

Comparative Life-Cycle Assessment of Polycrystalline and Monocrystalline Solar Photovoltaic Systems in the Kingdom of Saudi Arabia

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ABSTRACT

Utility-scale solar photovoltaic (PV) deployment in the Kingdom of Saudi Arabia is rapidly expanding under Vision 2030, bringing the total commissioned and under-construction capacity to over 4 GW. This study evaluated the life-cycle carbon emissions of largescale crystalline-silicon PV systems in Saudi Arabia, comparing polycrystalline and monocrystalline panels in projects exceeding 200 MW. Representative plants included Sakaka (300 MW, Al Jouf), Sudair (1,500 MW, Riyadh Province), Jeddah (300 MW), and Shuaibah (2,060 MW), reflecting current international supply chains with upstream silicon production concentrated in China and cell and module assembly occurring across Southeast Asian hubs. The life-cycle assessment (LCA) followed the ISO 14040/14044 principles and International Energy Agency (IEA) PV Power Systems (PVPS) Task 12 guidelines, applying a cradle-to-gate-plus-use boundary covering raw material extraction, wafer and cell processing, module assembly, balance-of-system components, transportation, installation, and operation. Life-cycle-inventory data were obtained from the IEA PVPS Task 12 consensus inventory and cross-validated against recent peer-reviewed and National Renewable Energy Laboratory-maintained utility-scale LCA literature. Energy yield was estimated using RETScreen Expert for NEOM, Riyadh, and Jeddah, representing distinct climatic zones. The results indicate that monocrystalline systems exhibit marginally higher embodied emissions per unit of installed capacity than those of polycrystalline systems, whereas the yield-normalized carbon intensity is comparable within each location. Higher electricity generation at NEOM and Jeddah resulted in lower life-cycle greenhouse gas intensities, indicating that the location effect is greater than the technology effect. These findings support evidence-based PV technology selection and deployment for low-carbon electricity generation in Saudi Arabia.

Keywords: life-cycle assessment, utility-scale photovoltaic system, monocrystalline silicon, polycrystalline silicon, carbon intensity, Kingdom of Saudi Arabia

1. INTRODUCTION

Utility-scale solar photovoltaic (PV) deployment in the Kingdom of Saudi Arabia (KSA) is accelerating under the Vision 2030 initiative, with multiple power plants, each delivering hundreds of megawatts of capacity, already commissioned or currently under construction. As PV is emerging as a major contributor to the national power generation portfolio, technology selection and supply-chain-related decisions should be evaluated not only on energy output and cost but also on environmental performance across the full life cycle. Harmonization and synthesis efforts have consistently placed PV technology among the low-greenhouse gas (GHG) electricity generation options when assessed over their full life cycle, with life-cycle GHG emissions significantly below those from fossil-based generation (Figure 1). However, the reported results obtained over the PV life cycle vary across studies owing to differences in system boundaries, inventory datasets, electricity mixes used during manufacturing, and methodological choices¹⁻³. For deployment-oriented decision

making, this variability must be addressed through transparent scope definitions and data choices that are consistent with the intended application, that is, utility-scale PV system development in the KSA.

Life-cycle assessment (LCA) provides a standardized framework for quantifying environmental impacts over the life cycle of a product system and is commonly conducted in accordance with the specifications of ISO 14040 (principles and framework) and ISO 14044 (requirements and guidelines)^{8,9}. For electricity-generating systems, the life-cycle carbon intensity (g CO₂-eq/kWh) is a central climate-change metric, which can be expressed as the ratio of life-cycle GHG emissions per installed capacity (expressed in kg CO₂-eq/kWp) to lifetime electricity generation delivered to the grid^{1,4,5}. Consequently, the carbon intensity is strongly influenced by location-specific solar resource and performance assumptions. Reviews and foundational PV life-cycle analyses identify irradiation/insolation, module conversion efficiency, performance ratio, and lifetime/degradation as key drivers affecting the resulting GHG emission rate per kWh^{4,5}.

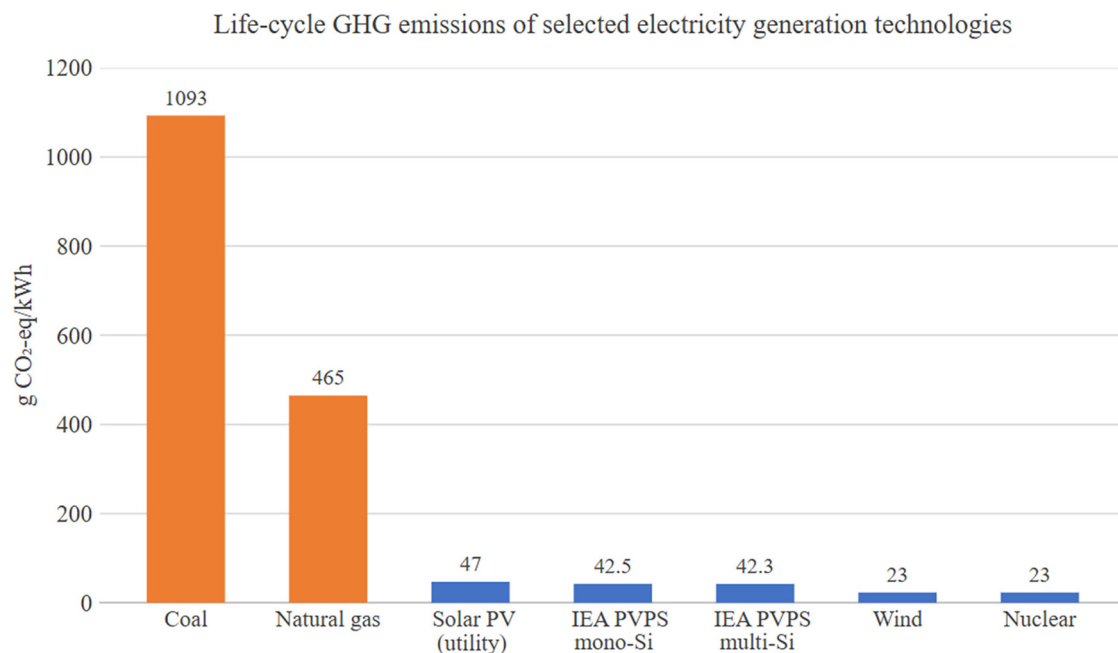


Figure 1. Life-cycle GHG emissions of selected electricity generation technologies, illustrating the low-carbon position of PV relative to that of fossil-based generation^{1,4}

Similarly, recent utility-scale PV LCAs have emphasized that installation location (via yield) and supply-chain assumptions (via embodied emissions) can significantly influence life-cycle carbon intensity¹. Consequently, PV system comparisons that are intended to guide deployment decisions in the KSA should represent embodied emissions in a traceable kg CO₂-eq/kWp form and be normalized to delivered electricity using site-specific yield estimates that represent the climatic zones of KSA.

Across PV LCAs, a consistent finding is that upstream processes dominate the GHG footprint, whereas operational contributions are minimal; within total system impacts, module manufacturing and major balance-of-system (BOS) components typically account for most of the embodied burden^{1,2}. This stage-based dominance is illustrated in Figure 2, which shows that PV panel manufacturing is the largest contributor to GHG emissions per kWh across PV technologies in the referenced dataset, with inverter and BOS components providing additional contributions; conversely, the contributions from operation is comparatively minor². Similarly, recent utility-scale PV LCA inventory results show that capacity-based emissions arise predominantly from electricity- and material-intensive upstream steps (e.g., silicon feedstock and wafer, cell, or module production) and from BOS elements such as trackers and inverters, thus reinforcing the importance of procurement and supply-chain choices when comparing PV systems expressed in kg CO₂-eq/kWp¹.

Because PV manufacturing is an electricity-intensive process, the carbon intensity of the electricity supply used during production is one of the strongest factors affecting embodied emissions. For single-crystalline-silicon (sc-Si) module manufacturing, Müller et al. reported that module production in China is associated with substantially higher climate-change impacts than that of production in regions with lower-carbon electricity grids. On an installed-capacity basis, the embodied emissions were estimated to be 810 kg CO₂-eq/kWp for glass-backsheet

modules manufactured in China, compared to 480 kg CO₂-eq/kWp for equivalent modules produced in the European Union⁵. This study also attributed a dominant share of GHG emissions across the process chain to electricity consumption and highlighted that emission-intensive stages in the manufacture of sc-Si PV modules include polysilicon production and Czochralski crystal growth, both of which require substantial electricity inputs⁵. This sensitivity characteristics in the electricity supply chain motivates the reporting of life-cycle GHGs emissions on an installed-capacity basis (kg CO₂-eq/kWp) before normalizing the results based on electricity generation (g CO₂-eq/kWh). Frischknecht⁶ compiled an updated LCA of PV electricity for International Energy Agency (IEA) PV Power Systems (PVPS) Task 12, reporting life-cycle GHG intensities of 42.5 and 42.3 g CO₂-eq/kWh for monocrystalline silicon (mono-Si) and multicrystalline/polycrystalline silicon (multi-/poly-Si) technologies, respectively. These values were substantially lower than those of fossil-fuel generators (approximately 1 kg CO₂-eq/kWh). Ali et al.⁷ reported CO₂ emissions for grid-only and grid + PV cases and provided the corresponding annual electricity served for each city. When converted to an intensity basis, the grid-only case yielded 632 g CO₂-eq/kWh across Riyadh, Jeddah, and NEOM. Under the optimal grid + PV configuration, the intensity decreased to 627.1, 582.6, and 581.4 g CO₂-eq/kWh for Riyadh, Jeddah, and NEOM, respectively.

