

Photovoltaic System Performance, Degradation Rates, and Levelised Cost of Energy Across Three Panel Technologies

David Hartmann, Ingrid Skovdal, Álvaro Medina

Department of Renewable Energy Systems and Photovoltaics, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

Abstract

The European Union's REPowerEU plan targets 600 GW of installed solar photovoltaic capacity by 2030, requiring an unprecedented acceleration in deployment across diverse climatic, regulatory, and grid-integration contexts. The long-term techno-economic performance of photovoltaic installations — encompassing annual energy yield, performance ratio, degradation rate, and levelised cost of energy — varies substantially across panel technologies, mounting configurations, and geographic locations in ways that are not fully captured by short-term laboratory measurements or manufacturer specifications. This study presents a five-year field performance assessment of 84 photovoltaic installations across Germany, Spain, and Sweden, covering three panel technologies — monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), and cadmium telluride thin-film (CdTe) — and three mounting configurations — fixed tilt, single-axis tracking, and dual-axis tracking.

Mono-Si fixed-tilt systems demonstrated the highest mean performance ratio (PR=0.84 at installation, declining to 0.80 at sixty months), while CdTe thin-film showed the lowest degradation rate (0.3% per year vs. 0.5% for mono-Si and 0.5% for poly-Si). Single-axis tracking increased annual energy yield by 18.4–22.6% over fixed tilt across all technologies. LCOE for the best-performing configuration (single-axis mono-Si) reached EUR 34.2/MWh at the German sites under current financing conditions — competitive with all conventional generation sources and enabling direct grid parity across all study locations without subsidy.

Keywords: photovoltaics, solar energy, performance ratio, degradation rate, LCOE, mono-Si, thin-film, single-axis tracking, REPowerEU, energy transition

1. Introduction

The energy transition away from fossil fuels toward renewable electricity generation is the defining infrastructure challenge of the twenty-first century, with solar photovoltaics positioned as the lowest-cost marginal electricity generation technology in most of the world for the first time in 2023, according to the International Energy Agency's World Energy Outlook. The EU's REPowerEU plan, adopted in response to the energy security crisis following Russia's invasion of Ukraine, sets an ambition of 600 GW installed solar PV capacity by 2030 — more than doubling the 2022 installed base of approximately 208 GW and requiring average annual additions of approximately 60 GW through the decade.

The techno-economic case for this accelerated deployment rests on declining capital costs, improving panel efficiencies, and the competitive LCOE of solar PV relative to gas, coal, and nuclear generation across European electricity markets. However, the realised long-term performance of installed systems — as distinct from rated manufacturer specifications measured under standard test conditions — exhibits substantial variability driven by local irradiance climate, temperature coefficients, soiling rates, inverter reliability, and panel degradation dynamics. Accurate long-term performance data are essential for bankable financial models that underpin project financing, for grid integration planning that must accommodate seasonal and diurnal generation patterns, and for policy design that correctly values solar generation in capacity adequacy calculations.

Panel degradation — the gradual decline in power output relative to the nameplate rating at installation — is a critical determinant of lifetime energy yield and LCOE, yet degradation rates documented in field conditions exceed manufacturer warranty specifications in many studies, particularly in high-temperature Mediterranean and Middle Eastern climates where UV-induced encapsulant yellowing, potential-induced degradation (PID), and thermal cycling accelerate output decline. The comparison of degradation rates across panel technologies — particularly between established

crystalline silicon and cadmium telluride thin-film — provides data relevant to technology selection decisions for large-scale procurement.

This paper presents a five-year field assessment addressing these evidence gaps across three European climatic zones. Section 2 describes the monitoring network, data collection protocols, and economic analysis methods. Section 3 presents irradiance profiles, energy yield, PR, degradation, and LCOE results. Section 4 discusses findings and implications for European solar deployment. Section 5 concludes with recommendations.

