both avoided emissions and percentage reduction are maximized. As grid carbon intensity declines, the relative reduction remains substantial, but the carbon-related margin progressively narrows [38]. This pattern is consistent with the results presented in Sections 3.3 and 3.4, where the gross life-cycle GHG burden of the PV system remained comparatively low, but the absolute avoided emissions and net GHG benefit decreased under cleaner electricity mixes. In this sense, the carbon-related value of photovoltaic deployment should be interpreted not as a fixed property of the technology itself, but as a context-dependent outcome shaped by the surrounding electricity system. To synthesize these relationships, Figure 7 presents the percentage reduction in greenhouse gas emissions achieved by photovoltaic electricity relative to each electricity-mix scenario, while Figure 8 provides a comparative matrix summarizing the gross GHG burden, avoided emissions, net GHG benefit, and percentage reduction across all scenarios. Together, these figures offer a concise visual representation of how the comparative carbon-related performance of grid-connected PV systems evolves along the electricity decarbonization pathway. Because the analysis relies on literature-derived PV emission factors and benchmark grid carbon-intensity values, these results should be interpreted as scenario-based comparative estimates rather than as outputs from a full process-based life-cycle inventory model. Figure 7 shows that photovoltaic electricity achieves a greenhouse gas reduction above 90% relative to all electricity-mix scenarios considered. The relative advantage is greatest in carbon-intensive grids and progressively smaller in cleaner electricity systems, although it remains substantial in all cases [4, 27].

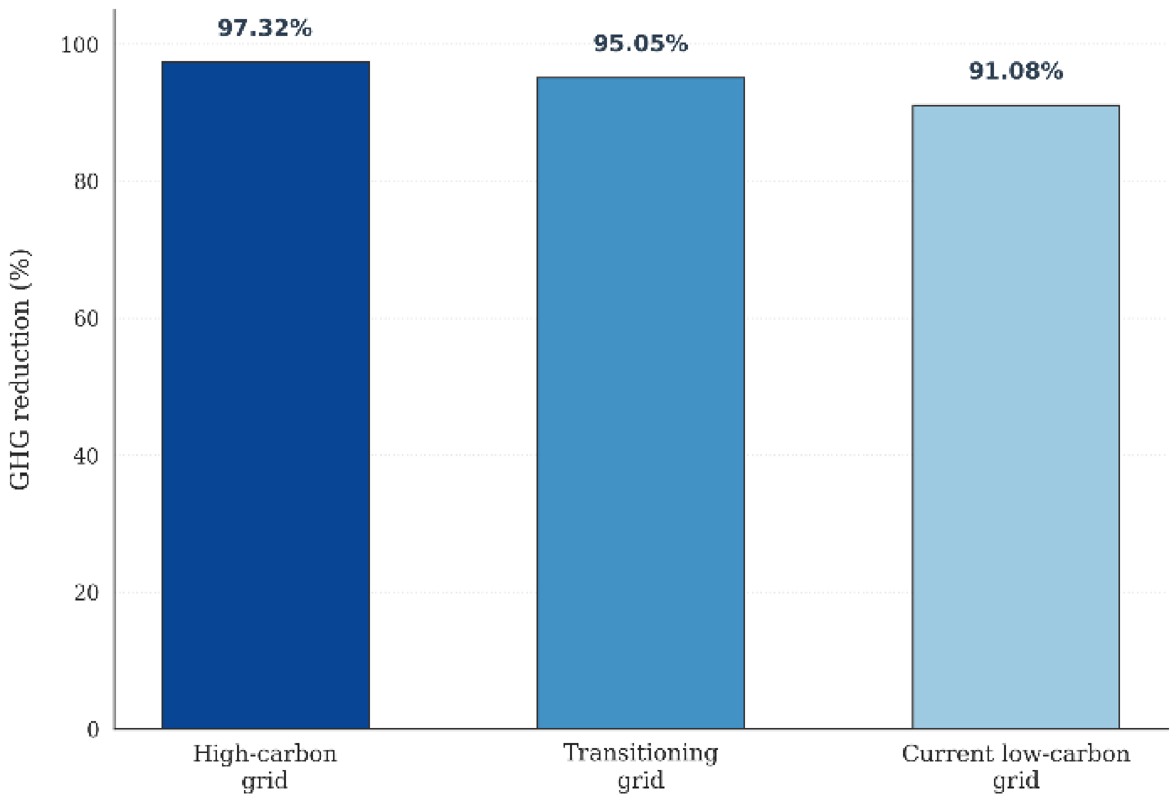

Figure 7 Percentage reduction in greenhouse gas emissions achieved by photovoltaic electricity relative to the selected electricity-mix scenarios. Source: Prepared by the authors based on the calculated GHG indicators reported in this study.