Among crystalline-silicon technologies, the choice between mono-Si and multi-/poly-Si modules presents a documented tradeoff between energy- and emission-intensive manufacturing approaches and the delivered electrical performance. Reviews of PV LCA literature have indicated that mono-Si PV systems exhibit comparatively high life-cycle energy requirements, with correspondingly higher GHG emissions during production, which can be attributed to the energy intensity of the Czochralski crystal growth process². Process pathways also differ: multi-Si is

Table 1. Mono-Si versus multi-/poly-Si indicators (per 1 kWh of PV electricity) and module efficiency, extracted from the IEA PVPS Task 12 fact sheet (data vintage 2017–2019)⁴

Indicator	Unit	Mono-Si	Multi-/Poly-Si
GHG emissions	g CO ₂ -eq/kWh	42.5	42.3
Resource use, fossil fuels	MJ	0.54	0.54
Resource use, minerals and metals	mg Sb-eq	5.28	5.35
Particulate matter	10-9 disease incidences	3.63	3.51
Acidification	mmol H ⁺ -eq	0.36	0.36
Water scarcity	l water-eq	7.49	6.71
Module efficiency	%	19.5	18.0
Data vintage	—	2017–2019	2017–2019

produced via directional solidification, whereas mono-Si wafers are produced using the Czochralski crystal growth process³. However, mono-Si modules typically achieve higher conversion efficiency than that of multi-/poly-Si, which can increase lifetime electricity generation for a given installed capacity and therefore reduce life-cycle carbon intensity (g CO₂-eq/kWh) after normalization^{2,4}. Table 1 lists the mono-Si and multi-/poly-Si indicators (per 1 kWh of PV electricity) reported in the IEA PVPS Task 12 fact sheet. The data show significantly similar GHG emissions per kWh (42.5 versus 42.3 g CO₂-eq) alongside higher reported module efficiency for mono-Si (19.5% versus 18.0%)⁴. These observations motivate a KSA-specific comparison that combines capacity-based embodied emissions (kg CO₂-eq/kWp) with site-specific yield to obtain carbon intensity per kWh under local operating conditions.

Another requirement for decision-relevant PV comparisons is that the yield assumptions reflect the installation context. PV LCA reviews emphasize that solar irradiation, module efficiency, system performance ratio, and assumed lifetime are key drivers affecting the reported GHG emission rate per kWh². These drivers are particularly important in the KSA because irradiation and climatic conditions vary across regions, and utility-scale PV plants frequently employ design choices (e.g., tracker configurations) that directly influence annual yield. Therefore, comparing mono- and poly-Si systems using a fixed generic yield can obscure the effect of site conditions in the KSA on the life-cycle carbon intensity, even when the embodied impacts per kW peak are known².

Motivated by these considerations, this study evaluated the embodied and yield-normalized GHG performance of utility-scale crystalline-silicon PV systems in the KSA, focusing on the poly- and mono-Si technologies that are currently used in projects exceeding 200 MW. The representative plants that were analyzed include Sakaka (300 MW, Al Jouf), Sudair (1,500 MW, Riyadh Province), Jeddah (300 MW), and Shuaibah (2,060 MW), which were developed by ACWA Power. Module and BOS embodied emissions were quantified using the technology-differentiated consensus life-cycle inventory (LCI) compiled by IEA PVPS Task 12 (Report T12-19:2020)¹⁴, with the corresponding system-level GHG intensities reported in the associated IEA PVPS fact sheet^{1,6}. This inventory basis is consistent with the documented geographic structure of the global crystalline-silicon supply chain and is cross-validated in this study against the updated utility-scale PV LCA reported by Smith

et al.¹ and the supplier-specific 2023 Chinese mono-Si module footprint reported by Li et al.^{1,5}. The assessment applies an ISO 14040/44-aligned carbon-intensity methodology, as implemented in the referenced PV LCA literature.^{3–5,8,9} LCI data were obtained from the National Renewable Energy Laboratory (NREL) databases and peer-reviewed PV LCA studies to quantify the embodied GHG emissions per installed capacity (kg CO₂-eq/kWp). This approach is consistent with the recommendations in the literature, which identify that upstream processes are the dominant contributors to the life-cycle GHG emissions of PV systems (Figure 1 and Figure 2)^{1,4}. Energy generation potential is estimated using RETScreen Expert for three high-irradiance sites at NEOM, Riyadh, and Jeddah, representing distinct climatic zones in the KSA, enabling normalization of life-cycle GHG emissions per installed capacity (kg CO₂-eq/kWp) to life-cycle carbon intensity (g CO₂-eq/kWh) using site-specific annual yields.

2. METHODOLOGY

As shown in Figure 3, the methodology comprises of two linked analytical streams. In the first stream, RETScreen was used to simulate the site-specific PV performance for NEOM, Riyadh, and Jeddah. Then, tilt-angle optimization was performed to identify the angle corresponding to the maximum annual specific electricity yield; subsequently, the results were normalized to annual specific energy yield (kWh/kW/year) and annual energy yield per unit module area (kWh/m²/year). In the second stream, literature-based LCI data were compiled to estimate the embodied GHG emissions, expressed as kg CO₂-eq/kWp, which include module manufacturing, BOS components, transport, installation, and operation and maintenance (O&M). The normalized electricity-yield results and embodied-emission estimates were then combined to calculate the final life-cycle carbon intensity (in g CO₂-eq/kWh), which formed the basis for the comparative evaluation of the poly- and mono-Si PV systems across the three study locations.

2.1. Goal, Scope, and Functional Unit. **Goal.** The goal of this study was to quantify and compare the life-cycle carbon intensity (g CO₂-eq/kWh of grid-delivered electricity) of utility-scale crystalline-silicon PV systems deployed in Saudi Arabia, distinguishing between mono-Si and multi-/poly-Si module

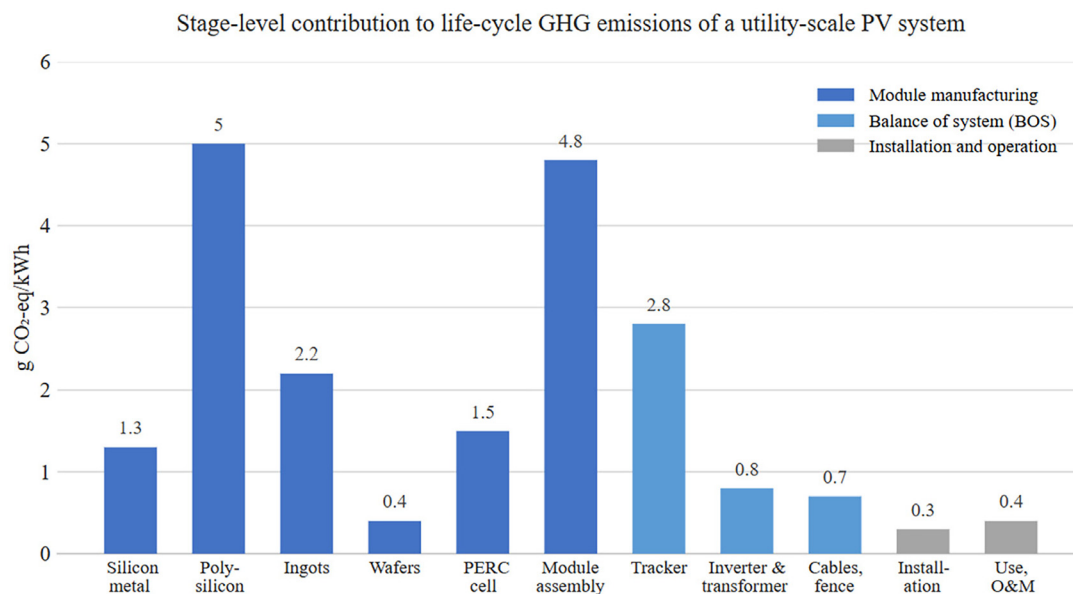


Figure 2. Stage-level contribution to life-cycle GHG emissions (g CO₂-eq/kWh) across PV technologies: panel manufacturing dominates, with additional contributions from the inverter and BOS components¹

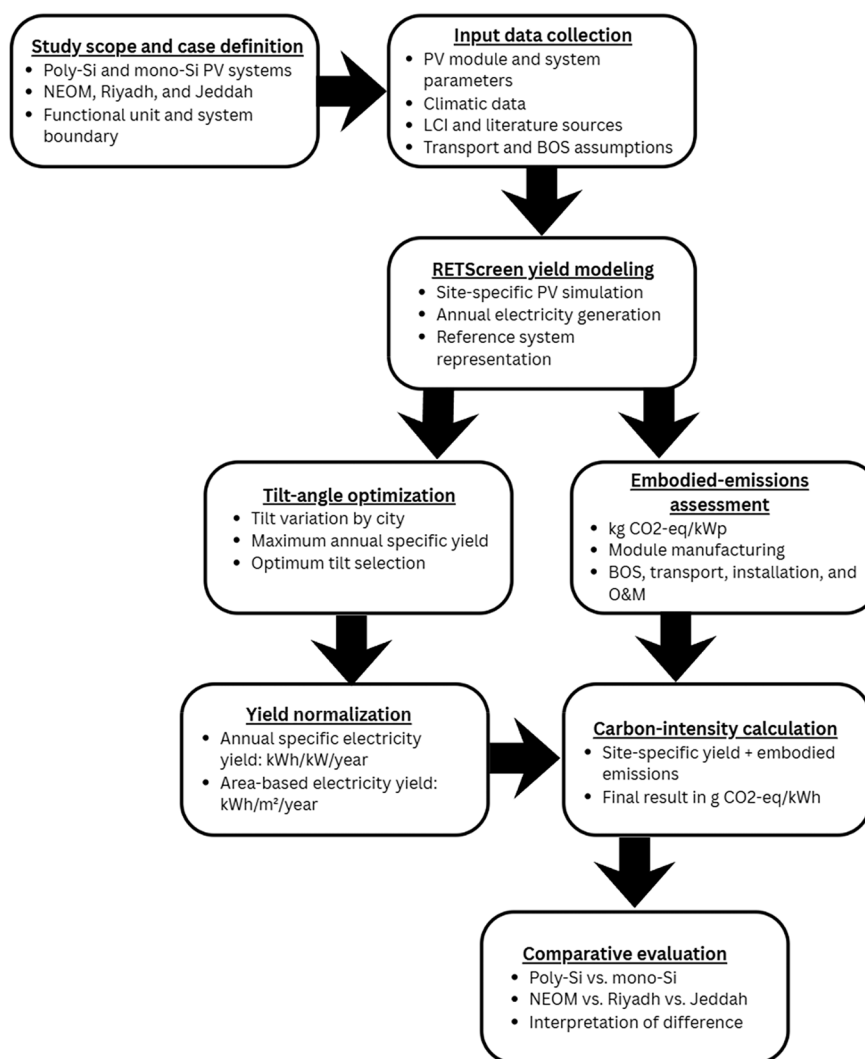


Figure 3. Methodological framework adopted in the present study

technologies that are operating in three climatic zones represented by NEOM, Riyadh, and Jeddah. The intended application is a deployment-oriented technology and site selection for the utility-scale solar portfolio of the KSA.