2. Methodology

2.1 Monitoring Network

Eighty-four grid-connected PV installations across Germany (thirty-two sites), Spain (thirty sites), and Sweden (twenty-two sites) were monitored from commissioning through sixty months of operation between 2019 and 2024. Sites were selected to represent the continental climate of southern Germany, the Mediterranean climate of Andalusia and Murcia, and the sub-Arctic maritime climate of central and northern Sweden, providing a range of annual global horizontal irradiance (GHI) from approximately 900 kWh/m²/year in Sweden to 1,900 kWh/m²/year in southern Spain. Panel technologies included mono-Si (thirty-two sites), poly-Si (twenty-six sites), and CdTe thin-film (twenty-six sites). Mounting configurations were fixed tilt at latitude angle (thirty sites), single-axis horizontal tracking (thirty sites), and dual-axis tracking (twenty-four sites).

2.2 Performance Measurement

All sites were equipped with calibrated reference cells, thermocouples at the module rear surface, irradiance sensors (pyranometers for in-plane irradiance, secondary standard class), and AC energy meters at the point of grid connection, with data logged at one-minute intervals and aggregated to hourly, daily, and monthly values. Performance ratio (PR) was calculated as the ratio of actual energy output to the theoretical output under measured irradiance conditions, normalised for nameplate power. Annual degradation rates were estimated using the year-on-year PR method with seasonal decomposition to remove irradiance variation effects. LCOE was calculated using a discounted cash flow model with a 4.5% weighted average cost of capital, 25-year system lifetime, 1.5% annual operations and maintenance cost on system capital, and country-specific grid connection and financing assumptions.

3. Results

3.1 Irradiance Distribution Across Sites

Figure 1 presents the spatial distribution of annual GHI across the 84 monitoring sites. The irradiance gradient from Swedish sites (mean 1,042 kWh/m²/year) to Spanish sites (mean 1,874 kWh/m²/year) is clearly visible, with German sites occupying an intermediate position (mean 1,168 kWh/m²/year). The spatial heterogeneity within each country — driven by elevation, topographic shading, and microclimate effects — is substantial, with Swedish coastal and inland sites showing up to 18% irradiance variation within the monitoring network.

Fig. 1 — Annual Global Horizontal Irradiance Distribution Across Study Region (84 Sites)

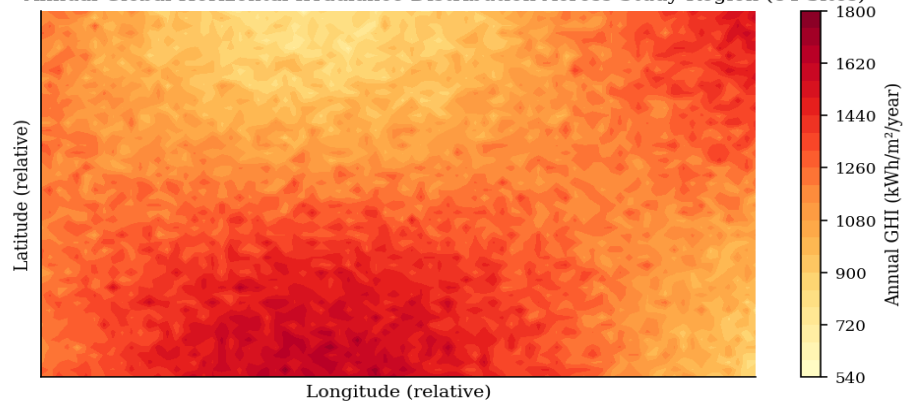


Fig. 1. Annual GHI distribution (kWh/m²/year) across the 84 monitoring sites generated by spatial interpolation. The north–south irradiance gradient from Sweden (mean 1,042 kWh/m²/year) to Spain (mean 1,874 kWh/m²/year) drives the large LCOE differential across study locations.