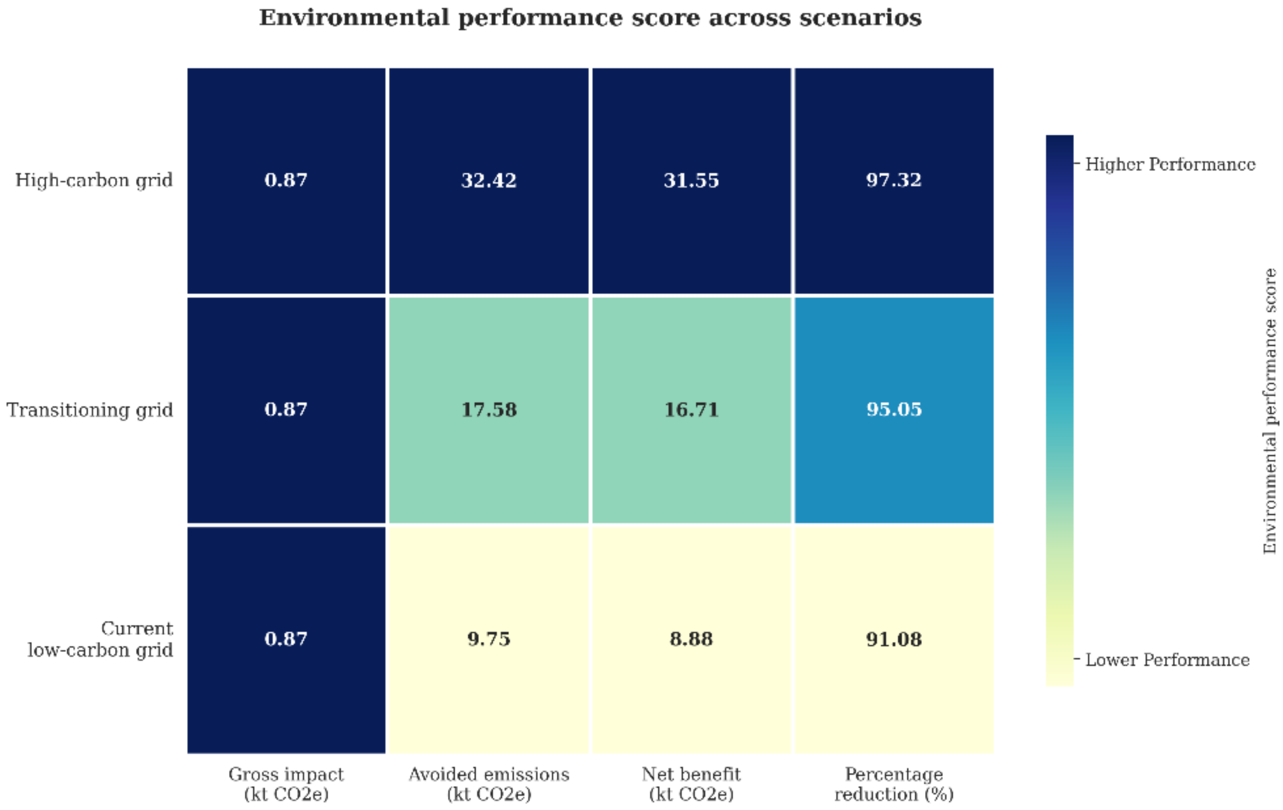

Figure 8 Normalized heatmap of PV carbon-related performance across electricity-mix scenarios. Source: Prepared by the authors based on the calculated GHG indicators reported in this study.

Figure 8 provides a normalized comparative summary of the carbon-related performance of the reference PV system across the selected electricity-mix scenarios. Each indicator was normalized by column to support cross-scenario comparison. For gross life-cycle GHG burden, lower values were interpreted as preferable from a GHG-emissions perspective, whereas for avoided emissions, net GHG benefit, and percentage reduction, higher values indicated better carbon-related performance [4, 12, 20, 26]. The heatmap confirms that the high-carbon grid offers the greatest GHG mitigation advantage, while the low-carbon benchmark grid remains beneficial but with a smaller mitigation margin. Accordingly, the heatmap should be interpreted as a scenario-based comparative visualization rather than as evidence from a full process-based LCA model.