Scope and system boundary. A cradle-to-gate-plus-use system boundary was adopted, which is consistent with the principles of ISO 14040 and 14044^{8,9}, and follows the IEA PVPS Task 12 methodology guidelines (Report T12-18:2020)¹³. The foreground stages include silica-sand extraction, metallurgical-grade silicon production, polysilicon refining, ingot growth (Czochralski for mono-Si and directional solidification for multi-Si), wafer slicing, cell fabrication, module encapsulation, BOS manufacturing (tracker, inverter, transformer, cables, mounting), installation, and O&M. End-of-life treatment was excluded because largescale PV decommissioning has not yet occurred on an industrial scale in Saudi Arabia, and recycling pathways for Saudi-deployed plants have not yet been defined. Transport from the manufacturing hub to the installation site was included as a scenario-based sensitivity analysis (Section 2.6.3); however, it was not included in the GHG emissions used to calculate the reported carbon intensity, which is consistent with the findings in the PV LCA literature that transport contributes less than ~1% of module life-cycle emissions.

Functional unit and reference flow. The functional unit was 1 kWh of AC electricity that is delivered to the KSA grid over the 25-year operating life of the PV system at a location-specific optimum tilt angle. The reference flow is the share of the installed PV capacity (kWp), BOS, installation, and O&M activities required to deliver this functional unit under the site-specific yield modeled in RETScreen.

Impact category, allocation, and cutoff. The single impact category assessed was climate change, expressed as the 100-year global warming potential (GWP100) that is calculated using the Intergovernmental Panel on Climate Change characterization factors, which is consistent with the IEA PVPS Task 12 guidelines and NREL utility-scale PV LCA practice. Multifunctional allocation was not performed because electricity is the only product of the system. The cutoff criterion followed the referenced inventory sources, in which background processes were drawn from a consistent LCI database with a mass cutoff below 1%. The embodied-emission inventory is independent of the installation site because it depends on the manufacturing supply chain, whereas the energy yield (denominator term) is site-specific. The combined metric (g CO₂-eq/kWh) is therefore consistent with the convention of allocating the same module and BOS inventory over the site-specific lifetime electricity delivery. This approach is similar to that used by Smith et al.¹, who combined a reference inventory with location-specific yields to report life-cycle carbon intensities of 10–36 g CO₂-eq/kWh range for U.S. utility-scale systems.

Assessment approach and scope of ISO alignment. The assessment approach applied in this study constitutes a structured carbon-intensity calculation that draws on established literature-based LCIs rather than performing original LCI modeling in a dedicated LCA software environment. LCI data were compiled from published consensus sources, predominantly the IEA PVPS Task 12 Report T12-19:2020¹⁴ and NREL utility-scale benchmarks of Smith et al.¹. The resulting capacity-based embodied-emission values were combined with site-specific yield

outputs from RETScreen to derive the carbon intensity (g CO₂-eq/kWh). This approach applies the principles of ISO 14040 and 14044 and is consistent with the established practice in the PV LCA literature for deployment-oriented assessments. It differs from a completely original ISO-compliant LCA as it does not employ LCI modeling in a background database or LCA software; moreover, no independent critical review was conducted. These characteristics are noted here in the interest of transparency and do not affect the validity of the methodology for the intended purpose of comparing site-specific carbon intensities on a consistent and traceable inventory basis.

2.2. Study Locations and Climatic Data. NEOM, Riyadh, and Jeddah were selected as representative study locations because they reflect distinct climatic conditions within the KSA and provide a suitable basis for site-specific comparisons of PV system performance. These locations align with previous assessments of grid-connected PV systems in major Saudi cities, where differences in solar resources and ambient conditions were shown to affect the annual system output and overall feasibility⁷.

The monthly climatic inputs used in the RETScreen simulations included the mean air temperature and mean daily solar irradiation for each city. These data were extracted from the RETScreen Expert climate database 10 and used to characterize the local environmental conditions governing PV electricity generation. The selected variables are methodologically important because the annual electricity yield, energy payback, and yield-normalized life-cycle carbon intensity depend strongly on local irradiation and ambient temperature²⁻⁴. Figure 4 shows the monthly climatic profiles that were adopted for NEOM, Riyadh, and Jeddah in the present study.

The annual mean air temperatures adopted in the simulations were 21.9, 25.7, and 28.2 °C for NEOM, Riyadh, and Jeddah, respectively, whereas the annual mean daily solar irradiation values were 6.29, 5.13, and 5.94 kWh/m²/day, respectively. These climatic differences were retained explicitly in the RETScreen model so that subsequent comparisons of electricity yield and life-cycle carbon intensity would reflect the influence of local site conditions rather than represent a single generalized reference case for Saudi Arabia.

2.3. PV Module and System Input Parameters. This subsection describes the PV module and system parameters adopted in the RETScreen yield model. One each of polycrystalline and monocrystalline modules, both manufactured by Jinko Solar, were selected as representative commercially available crystalline-silicon products from Chinese companies. This configuration provides a consistent comparative basis for yield modeling under identical operating assumptions and does not represent the installed capacity of a utility-scale plant. The manufacturer-based module properties were entered directly into RETScreen¹⁰, whereas identical common operating assumptions were maintained for both technologies to isolate the effect of the module characteristics on the electricity yield.

Table 2 lists the technology-specific input parameters used in the simulations. The poly- and mono-Si cases are represented by modules JKM330PP-72-V and JKM610N-78HL4-BDV, respectively. A reference configuration of 10 modules was assigned to each case, resulting in total PV array capacities of 3.30 and 6.10

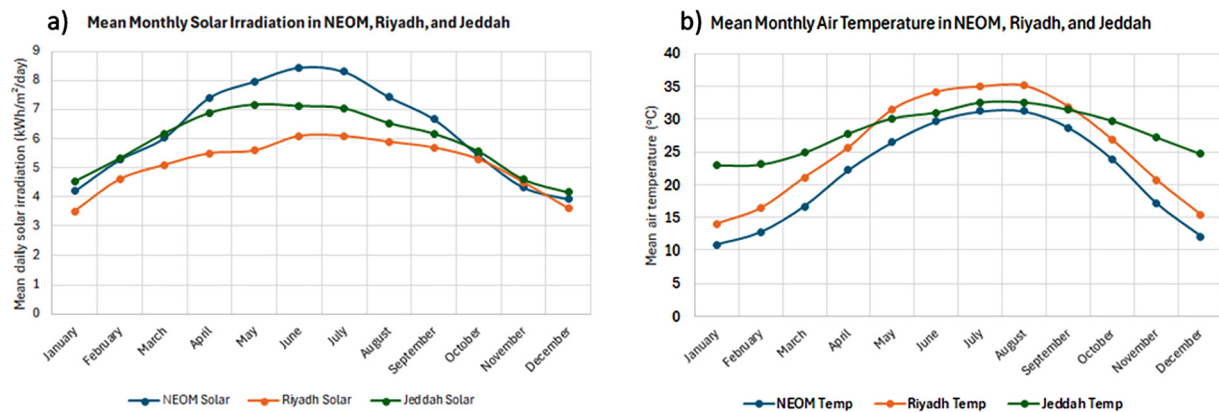


Figure 4. Mean monthly climatic conditions used in the RETScreen simulations for NEOM, Riyadh, and Jeddah: (a) mean daily solar irradiation and (b) mean air temperature

kW for the poly- and mono-Si systems, respectively. A fixed module count of 10 was selected as the minimum reference unit that produces a practically meaningful absolute annual yield in RETScreen while ensuring a tractable simulation. Because the two modules differ substantially in their rated power (330 W for the poly-Si module versus 610 W for the mono-Si module), this fixed module count resulted in different installed capacities for the two reference configurations. Therefore, all technology comparisons in this study were conducted on a normalized per-kWp or per-kWh basis, as explained in Sections 2.4 and 2.7, which are independent of the absolute installed capacity of the reference configuration. The poly- and mono-Si module efficiencies were 17.01 and 21.82%, respectively, whereas the total solar collector areas were 19.3 and 31.1 m², respectively. These differences were retained in the yield model so that variations in annual electricity generation could be interpreted in relation to the module characteristics rather than to changes in common operating assumptions.