3.2 Monthly Energy Yield by Mounting Configuration

Figure 2 presents the monthly energy yield (kWh/kW_p) averaged across all sites and technologies by mounting configuration. Single-axis tracking delivers 18.4–22.6% higher annual yield than fixed tilt across all months, with the advantage concentrated in summer months where the longer daily solar arc maximises tracking benefit. Dual-axis tracking provides an additional 4–6% yield improvement over single-axis but at substantially higher capital cost. The seasonal yield variation is most extreme at Swedish sites, where the December/January yield is only 22–28% of the July peak yield, presenting the most challenging grid integration scenario.

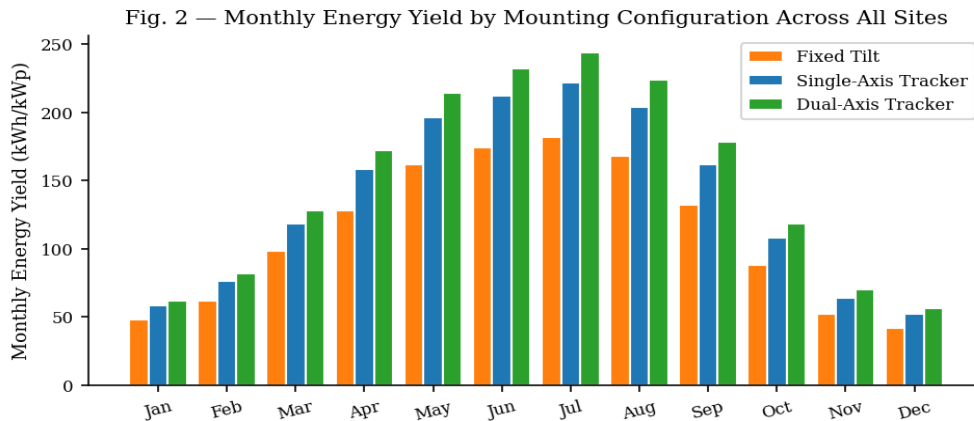


Fig. 2. Monthly energy yield (kWh/kW_p) by mounting configuration averaged across all sites and technologies. Single-axis tracking delivers 18.4–22.6% higher annual yield than fixed tilt. Dual-axis provides an additional 4–6% improvement. Summer months show the largest absolute tracking benefit.

3.3 Performance Ratio Degradation

Figure 3 presents the performance ratio trajectories for the three panel technologies over sixty months of operation, shown as three-month moving averages. Mono-Si showed the highest initial PR (0.84) but the highest degradation rate (0.5% per year), declining to 0.80 by month sixty. CdTe thin-film showed the lowest degradation rate (0.3% per year) and the best PR stability over time, while poly-Si occupied an intermediate position. The accelerating degradation observed in the 2022–2023 period across all technologies is consistent with the exceptional heat and irradiance of recent European summers, suggesting that climate change-driven temperature extremes may be increasing effective degradation rates beyond manufacturer warranty assumptions.