3.6 Sensitivity Analysis and Strategic Interpretation

The sensitivity of the net GHG benefit was examined by testing how the results change across the literature-based range of PV life-cycle greenhouse gas emission factors adopted in Section 3.3. Using the lower, median, and upper values of 10, 19, and 36 g CO_2e/kWh, respectively, the net GHG benefit of the reference PV system was recalculated for each electricity-mix scenario. This analysis provides a focused assessment of how uncertainty in the gross life-cycle GHG burden of the photovoltaic system influences the final scenario-based GHG outcome.

The results show that the net GHG benefit remains positive across the tested PV emission-factor range and for all electricity-mix scenarios considered. Under the high-carbon grid scenario, the net benefit varies from approximately 31.96 kt CO_2e at the low emission factor to 30.77 kt CO_2e at the high emission factor. Under the transitioning grid scenario, the corresponding range is 17.12-15.93 kt CO_2e, whereas under the low-carbon benchmark scenario the net benefit ranges from 9.29 to 8.10 kt CO_2e [4, 12, 20, 26].

These results indicate that the main interpretation remains stable within the tested PV life-cycle emission-factor range. However, this should not be interpreted as a comprehensive robustness assessment across all technical, geographic, and grid-related assumptions. Other parameters, including annual PV yield, degradation rate, system lifetime, grid carbon intensity, manufacturing location, end-of-life scenario, and marginal emission factors, were not fully varied in the present analysis and should be examined in future sensitivity studies.

To complement the sensitivity analysis and support the interpretation of the main findings, Table 5 summarizes the principal results, their main implications, and their relevance for photovoltaic deployment and planning.

Table 5 Comparative interpretation of the main results and planning relevance.

Result	Main implication	Relevance for planning
The PV system shows low gross life-cycle GHG emissions relative to benchmark grid scenarios	Photovoltaic electricity remains a low-carbon option even before avoided emissions are considered	Supports continued deployment of grid-connected PV in both carbon-intensive and cleaner grids
Avoided emissions are highest under the high-carbon grid scenario	The climate mitigation value of PV is strongly context-dependent	Deployment in carbon-intensive systems delivers the largest immediate climate benefit
Net GHG benefit remains positive in all scenarios	The overall climate advantage of PV is stable within the tested range across contrasting electricity systems	PV remains environmentally favorable even in relatively low-carbon grids
Manufacturing dominates the gross life-cycle burden	Upstream production processes are the main hotspot for emissions reduction	Cleaner manufacturing electricity and material efficiency should be prioritized
Sensitivity analysis shows stable positive net benefit across the 10-36 g CO_2e/kWh range	Results remain stable within the tested PV life-cycle emission-factor range.	Strengthens confidence in the GHG relevance of PV deployment
Circularity and end-of-life management influence long-term sustainability	Recycling and material recovery can further improve carbon-related performance	Planning should include recovery infrastructure and circular economy strategies

Source: Prepared by the authors.

The sensitivity range of the net GHG benefit is illustrated in Figure 9.