Table 2. PV module and system input parameters used for yield-model representation

Parameter	Polycrystalline (poly-Si)	Monocrystalline (mono-Si)
Module model	JKM330PP-72-V	JKM610N-78HL4-BDV
Number of units	10	10
Rated power per module (W)	330	610
Total PV array power capacity (kW)	3.30	6.10
Module efficiency (%)	17.01	21.82
Solar collector area (total) (m ²)	19.3	31.1

Note: Both module sets are Jinko Solar products under single-axis tracking. NOCT denotes the nominal operating cell temperature. Assumptions: NOCT = 45 °C, temperature coefficient = 0.4%/°C (Jinko datasheets), bifacial factor = 0%, miscellaneous losses = 10%; the latter is assumed to partially absorb summer NOCT exceedance and soiling. Soiling sensitivity is beyond the scope of this study (refer to Section 3.6).

The input parameters presented in Table 2 were subsequently used to estimate the annual electricity generation, perform tilt-angle optimization, and calculate the normalized yield indicators employed in the later stages of the analysis.

2.4. Yield Normalization Metrics. To enable a consistent comparison of PV performance across technologies and locations, the RETScreen outputs were normalized using both the installed PV capacity and total solar collector area. This approach was adopted because the PV electricity yield depends not only on local climatic conditions but also on differences in module rating, efficiency, and collector area²⁻⁴. Because this study used 10-panel reference systems for the poly- and mono-Si cases, the installed PV capacity of each system was first calculated from the number of modules and rated power of the selected module¹⁰. The normalization metrics used in this study are presented in Eqs. 1, 2, and 3.

$$P_{inst} = N \times P_{module} / 1000, \quad (1)$$

where P_{inst} is the installed PV capacity (kWp), N is the number of modules, and P_{module} is the rated power of an individual module (W). The adopted 10-module configurations yielded installed capacities of 3.30 and 6.10 kWp for the poly- and mono-Si systems, respectively.

The first normalization metric, the annual specific electricity yield, was used to evaluate the electricity generation per unit of installed PV capacity and is calculated as follows:

$$Y_{cap} = E_{ann} / P_{inst}, \quad (2)$$

where Y_{cap} is the annual specific electricity yield (kWh/kWp/year), E_{ann} is the annual electricity exported to the grid (kWh/year), and P_{inst} is the installed PV capacity (kWp).

The second normalization metric, area-based electricity yield, was used to evaluate electricity generation per unit of collector area and is calculated as follows:

$$Y_{area} = E_{ann} / A_{col}, \quad (3)$$

where Y_{area} is the area-based electricity yield (kWh/m²/year), E_{ann} is the annual electricity exported to the grid (kWh/year), and A_{col} is the total solar collector area (m²).

The use of both indicators facilitated a comparison to distinguish between the electricity yield per unit of installed PV capacity and electricity yield per unit of collector area. This was particularly relevant in the present study because the selected mono- and poly-Si systems differed in their rated module power, module efficiency, and total collector area. Accordingly, the normalized metrics provided a consistent basis for the comparison of the tilt-angle performance, annual electricity yield, and yield-normalized life-cycle carbon intensity across NEOM, Riyadh, and Jeddah^{2-4,10}.

2.5. Tilt-Angle Optimization. To determine the most suitable tilt configuration for each study location, the tracking tilt angle was varied systematically in the RETScreen yield model, while all other system parameters were kept constant. Separate simulations were performed for NEOM, Riyadh, and Jeddah to account for the differences in local climatic conditions and solar-resource characteristics^{7,10}. For each city, the annual electricity output of the reference PV system was evaluated at different tilt settings, and the angle corresponding to the maximum annual specific electricity yield was selected as the optimum tilt angle for the subsequent analysis.

The optimization criterion adopted in this study was based on the annual specific electricity yield defined in Eq. 2 because this metric provides a consistent basis for comparing PV performance per unit of installed capacity across different system configurations²⁻⁴. Therefore, the optimum tilt angle for each city was determined as follows:

$$\theta_{opt} = \arg \max_{\theta} Y_{cap,\theta}, \quad (4)$$

where θ_{opt} is the optimum tilt angle ($^{\circ}$), θ is the tracking tilt angle considered in the simulation, and $Y_{cap,\theta}$ is the annual specific electricity yield (kWh/kWp/year) obtained at tilt angle θ .

This optimization step was performed separately for each location before calculating the annual electricity yield, area-based electricity yield, and yield-normalized life-cycle carbon intensity. By using a location-specific optimum tilt rather than a single fixed angle for all cases, the analysis can accurately reflect the influence of local solar conditions on the PV system performance and final carbon-intensity results^{2-4,7,10}.

2.6. LCI Data and Embodied-emissions Assumptions.

The LCI data used to quantify embodied emissions in this study were drawn primarily from the IEA PVPS Task 12 consensus inventory (Report T12-19:2020)¹⁴ and cross-validated against recent peer-reviewed and NREL utility-scale PV LCA literature, with values expressed on an installed-capacity basis (in kg CO₂-eq/kWp)^{1,5,6}. Consistent with the system boundary defined in Section 2.1, the embodied-emissions inventory included module manufacturing, BOS components, transport, installation, and O&M, whereas end-of-life treatment was excluded. Therefore, the total embodied-emissions term adopted in this study is represented as the sum of the following components:

$$E_{emb} = E_{mod} + E_{BOS} + E_{trans} + E_{inst} + E_{O\&M}, \quad (5)$$

where E_{emb} is the total embodied emission (kg CO₂-eq/kWp); E_{mod} , E_{BOS} , E_{trans} , and E_{inst} denote the module manufacturing, BOS, transport, installation, and O&M contributions, respectively.

2.6.1. Module manufacturing emissions. The module manufacturing and BOS embodied-emission inventories for both technologies were obtained from the IEA PVPS Task 12 consensus LCI (Report T12-19:2020)¹⁴, which provides stage-resolved material and energy flow data for mono- and multi-Si PV module manufacturing across four world regions (China, Europe, North America, and Asia-Pacific) for the 2018 supply-chain status. The corresponding system-level GHG intensities, obtained by applying GWP100 characterization factors to these inventory data, are reported in the associated IEA PVPS fact sheet as 42.5 and 42.3 g CO₂-eq/kWh for mono- and multi-/poly-Si, respectively, for a ground-mounted reference system with 975 kWh/kWp annual yield and 0.7%/year linear degradation^{4,6}. The module efficiencies embedded in the Report T12-19:2020 reference (19.5% for mono-Si and 18.0% for multi-Si) were consistent with the technology indicators adopted in the present study (Table 1). This source was selected because it provides technology-specific inventory data for complete mono-Si and multi-/poly-Si at the system level, which represent the current IEA PVPS Task 12 consensus dataset that was developed jointly by PV LCA experts from NREL, Europe, and Asia; moreover, it follows the ISO 14040/14044-aligned IEA PVPS methodology guidelines.

Note that the IEA PVPS Task 12 reference system corresponds to a 3 kWp roof-mounted configuration, whereas the present study focused on utility-scale ground-mounted systems with single-axis trackers. The BOS composition of a small rooftop system, which typically includes cabling, a residential inverter, and a simple mounting structure, differs from that of a utility-scale plant, which additionally incorporates tracker systems, utility-grade inverters, high-voltage transformer stations, and an extended electrical infrastructure. Cross-validation against the study by Smith et al.¹, which provides a dedicated utility-scale inventory inclusive of tracker and transformer contributions, is included to highlight this BOS difference and confirm that the IEA PVPS-based embodied emission is consistent in magnitude with a purpose-built utility-scale benchmark. The agreement between the two sources at the system level (Section 3.5) supports the use of the IEA PVPS Task 12 inventory as a reasonable approximation for the complete PV system while acknowledging that a dedicated utility-scale BOS inventory will further refine the BOS component.

In this framework, module manufacturing term is the principal technology-differentiating component between the poly- and mono-Si cases because the two technologies differ in terms of the silicon processing method, module efficiency, and material intensity^{5,6}. The IEA PVPS carbon intensities (reported in g CO₂-eq/kWh) were converted to capacity-based embodied emissions (kg CO₂-eq/kWp) because the published values are based in reference European yield condition (975 kWh/kWp/year yield and 0.7%/year linear degradation), which cannot be applied directly to the site conditions in Saudi Arabia. Expressing embodied emissions on a capacity basis separates supply-chain-dependent emissions from location-dependent electricity generation, allowing the same embodied-emissions estimate to be combined with

site-specific lifetime electricity yields in Saudi Arabia. This procedure is methodologically equivalent to that employed by Smith et al.¹ and is consistent with the IEA PVPS Task 12 methodology guidelines. The capacity-based embodied-emissions values were obtained by back calculating the implied emissions from the IEA PVPS reference conditions with a 0.7%/year degradation. These capacity-based values were subsequently combined with the site-specific lifetime electricity yields in Eq. 9.

Note that the RETScreen yield model in this study does not account for module degradation, whereas the IEA PVPS reference incorporates 0.7%/year linear degradation over its 30-year operational period. Consequently, the lifetime electricity yield used in Eq. 9 is marginally overestimated relative to the degradation-adjusted yield, producing a marginally underestimated carbon intensity. The directional bias is 8–10% over a 25-year period and is examined as part of the sensitivity analysis in Section 3.6. The influence of the 2018 supply-chain vintage of the IEA PVPS dataset on the reported carbon intensity relative to more recent estimates are examined in Section 3.6.

2.6.2. BOS, installation, and O&M emissions. The BOS, installation, and O&M contributions were primarily adopted from the updated utility-scale PV LCA framework reported by NREL¹, and supported by the broader inventory structure summarized by the IEA PVPS guidelines⁶. These terms included the tracker and mounting system contributions, inverter and transformer components, electrical BOS materials, installation activities, and maintenance-related burdens over the study period. In the present methodology, these system-level terms were treated on the same capacity basis as the module manufacturing inventory so that all embodied-emission contributions remained consistent in units of kg CO₂-eq/kWp. This treatment is appropriate because the purpose of the study was to compare module technologies and also evaluate the final carbon intensity of complete PV systems rather than modules alone^{1,6}.