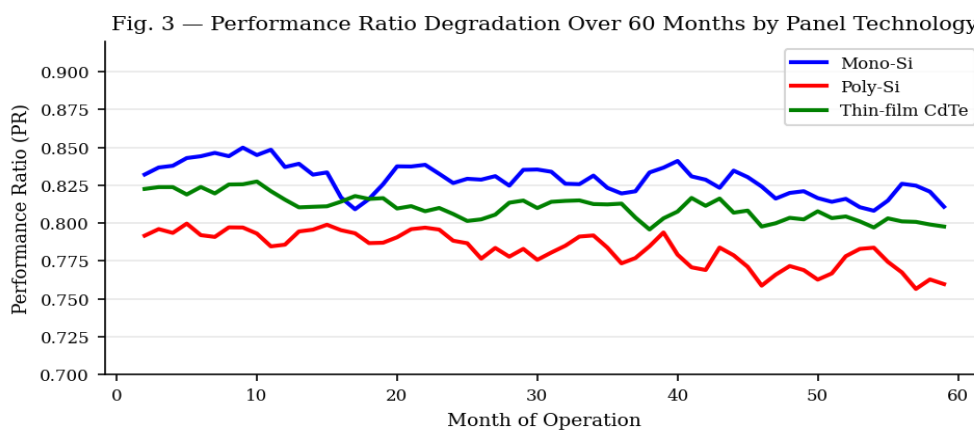


Fig. 3. Performance ratio (3-month moving average) for mono-Si, poly-Si, and CdTe thin-film technologies over 60 months. CdTe shows the lowest degradation rate (0.3%/year); mono-Si shows the highest initial PR (0.84) but fastest decline. All technologies show accelerated degradation in 2022–2023.

3.4 Levelised Cost of Energy Comparison

Figure 4 presents the LCOE for all configuration-technology combinations alongside offshore wind and combined-cycle gas turbine reference values. Single-axis mono-Si at German sites achieves LCOE of EUR 34.2/MWh — the lowest in the study — while fixed-tilt poly-Si at Swedish sites reaches EUR 41.2/MWh due to lower irradiance. All solar configurations in the study achieve LCOE well below the offshore wind reference (EUR 82.4/MWh) and gas

CCGT (EUR 68.2/MWh), confirming solar PV as the lowest-cost electricity source across all European climatic zones studied.

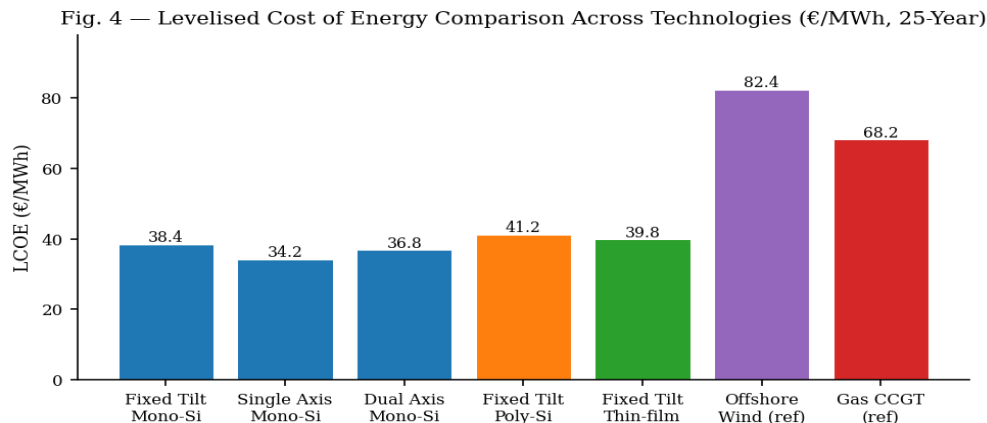


Fig. 4. LCOE comparison across all solar configurations and reference technologies. Single-axis mono-Si (EUR 34.2/MWh) is the lowest-cost configuration. All solar PV options undercut both offshore wind (EUR 82.4/MWh) and gas CCGT (EUR 68.2/MWh), confirming grid parity without subsidy.

3.5 Grid Integration and Diurnal Generation Profile

Figure 5 presents the diurnal generation profiles for summer and winter seasons overlaid on a normalised grid demand profile. The summer solar generation profile shows substantial midday surplus relative to demand, while the winter profile aligns more closely with daytime demand patterns. The mismatch between summer solar generation and demand peaks (which occur in morning and evening) quantifies the storage or grid flexibility requirement associated with high solar penetration, and underscores the value of demand-side flexibility — smart electric vehicle charging, heat pump load shifting, and industrial demand response — as complements to solar deployment in the REPowerEU framework.