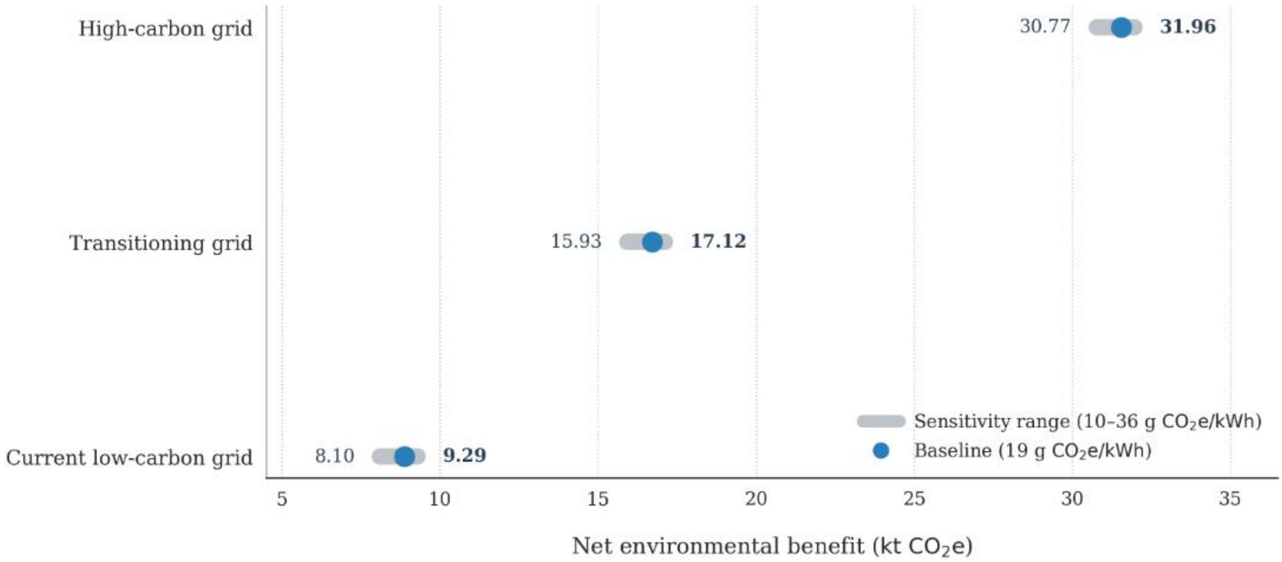

Figure 9 Sensitivity of net GHG benefits to changes in the PV life-cycle emission factor across electricity-mix scenarios. Source: Prepared by the authors based on the PV life-cycle emission-factor range reported by NREL [4]. Net GHG benefit values were calculated by the authors using the grid carbon-intensity benchmarks and lifetime electricity generation estimated in this study.

4. Discussion

4.1 Interpretation of the Main Findings

The results confirm that the environmental performance of grid-connected photovoltaic systems is not fixed but strongly influenced by the carbon intensity of the electricity mix into which they are integrated. From a broader life-cycle perspective, which also considers supply-chain implications in renewable energy projects [39], the reference PV system had a low gross life-cycle greenhouse gas burden, although its climate-mitigation value varied substantially across the selected scenarios. In all cases, the avoided emissions exceeded the system's own gross life-cycle emissions, resulting in a positive net GHG benefit. However, the magnitude of this benefit was highest in the high-carbon grid and progressively lower in cleaner electricity systems. This indicates that PV remains environmentally advantageous across contrasting grid conditions, although its relative mitigation value decreases as surrounding electricity systems decarbonize [40].

4.2 Implications of Electricity-Mix Dependence

The scenario comparison highlights that the environmental relevance of photovoltaic deployment depends on the characteristics of the grid electricity displaced. In carbon-intensive systems, photovoltaic generation yields the largest immediate greenhouse gas reductions by replacing high-emission electricity. In cleaner grids, the GHG mitigation benefit remains clearly positive, but the mitigation margin is narrower. This finding has important planning implications [41, 42]. It suggests that PV deployment can support both short-term emissions reductions in fossil-intensive systems and long-term decarbonization in cleaner systems, though the scale of its direct climate benefit differs across contexts. Therefore, the environmental value of PV should be understood as a context-dependent outcome rather than a uniform property of the technology itself.

4.3 Manufacturing Burden, Carbon Debt, and Circularity

The stage contribution analysis shows that the reference PV system's gross life-cycle burden is dominated by upstream processes, particularly manufacturing and raw material supply. This result is consistent with the broader PV LCA literature and indicates that future environmental improvements increasingly depend on cleaner industrial production rather than operational changes alone. In this context, the concept of carbon debt is especially relevant, since the low carbon intensity of PV electricity over time depends on distributing an initial embodied burden over a sufficiently large lifetime electricity output. The results also reinforce the importance of manufacturing geography, because supply chains linked to carbon-intensive electricity systems increase gross life-cycle emissions. In parallel, circularity and end-of-life management emerge as strategic priorities [41]. Even if end-of-life contributes only a modest share of current gross emissions, improved recycling and material recovery can reduce embodied impacts and strengthen long-term sustainability as large volumes of installed PV capacity approach retirement.