2.6.3. Transport emissions. Transportation emissions were treated as a scenario-based component of the embodied-emissions inventory. Jinko Solar identified the principal manufacturing hubs in Chinese provinces, including Jiangxi, Zhejiang, and Anhui¹². However, because the exact production facility of the selected module models could not be verified publicly, the transport emissions were modeled using a representative Chinese manufacturing origin rather than a confirmed module-specific factory location. The transport pathway comprised an inland road leg from a manufacturing location in China to Shanghai Port, an ocean-freight leg from Shanghai Port to Jeddah Port, and a final inland road leg from Jeddah Port to the installation site in the KSA, expressed as

$$E_{trans} = E_{CN-road} + E_{sea} + E_{SA-road}, \quad (6)$$

where E_{trans} is the total transport contribution (kg CO₂-eq/kWp), $E_{CN-road}$ is the inland transport contribution within China, E_{sea} is the ocean-freight contribution, and $E_{SA-road}$ is the inland transport contribution within Saudi Arabia. The ocean-freight segment was modeled using a representative 40-foot full-container-load shipping scenario from Shanghai Port to Jeddah Port. The carrier-based CO₂ estimates were obtained

using the SeaRates Carbon Calculator 11. Therefore, the resulting transport values should be interpreted as representative scenario-based estimates, rather than as shipment-specific records. Accordingly, the transport contribution was as a separate sensitivity case to provide greater supply-chain transparency, and was not included in the headline carbon-intensity numerator that is reported in Section 3.5.

Table 3 provides a concise summary of the LCI stages included in this study, together with the primary data source and basis for each contribution. It provides a transparent overview of the embodied-emissions estimate and clarifies the scope of the assessment.

2.7. Life-Cycle Carbon-intensity Calculation. The final life-cycle performance metric adopted in this study was the carbon intensity of PV electricity generation, expressed in g CO₂-eq/kWh. This metric was obtained by combining the literature-based embodied-emissions inventory (kg CO₂-eq/kWp) described in Section 2.6 with the site-specific electricity-yield outputs derived from RETScreen (kWh/kWp)¹⁰. Because the environmental burden of a PV system is ultimately normalized to the electricity generated during its operating life, the final carbon intensity is determined by the ratio of embodied-emissions to lifetime electricity generation^{2–4}. In this study, a project lifetime of 25 years was assumed as the basis for electricity yield. This lifetime represents the operational period of the PV system and does not imply the inclusion of the end-of-life treatment, which is excluded from the system boundary.

The lifetime electricity generation of the reference PV system is calculated as

$$E_{life} = E_{ann} \times L, \quad (7)$$

where E_{life} is the lifetime of the electricity generation (kWh), E_{ann} is the annual amount of electricity exported to the grid (kWh/year), and L is the project lifetime (years).

Because the embodied-emissions inventory in this study was assembled on an installed-capacity basis, the lifetime electricity yield is also expressed in normalized form as

$$Y_{life} = Y_{cap} \times L, \quad (8)$$

where Y_{life} is the lifetime electricity yield (kWh/kWp), Y_{cap} is the annual specific electricity yield (kWh/kWp/year), and L is the project lifetime (years).

The life-cycle carbon intensity is then calculated as

$$CI = (E_{emb} \times 1000) / Y_{life}, \quad (9)$$

where CI is the life-cycle carbon intensity (g CO₂-eq/kWh), E_{emb} is the total embodied emissions per unit installed capacity (kg CO₂-eq/kWp), and Y_{life} is the lifetime electricity yield per unit installed capacity (kWh/kWp).

This formulation allowed the final carbon intensity results to reflect both the embodied-emissions burden of the PV system and the influence of site-specific electricity generation. For the same value of embodied emissions, a location with a higher lifetime electricity yield produces a lower value of g CO₂-eq/kWh. Accordingly, the carbon-intensity metric used in this study directly links manufacturing- and system-level burdens to

Table 3. LCI structure and embodied-emission summary adopted in the present study

Stage	Mono-Si (kg CO ₂ -eq/kWp)	Multi-/Poly-Si (kg CO ₂ -eq/kWp)	Primary source	Status
Module manufacturing (silicon feedstock, ingot, wafer, cell, encapsulation)	Principal technology-differentiating term; in system total	Principal technology-differentiating term; in system total	IEA PVPS T12-19:2020 ¹⁴	Included
BOS (tracker, inverter, transformer, mounting, cabling)	In system total	In system total	IEA PVPS T12-19:2020 ¹⁴ ; Smith et al. ¹	Included
Installation	In system total	In system total	Smith et al. ¹	Included
O&M	In system total	In system total	Smith et al. ¹	Included
Transport (China → Saudi Arabia)	Scenario-based; excl. headline	Scenario-based; excl. headline	SeaRates; Section 2.6.3	Sensitivity
End-of-life	Excluded	Excluded	Section 2.1	Excluded
Total embodied emission (headline numerator, Eq. 9)	≈ 1,117	≈ 1,112	Derived, Section 2.6.1	Included

Note: Stage-level disaggregation within the total is indicated. The adopted sources (IEA PVPS T12-19:2020¹⁴; Smith et al.¹) report system-level totals; stage-level values were not publicly disaggregated at the resolution required for a complete numerical breakdown per stage. The headline numerator was derived by back calculation, as described in Section 2.6.1. Transport was excluded from the headline numerator and end-of-life was excluded from the system boundary as explained in Sections 2.6.3 and 2.1, respectively.

the climatic and operational conditions of NEOM, Riyadh, and Jeddah^{2–4,10}.

3. RESULTS AND DISCUSSION

This section presents the key findings of the study and discusses them in the context of the research objectives. Section 3.1 reports tilt-angle optimization, Sections 3.2–3.3 present the annual electricity-yield and grid-export results, Section 3.4 reports the gross annual GHG emission reduction, Section 3.5 compares the life-cycle carbon intensity across technologies and locations, and Section 3.6 provides a critical evaluation of the underlying assumptions and limitations.

3.1. Tilt-Angle Optimization. Figure 5 shows the variation in the annual specific electricity yield with tilt angle for the three study locations. In all cases, the yield increased to its maximum value and then decreased, indicating a distinct optimum tilt angle for each city. The optimum tilt values obtained from the yield model were 27.7°, 20.1°, and 23.9° for NEOM, Jeddah, and Riyadh, respectively. Among the three locations, NEOM exhibited the highest annual specific electricity

yield, followed by Jeddah; Riyadh exhibited the lowest yield. These results confirm that the tilt-angle optimization is location-dependent and should therefore be determined separately for each city before comparing the annual electricity exports and subsequent yield-normalized life-cycle results. The sensitivity of the annual yield to the tilt angle was moderate, reinforcing the importance of the site-specific configuration in maximizing the lifetime electricity denominator of Eq. 9.

3.2. Annual Electricity-yield Comparison. After applying the optimum tilt angle for each location, the PV performance was compared using two normalized yield indicators. The first was the annual specific electricity yield (kWh/kWp/year), which measures electricity generation per unit of installed PV capacity. The second was the area-based electricity yield (kWh/m²/year), which measures the electricity generation per unit of the collector area. Table 4 lists the annual specific electricity yields obtained for the optimized systems in NEOM, Jeddah, and Riyadh.

The annual specific electricity yield was the highest at NEOM, followed by Jeddah; Riyadh recorded the lowest value. This indicates that the local climatic and solar-resource conditions governed the normalized electricity output more strongly than

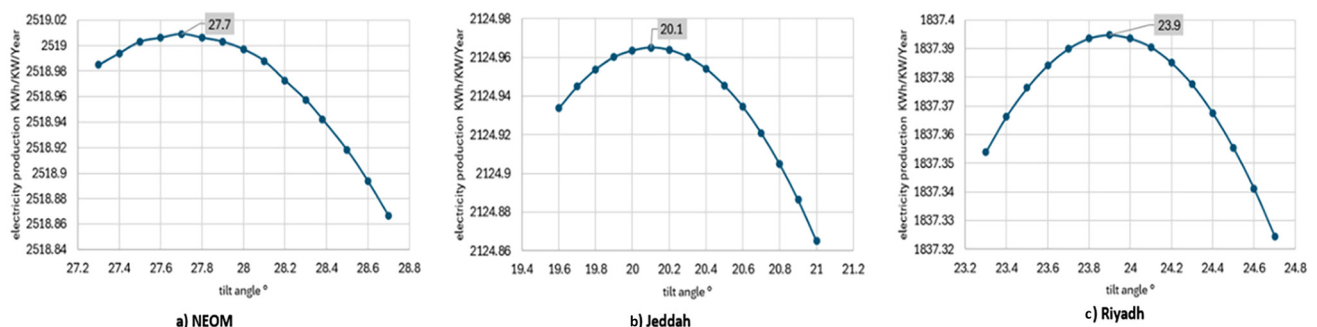
**Figure 5.** Effect of tilt angle on annual specific electricity yield at (a) NEOM, (b) Jeddah, and (c) Riyadh

Table 4. Annual specific electricity yield of the optimized PV systems in the three study locations

City	Annual specific electricity yield (kWh/kWp/year)
NEOM	2,465
Jeddah	2,125
Riyadh	1,839

Note: The normalized annual specific electricity yield was identical for the mono-Si and poly-Si systems at each location under the adopted modeling assumptions.

the selected module technology when generation was expressed per unit of installed capacity. The difference between the yields at NEOM (2,465 kWh/kWp/year) and Riyadh (1,839 kWh/kWp/year) was approximately 34%, which directly propagates into the final carbon intensity through Eq. 9; that is, a higher yield (denominator term) for the same embodied-emission value (numerator term) yields a proportionally lower carbon intensity value (g CO₂-eq/kWh). This location effect is the dominant driver of the carbon-intensity differences reported in Section 3.5, and it substantially exceeds the technological effect demonstrated by the mono- and poly-Si modules.

When the electricity generation was normalized by the total collector area, the mono-Si system showed consistently higher values than those of the poly-Si system at all three locations, as illustrated in Figure 6. In NEOM, the area-based yields of the mono- and poly-Si systems are 484 and 422 kWh/m²/year, respectively. The corresponding values in Jeddah are 417 and 363 kWh/m²/year, whereas those in Riyadh are 361 and 314 kWh/m²/year. This difference reflects the higher module efficiency of the mono-Si module, which enables greater electricity generation per unit collector area. Across both technologies, the rankings of the three cities remained unchanged, confirming that NEOM offered the most favorable solar-resource conditions for both module types.

3.3. Annual Electricity Exported to the Grid. Because the two reference configurations differed in installed capacity (6.10 kWp for mono-Si and 3.30 kWp for poly-Si), the absolute

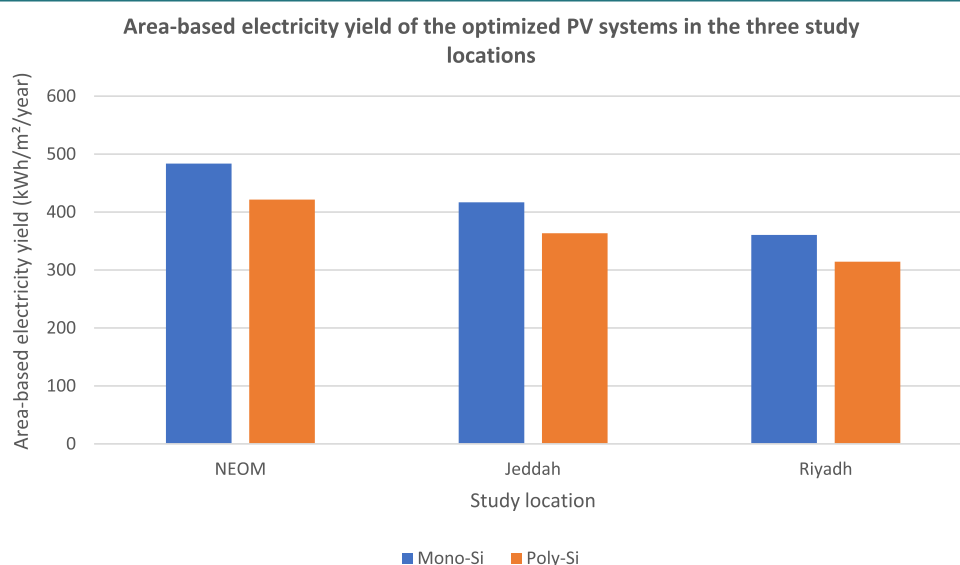
generation values presented in this section are not directly comparable across technologies, that is, under any fixed grid emission factor, the larger system will produce more electricity and displace more emissions simply by virtue of its size. These values are reported for completeness. Note that all technology-related conclusions in this study were drawn from the yield-normalized metrics presented in Sections 3.2 and 3.5.

Figure 7 shows a comparison of the annual electricity exported to the grid by the optimized mono- and poly-Si PV systems at the three study locations normalized by the installed DC capacity. Expressed on a per-kWp basis, the two technologies achieved identical results at every site: 2,465 kWh/kWp · year in NEOM, 2,125 kWh/kWp · year in Jeddah, and 1,839 kWh/kWp · year in Riyadh. These results confirm that the specific electricity yield is governed by site irradiance rather than by module technology. The absolute difference in electricity generation between the two reference configurations is a direct consequence of their differing installed capacities and not influenced by differences in technology. The rationale for capacity normalization is described in Section 2.4.

The location ranking was consistent across both technologies, with NEOM providing the most favorable generation conditions, followed by Jeddah and Riyadh. This ranking matches the area-based yield results presented in Section 3.2, confirming that the superior solar resource of NEOM is preserved, regardless of the normalization basis applied.

3.4. Gross Annual GHG Emission Reduction. Because the two reference configurations differ in installed capacity (6.10 kWp for mono-Si versus 3.30 kWp for poly-Si) and the same Saudi grid emission factor was applied to both, the absolute GHG reduction values presented in this section scale directly with installed capacity rather than with any technology-dependent characteristic. Therefore, they are reported for completeness and do not constitute a technology comparison, which is conducted on a yield-normalized basis in Section 3.5.

Figure 8 illustrates a comparison of the gross annual GHG emission reductions of the optimized mono- and poly-Si PV systems in NEOM, Jeddah, and Riyadh. For the mono-Si system,

**Figure 6.** Area-based electricity yield of the optimized mono- and poly-Si PV systems in NEOM, Jeddah, and Riyadh

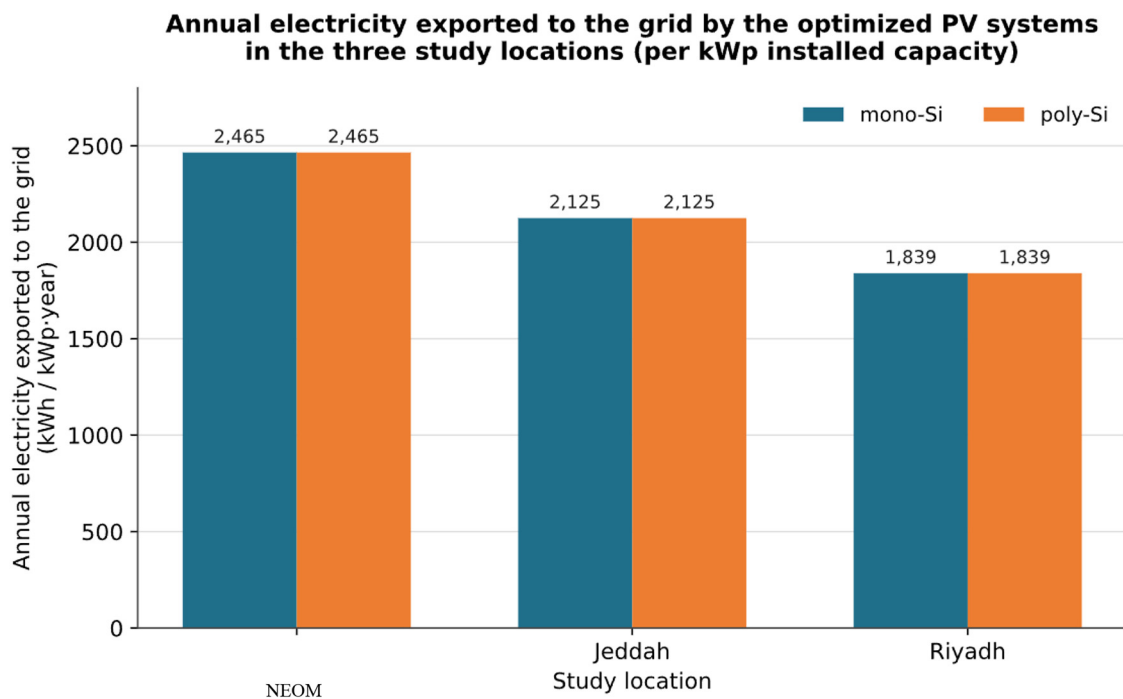


Figure 7. Annual electricity exported to the grid by the optimized mono- and poly-Si PV systems in NEOM, Jeddah, and Riyadh, normalized by installed DC capacity (kWh/kWp · year). On a per-kWp basis the two technologies are identical; the variation is based on location

the gross annual GHG emission reductions were 8.36, 7.21, and 6.24 t CO₂-eq/year in NEOM, Jeddah, and Riyadh, respectively. The corresponding values for the poly-Si system were 4.52, 3.90, and 3.37 t CO₂-eq/year, respectively.

3.5. Life-Cycle Carbon-intensity Comparison. The final performance indicator considered in this study was the life-cycle carbon intensity of PV electricity generation, expressed in

g CO₂-eq/kWh. Carbon intensity was calculated using Eq. 9 by combining the capacity-based embodied-emission values derived from IEA PVPS Task 12 (approximately 1,117 and 1,112 kg CO₂-eq/kWp for mono-Si and multi-/poly-Si, respectively; refer to Section 2.6.1), with the site-specific lifetime electricity yields calculated using Eq. 8 and listed in Table 4. Figure 9 shows the resulting life-cycle carbon-intensity values for the optimized mono- and poly-Si systems in NEOM, Jeddah, and Riyadh. The