4.4 Strategic Implications for PV Deployment and Low-Carbon Manufacturing

Beyond the numerical comparisons of avoided emissions and net GHG benefits, the findings offer several practical implications for photovoltaic deployment, supply-chain decarbonization, circular economy planning, and low-carbon manufacturing. First, PV deployment can deliver the largest immediate GHG mitigation benefit in electricity systems with high carbon intensity. From a short-term climate perspective, this suggests that prioritizing PV expansion in fossil-intensive grids may produce greater avoided emissions per unit of installed capacity than deployment in already low-carbon systems. However, PV remains relevant in cleaner grids because it supports long-term electrification, diversification of electricity supply, and the continued displacement of residual fossil generation [8]. Second, the findings highlight the need to reduce emissions within the PV supply chain itself. Since the gross life-cycle GHG burden is strongly influenced by upstream processes, particularly raw material supply, silicon purification, and module manufacturing, further improvements in PV sustainability will require low-carbon manufacturing electricity, cleaner industrial processes, material efficiency, and more transparent supply-chain governance. In this sense, PV deployment and PV manufacturing decarbonization should be treated as complementary strategies rather than separate policy objectives [31-33].

Third, circular economy strategies are essential for improving the long-term carbon-related performance of PV systems. Although detailed end-of-life impacts were not fully modeled in the present study, the growing volume of retired modules makes recycling, material recovery, and design for recyclability increasingly important. Strengthening circular pathways can reduce future material demand, mitigate waste-management pressures, and improve the sustainability of PV deployment over successive technology cycles. Therefore, policies supporting PV expansion should be accompanied by planning instruments for low-carbon manufacturing, recycling infrastructure, material recovery, and responsible end-of-life management [12, 13, 20, 39].

4.5 Limitations and Future Research

Several limitations should be acknowledged. The quantitative scope of this study was limited to life-cycle GHG emissions, avoided emissions, and net GHG benefit. Therefore, the results should not be interpreted as a comprehensive environmental life-cycle assessment covering all impact categories.

Other relevant indicators, including energy payback time, mineral resource depletion, land use, toxicity, water use, and detailed end-of-life impacts, were not fully modeled in the present assessment. These categories should be incorporated in future research to provide a more comprehensive environmental evaluation of grid-connected PV systems.

First, the study used a literature-based, scenario-oriented life-cycle GHG emissions assessment based on public data, rather than a full process-based industrial LCA with proprietary or newly developed inventories.

Second, the electricity-mix scenarios were treated as static analytical benchmarks, whereas real grids will continue to evolve over the operating lifetime of the PV system. Because PV systems operate for several decades, future grid decarbonization may reduce the avoided emissions per unit of PV electricity over time. However, the present study does not implement a quantified dynamic grid-decarbonization pathway, does not assign year-specific grid carbon-intensity values, and does not calculate dynamic avoided-emissions results. Therefore, the fixed scenarios used in the main analysis should be interpreted as comparative benchmarks rather than as dynamic lifetime projections.

A future dynamic assessment could estimate dynamic avoided emissions by using a time-dependent grid carbon-intensity factor:

$$GHG_{avoided,dynamic} = \sum_{t=1}^{N} \left[E_{annual} \times (1-d)^{t-1} \times EF_{grid,t} \right] \tag{6}$$

where $GHG_{avoided,dynamic}$ represents the dynamic avoided emissions over the system lifetime, E_{annual} is the first-year annual electricity output, d is the annual degradation rate, t is the year of operation, N is the system lifetime in years, and EF_{grid} is the grid carbon intensity in year t. This equation is proposed as a future research approach and was not applied in the present study.

Third, average grid carbon intensity was used instead of marginal emission factors, which would be more appropriate for a fully consequential assessment of avoided emissions. Finally, battery energy storage was excluded to preserve clarity in interpreting the photovoltaic generation system itself.

The environmental indicators considered in the present study and the corresponding future research needs are summarized in Table 6.

Table 6 Environmental indicators considered and future research needs.

Indicator	Treatment in this study	Future research need
Life-cycle GHG emissions	Quantitatively assessed	Refine with process-based inventory data.
Avoided emissions	Quantitatively assessed	Incorporate marginal emission factors and dynamic grid trajectories.
Net GHG benefit	Quantitatively assessed	Expand sensitivity analysis across additional system parameters.
Energy payback time	Discussed as complementary context	Model EPBT explicitly under different manufacturing and installation contexts.
Mineral resource depletion	Not fully modeled	Include material demand and critical mineral depletion indicators.
Land use	Not fully modeled	Evaluate land occupation and site-specific ecological implications.
Water use	Not fully modeled	Assess water-related impacts, especially in high-irradiation and water-stressed regions.
Toxicity	Not fully modeled	Include human toxicity and ecotoxicity indicators.
Detailed end-of-life impacts	Discussed qualitatively	Quantify recycling, recovery rates, disposal pathways, and circularity scenarios.