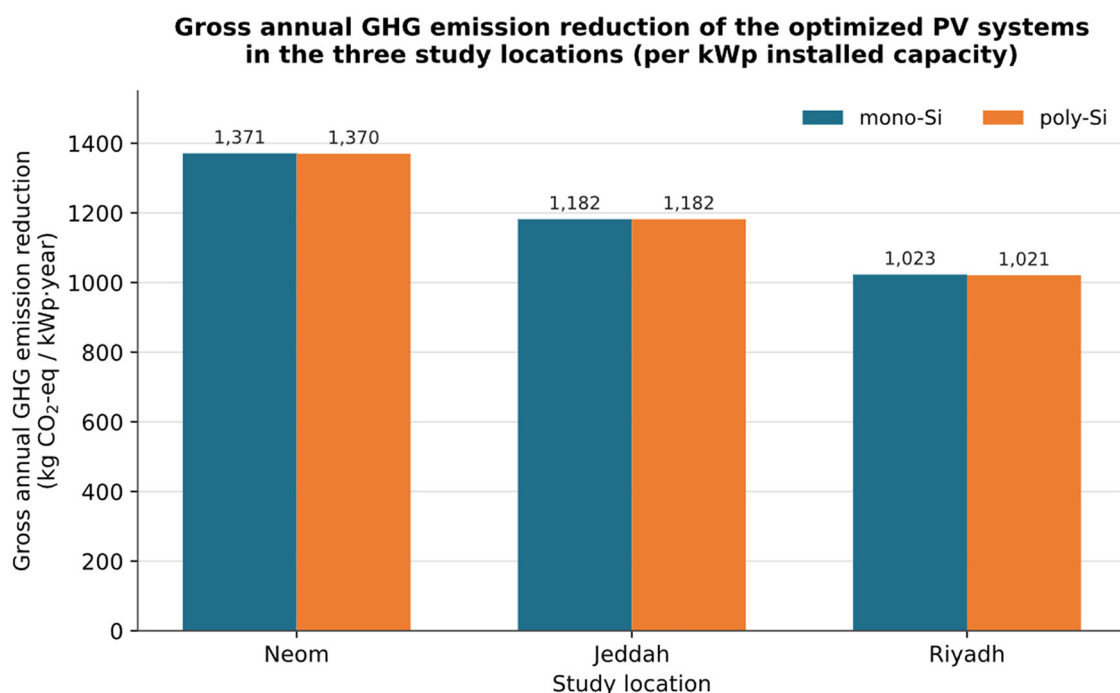


Figure 8. Gross annual GHG emission reduction of the optimized mono- and poly-Si PV systems in NEOM, Jeddah, and Riyadh, normalized by installed DC capacity (kg CO₂-eq/kWp · year). On a per-kWp basis, the two technologies are effectively identical; the variation is based on location

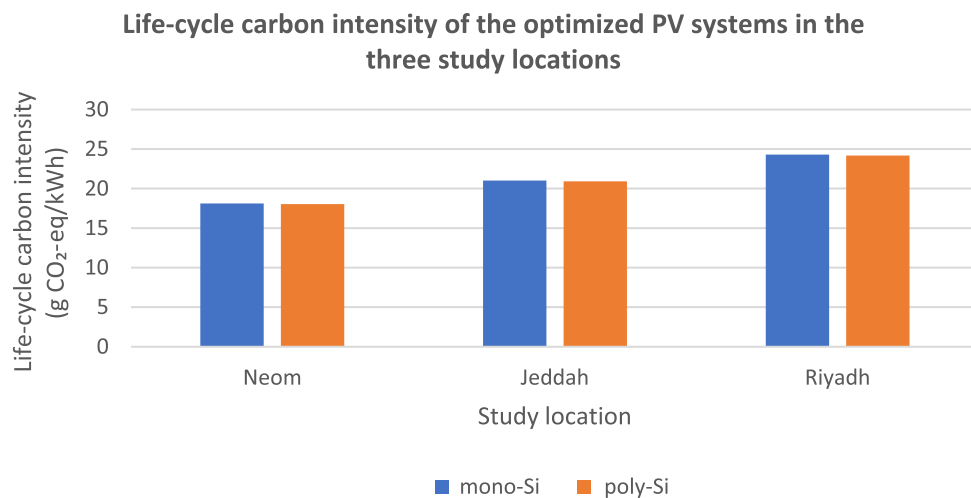


Figure 9. Life-cycle carbon intensity (g CO₂-eq/kWh) of the optimized mono- and poly-Si PV systems in NEOM, Jeddah, and Riyadh

complete derivation of the embodied-emission values and cross-validation against the studies by Smith et al.¹ and Li et al.¹⁵ are presented in Sections 2.6.1 and 3.6.

Among the three locations, NEOM exhibited the lowest life-cycle carbon intensity for both PV technologies, followed by Jeddah; Riyadh showed the highest values. This trend directly reflects the differences in annual and lifetime electricity yields; for the same embodied-emissions value, a site with higher lifetime electricity generation produces a lower carbon intensity, expressed in g CO₂-eq/kWh. The difference between the carbon intensities of NEOM and Riyadh (approximately 6 g CO₂-eq/kWh) was substantially larger than the difference between the two module technologies at any given site (approximately 0.2 g CO₂-eq/kWh), demonstrating that site-specific solar-resource conditions exert a stronger influence on the final carbon intensity than the technology-dependent difference in embodied emissions under the IEA PVPS Task 12 consensus inventory. The resulting range of 18.0–24.3 g CO₂-eq/kWh is lower than the IEA PVPS European reference intensities (42.5 and 42.3 g CO₂-eq/kWh for mono- and poly-Si, respectively) because the Saudi sites provide substantially higher lifetime electricity yield. These values fall within the modern utility-scale benchmark range of 10–36 g CO₂-eq/kWh that was reported by the NREL for tracker-based utility-scale silicon PV systems¹; their position toward the upper portion of that range reflects the conservative 2018 supply-chain vintage of the IEA PVPS inventory, as analyzed in Section 3.6.

Note that the embodied-emission value used in these calculations was drawn from the 2018 supply-chain IEA PVPS Task 12 inventory and should be regarded as a conservative, upper-bound basis relative to the current Chinese manufacturing conditions. More recent inventory data from the studies by Smith et al.¹ and Li et al.¹⁵ indicate that the current Chinese module production operates at substantially lower carbon intensities, which will shift the values reported here toward the lower portion of the NREL benchmark range. The results presented in this section are therefore best interpreted as conservative estimates reflecting a 2018 supply chain rather than the current best estimates. Refer to Section 3.6 for a quantified sensitivity analysis of this supply-chain effect.

Table 5 summarizes the selected benchmark values that are relevant to the interpretation of the present results. In addition to the IEA PVPS Task values used in this study, the table also includes the updated NREL utility-scale benchmark range¹, supplier-specific 2023 Chinese mono-Si module footprint¹⁵, and module-level Chinese mono-Si benchmarks reported by Müller et al.⁵. Taken together, these benchmarks confirm that the carbon intensity of PV electricity is jointly governed by manufacturing supply-chain assumptions, data vintage, and site-specific yield conditions; moreover, the present results are consistent with the range reported by current peer-reviewed studies and the NREL.

3.6. Critical Evaluation of the Assumptions Underlying the Carbon-Intensity Result. Three assumptions primarily influence the magnitude of the carbon intensity reported in Section 3.5: the embodied-emission inventory, lifetime electricity-yield denominator, and supply-chain electricity mix assumed during module manufacturing. Each is critically examined below.

Sensitivity to the embodied-emission inventory. Recent factory-level data from Li et al.¹⁵ indicate that the carbon footprint of current Chinese mono-Si modules has declined to 310–390 kg CO₂-eq/kWp at the module gate, reflecting an approximately 90% reduction over 15 years that can be attributed to grid decarbonization and process efficiency improvements. Smith et al.¹ reported a utility-scale system value of approximately 924 kg CO₂-eq/kWp (imported weighted-average case, excluding the end-of-life), whereas Müller et al.⁵ reported emission of 810 kg CO₂-eq/kWp for a 2012 grid comprising China-produced glass-backsheet modules. Therefore, the choice of supply-chain reference changes the calculated carbon intensity by a factor of 1.2–2.0. Applying the inventory data from Smith et al.¹ under the NEOM yield would reduce the mono-Si carbon intensity from 18.1 to approximately 15 g CO₂-eq/kWh. Combining the 2023 Jinko module inventory (reported by Li et al.¹⁵) with the BOS inventory reported by Smith et al.¹ would shift it further toward the lower bound of the NREL utility-scale benchmark range. These results indicate that the choice of supply-chain inventory is the largest source of uncertainty, and the 2018 IEA PVPS dataset

Table 5. Literature benchmarks relevant to the interpretation of life-cycle carbon intensity

Source	Technology / case	Value	Unit	Scope / note
IEA PVPS Fact Sheet ⁴	Mono-Si PV system	42.5	g CO ₂ -eq/kWh	3 kWp European roof-mounted system
IEA PVPS Fact Sheet ⁴	Multi-/Poly-Si PV system	42.3	g CO ₂ -eq/kWh	3 kWp European roof-mounted system
NREL ¹	Utility-scale PV benchmark range	10–36	g CO ₂ -eq/kWh	Utility-scale tracker-based silicon PV
Müller et al. ⁵	China mono-Si glass-backsheet module	810	kg CO ₂ -eq/kWp	Module-level; excl. BOS, install, O&M
Müller et al. ⁵	China mono-Si glass-glass module	750	kg CO ₂ -eq/kWp	Module-level; excl. BOS, install, O&M
Smith et al. ¹	Utility-scale mono-Si Passivated Emitter and Rear Cell (imported wtd-avg)	924	kg CO ₂ -eq/kWp	System-level; excl. EoL; ~2020 supply chain
Li et al. ¹⁵	China mono-Si module, 2023 (supplier range)	310–390	kg CO ₂ -eq/kWp	Module-level only; 2023 Chinese grid

should therefore be regarded as a conservative upper-bound estimate rather than a current best estimate.

Sensitivity to the mono-Si /poly-Si differential. Using the IEA PVPS reference values, the mono-Si and multi-/poly-Si intensities differed by only approximately 0.2 g CO₂-eq/kWh under identical conditions, which is smaller than the resolution of the underlying inventory and should therefore not be interpreted as a meaningful technology-dependent advantage. Other studies have reported larger differences in this aspect. For example, Ullah et al. ¹⁶ reported emissions of 250 and 180 g CO₂-eq/kWh for mono-Si and multi-/poly-Si systems, respectively, under a coal-intensive Nanjing grid, and Müller et al. ⁵ reported module-level embodied emissions of 810 and 750 kg CO₂-eq/kWp for mono-Si and multi-/poly-Si glass-glass configurations, respectively. A small technology gap is observed here because the same IEA PVPS technology-differentiated dataset was applied consistently to both technologies under identical Saudi operating conditions, which separates the technology effect from the differences in grid and module configurations. A dedicated current poly-Si inventory for the present Chinese supply chain is required to quantify this difference more precisely, and the limited availability of such data reflects the rapidly declining market share of poly-Si in the global module supply.

Limitations. Four limitations constrain the precision of the carbon-intensity values reported in Section 3.5, each with a defined directional effect on the results. First, the end-of-life treatment was excluded from the system boundary, which is consistent with the IEA PVPS Task 12 approach. Inclusion of module recycling credits under an avoided-burden convention would be expected to reduce the reported values by approximately 5–8%, on the basis of estimates reported in the PV LCA literature; accordingly, the reported values are marginally conservative. Second, the RETScreen yield model operates on monthly averaged climatic inputs and does not resolve year-to-year irradiance variability, seasonal dust storm events, or soiling-accumulation cycles. Soiling losses in desert environments can exceed 5% of annual electricity yield without regular cleaning. These losses are assumed to be partially represented within the

10% miscellaneous-loss allowance and are not separately quantified, introducing a downward bias on the yield and therefore an upward bias on carbon intensity that cannot be precisely bounded without site-specific soiling records. Third, transport from Chinese manufacturing hubs to Saudi installation sites was excluded from the embodied-emissions estimate; therefore, the reported carbon-intensity values represent lower bounds with respect to logistics emissions, although the transport contribution is expected to remain below approximately 1% of total life-cycle emissions on the basis of PV LCA literature values. Fourth, the two reference module configurations differ in installed capacity (3.30 kWp for poly-Si versus 6.10 kWp for mono-Si) are not technology-comparable. Therefore, all technology-comparative conclusions in this study rest exclusively on the yield-normalized carbon-intensity metric specified in Section 3.5.

Practical implications for technology selection in Saudi Arabia. The near-equivalence of the mono- and poly-Si carbon intensities under the IEA PVPS Task 12 inventory with a difference of approximately 0.2 g CO₂-eq/kWh, which is below the resolution of the underlying inventory data, implies that the choice between monocrystalline and polycrystalline modules cannot be made on the basis of life-cycle carbon intensity alone. The dominant discriminator identified in this study was the installation location. The carbon-intensity difference between NEOM and Riyadh (approximately 6 g CO₂-eq/kWh) was approximately 30 times larger than the difference between the two module technologies at the same site. This finding indicates that site selection, tilt-angle optimization, tracking configuration, and soiling management should be prioritized over module technology selection as a strategy to minimize the life-cycle carbon footprint of the Saudi utility-scale solar portfolio. Other factors not evaluated in this study, including module cost, electricity generation per unit of land area, supply-chain resilience, water requirements for soiling management under desert conditions, and degradation characteristics, will also be relevant inputs for a comprehensive technology selection framework and are recommended as topics for future investigation.

4. CONCLUSIONS

This study investigated the life-cycle carbon intensity of utility-scale crystalline-silicon PV systems in Saudi Arabia by comparing monocrystalline and polycrystalline configurations in NEOM, Jeddah, and Riyadh. This analysis aimed to assess the site-specific performance in terms of the optimized tilt angle, annual electricity yield, annual electricity exported to the grid, gross annual GHG reduction, and final life-cycle carbon intensity under a consistent ISO 14040/44-aligned carbon-intensity assessment methodology. Based on the modeling and IEA PVPS Task 12 consensus LCI, the following key conclusions were drawn.

1. The optimized tilt angle was location-dependent, confirming that the PV system orientation should be optimized for each city rather than assumed to be uniform across Saudi Arabia.
2. The site conditions significantly influenced the PV performance, with NEOM consistently showing the highest annual specific electricity yield, followed by Jeddah, whereas Riyadh recorded the lowest normalized yield. The yield difference between NEOM and Riyadh (~34%) propagated directly into the carbon-intensity results through the lifetime yield denominator.
3. When electricity generation was expressed on an areal basis, the mono-Si system consistently outperformed the poly-Si system at all three locations, reflecting the higher module efficiency of the selected mono-Si configuration.
4. The absolute annual electricity exported to the grid and gross annual GHG emission reduction scaled in direct proportion to the installed-capacity ratio of the two reference configurations ($6.10 / 3.30 = 1.85$) and therefore do not constitute a technology comparison; they are reported only for completeness.
5. The final life-cycle carbon-intensity results showed that NEOM achieved the lowest carbon intensity for both technologies, Jeddah ranked second, and Riyadh recorded the highest values, confirming that a higher lifetime electricity yield directly leads to lower g CO₂-eq/kWh values.
6. The difference between locations (~6 g CO₂-eq/kWh) was substantially more pronounced than the difference between the two module technologies (~0.2 g CO₂-eq/kWh), indicating that site-specific solar-resource conditions and electricity yield exert a stronger influence on final carbon intensity than the small technology-dependent difference in embodied emissions under the IEA PVPS Task 12 consensus inventory.
7. The resulting carbon-intensity values (approximately 18.0–24.3 g CO₂-eq/kWh, depending on location) are conservative estimates reflecting the 2018 IEA PVPS supply-chain vintage rather than current best estimates; they fall within the NREL utility-scale benchmark range (10–36 g CO₂-eq/kWh) and support the suitability of high-yield Saudi locations, particularly NEOM, for low-carbon utility-scale PV deployment.

These findings confirm that utility-scale PV assessments in Saudi Arabia should account for the combined effects of site selection, tilt optimization, electricity yield, and embodied emissions, rather than considering module technology in isolation. The near-equivalence of mono- and poly-Si carbon intensities under the adopted inventory implies that technology selection in the Saudi context should be guided primarily by cost, efficiency per

unit area, supply-chain factors, and soiling management, rather than by life-cycle GHG performance alone.

This study has several limitations. The embodied-emissions numerator was drawn from the IEA PVPS Task 12 consensus inventory (Report T12-19:2020)¹⁴, which reflects a 2018 supply-chain vintage and should be regarded as a conservative upper-bound basis relative to current Chinese manufacturing. The effect of more recent supply-chain data is examined as a sensitivity analysis in Section 3.6. Moreover, the transport assessment was treated as a representative scenario-based sensitivity analysis, end-of-life management was excluded from the adopted system boundary, and the yield model did not resolve year-to-year variability or soiling dynamics at the site level. Therefore, future work may include the development of more case-specific inventory data for Chinese-manufactured mono- and poly-Si modules, refinement of transport and supply-chain assumptions, inclusion of end-of-life and recycling pathways, dedicated soiling characterization for Saudi desert sites, and broader validation through plant-scale operational data and scenario-based sensitivity analyses.

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REFERENCES

- (1) Smith, B., Sekar, A., Mirlet, H., Heath, G. & Margolis, R. An Updated Life Cycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States. NREL/TP-7A40-87372, National Renewable Energy Laboratory, Golden, CO (2024). <https://www.nrel.gov/docs/fy24osti/87372.pdf>
- (2) Peng, J., Lu, L. & Yang, H. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renew. Sustain. Energy Rev.* 19, 255–274 (2013).

- (3) Fthenakis, V. M. & Kim, H. C. Photovoltaics: Life-cycle analyses. *Sol. Energy* 85, 1609–1628 (2011).
- (4) Frischknecht, R. & Krebs, L. Environmental Life Cycle Assessment of Electricity from PV Systems. IEA PVPS Task 12 Fact Sheet (2021). <https://iea-pvps.org/fact-sheets/factsheet-environmental-life-cycle-assessment-of-electricity-from-pv-systems/>
- (5) Müller, A., Friedrich, L., Reichel, C., Herceg, S., Mittag, M. & Neuhaus, D. H. A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory. *Sol. Energy Mater. Sol. Cells* 230, 111277 (2021). <https://doi.org/10.1016/j.solmat.2021.111277>
- (6) Frischknecht, R. Environmental Life Cycle Assessment of Electricity from PV Systems – 2021 Data Update. IEA PVPS Task 12 (2022).
- (7) Ali, A. et al. Techno-economic study on grid-connected PV system for major cities in Saudi Arabia. *E3S Web Conf.* 173, 02005 (2020).
- (8) ISO 14040:2006 – Environmental management — Life cycle assessment — Principles and framework. <https://www.iso.org/standard/37456.html>
- (9) ISO 14044:2006 – Environmental management — Life cycle assessment — Requirements and guidelines. <https://www.iso.org/standard/38498.html>
- (10) RETScreen – Natural Resources Canada. <https://natural-resources.canada.ca/maps-tools-publications/tools-applications/retscreen>
- (11) CO₂ Calculator: Carbon Emissions Calculator for Freight Shipping – SeaRates. <https://www.searates.com/carbon-emissions-calculator/>
- (12) Jinko Solar. Company profile / manufacturing locations. <https://www.jinkosolar.com/> (accessed May 2025).
- (13) Frischknecht, R., Stolz, P., Heath, G., Rauei, M., Sinha, P. & de Wild-Scholten, M. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 4th ed. IEA PVPS Task 12, Report T12-18:2020. International Energy Agency, Paris (2020).
- (14) Frischknecht, R., Stolz, P., Krebs, L., de Wild-Scholten, M., Sinha, P., Fthenakis, V., Kim, H. C., Rauei, M. & Stucki, M. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems. IEA PVPS Task 12, Report T12-19:2020. International Energy Agency, Paris (2020). <https://www.osti.gov/biblio/2308831>
- (15) Li, Z., Wang, X., Hu, K., Peng, L., Xie, K. & Li, J. Low-carbon transition of China's monocrystalline module and its global contributions. *iScience* 28, 113079 (2025). <https://doi.org/10.1016/j.isci.2025.113079>
- (16) Ullah, F., Hasrat, K., Abdelfattah, W. et al. Comprehensive life cycle analysis of monocrystalline and polycrystalline solar PV panels in Nanjing, China: Effects on the environment, performance, and recycling opportunities. *Chem. Eng. J.* 522, 167775 (2025). <https://doi.org/10.1016/j.cej.2025.167775>