Source: Prepared by the authors.

Future research should address these limitations by incorporating quantified dynamic grid-decarbonization trajectories, year-specific grid carbon-intensity values, marginal displacement factors, broader sensitivity parameters, additional environmental impact categories, more explicit comparisons of manufacturing geography, and battery-integrated PV configurations [43, 44]. Despite these limitations, the present results indicate that grid-connected photovoltaic systems provide a positive net GHG benefit within the comparative scenario conditions evaluated.

5. Conclusions

This study evaluated the carbon-related performance of grid-connected photovoltaic systems under different electricity generation mixes using a literature-based, scenario-oriented life-cycle GHG emissions assessment. The results show that photovoltaic electricity remains favorable from a GHG-emissions perspective in all scenarios considered, although the magnitude of its mitigation benefit depends strongly on the carbon intensity of the surrounding grid. The reference PV system exhibited a low gross life-cycle greenhouse gas burden, with literature-based values ranging from 10 to 36 g CO_2e/kWh and a median reference case of 19 g CO_2e/kWh. At the same time, the representative stage contribution analysis indicated that the gross GHG burden is dominated by upstream processes, particularly manufacturing and raw material supply, highlighting the importance of cleaner industrial production and lower-carbon supply chains.

The avoided-emissions analysis showed that the scenario-estimated GHG mitigation benefit of photovoltaic deployment is greatest in carbon-intensive electricity systems. Over the assumed 30-

year operating lifetime, the system was estimated to avoid 32.42 kt CO_2e in the high-carbon grid scenario, 17.58 kt CO_2e in the transitioning grid scenario, and 9.75 kt CO_2e in the low-carbon benchmark scenario. When these values were compared with the gross life-cycle GHG burden of the PV system, the resulting net GHG benefit remained positive in all cases, ranging from 31.55, 16.71, and 8.88 kt CO_2e, respectively.The sensitivity analysis further showed that the overall conclusion remains stable within the tested PV life-cycle emission-factor range. Even under the highest assumed gross PV emissions, the system maintained a positive net greenhouse gas benefit across all electricity-mix scenarios considered. Overall, the study demonstrates that grid-connected photovoltaic systems represent a strong low-carbon electricity option under contrasting grid conditions. Their GHG mitigation advantage is strongest where electricity remains carbon-intensive, but it remains positive even in cleaner systems. These findings support continued PV deployment while also emphasizing the importance of cleaner manufacturing, circularity, and end-of-life management for improving long-term carbon-related performance. However, because the analysis is based on literature-derived PV emission factors, average grid carbon-intensity benchmarks, and fixed scenario assumptions, the results should be interpreted as scenario-based comparative estimates rather than as outputs from a full process-based life-cycle inventory model. Future research should incorporate dynamic grid-decarbonization trajectories, marginal displacement factors, broader environmental impact categories, and battery-integrated PV configurations.

Author Contributions

María E. Raygoza-Limón: Conceptualization, methodology, investigation, formal analysis, data curation, visualization, writing—original draft, writing—review and editing, project administration, and supervision; Gabriel Trujillo-Hernández: Methodology, validation, formal analysis, and writing—review and editing; José Alejandro Amezquita Garcia: Investigation, literature analysis, validation, and writing—review and editing; Abelardo Mercado-Herrera: Investigation, formal analysis, validation, and writing—review and editing; Juan Carlos Ling-López: Data curation, visualization, investigation, and writing—review and editing; Fabian N. Murrieta-Rico: Validation and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

Data Availability Statement

The data supporting the findings of this study are available from publicly accessible sources cited in the manuscript, including NREL, IEA PVPS, Fraunhofer ISE, PVGIS, and Ember. Derived data generated during the study are included in the article, and additional calculation files are available from the corresponding author upon reasonable request.

AI-Assisted Technologies Statement

During the preparation of this manuscript, the authors used AI only to support language editing and grammar checking. The tool was not used to generate original data, perform calculations, create results, conduct the scientific analysis, or formulate the study conclusions.

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