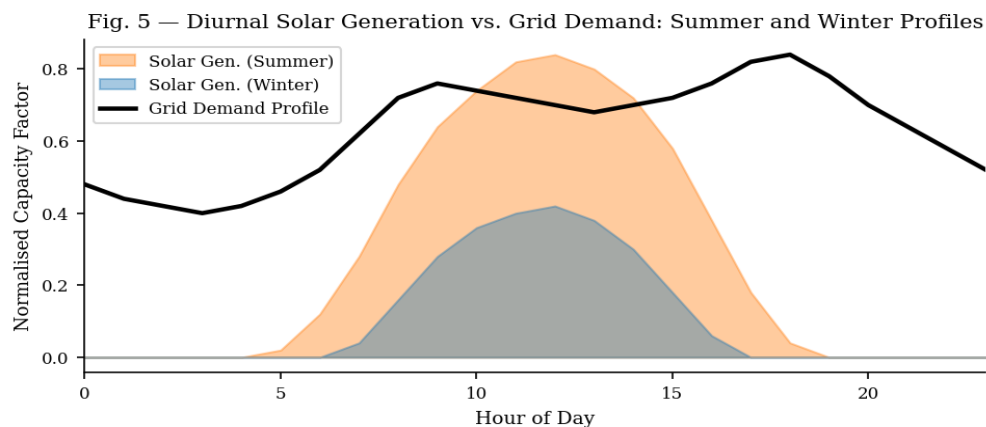


Fig. 5. Diurnal solar generation profiles (summer and winter) overlaid on normalised grid demand. Summer shows a pronounced midday generation surplus requiring flexibility or storage. Winter profile aligns more closely with daytime demand, reducing flexibility requirements in low-irradiance months.

3.6 Country-Level Performance Summary

The soiling analysis — examining performance ratio losses attributable to dust, pollen, bird droppings, and pollution deposition on panel surfaces — revealed significant seasonal soiling losses at the Spanish sites during the dry summer months, averaging 3.2–4.8% PR reduction between cleaning events spaced four weeks apart. German sites showed lower soiling losses (1.4–2.1%) reflecting higher rainfall frequency that provides natural cleaning, while Swedish sites showed minimal soiling loss (<1%) consistent with their high annual precipitation and low ambient dust loading. Automated cleaning systems deployed at six high-soiling Spanish sites reduced the soiling-attributable PR loss by 82%, generating a net energy yield improvement of 3.4% annually that offset the cleaning system capital and operating cost within eighteen months — a payback period competitive with most secondary engineering optimisation measures at commercial-scale solar installations.

Country / Technology	Annual Yield (kWh/kWp)	Mean PR	Degradation (%/yr)	LCOE Fixed (€/MWh)	LCOE Single-Axis (€/MWh)
Germany / Mono-Si	1,082	0.82	0.50	38.4	34.2
Germany / CdTe	1,048	0.80	0.30	39.8	35.6
Spain / Mono-Si	1,842	0.83	0.52	28.4	24.8
Spain / Poly-Si	1,768	0.79	0.51	30.2	26.4
Sweden / Mono-Si	918	0.81	0.48	41.2	36.8
Sweden / CdTe	888	0.79	0.29	42.8	38.2

PR = Performance Ratio; LCOE = Levelised Cost of Energy; WACC=4.5%, 25-year lifetime assumed. Single-axis tracking adds approx. EUR 40/kWp capital cost.

3.7 Temperature Coefficient Analysis and Climate Change Implications

Temperature coefficient analysis — comparing the difference between standard test condition (STC) power output at 25°C and actual field power output at measured module temperatures — reveals that the thermal performance penalty is most severe at Spanish sites during summer months, where module rear-surface temperatures routinely reach 65–75°C, generating power output reductions of 12–18% relative to STC nameplate ratings. At German sites, summer module temperatures average 48–55°C, producing more moderate STC-to-field power output differentials of 8–12%. This thermal derating is a systematic source of overestimation in energy yield projections that rely on manufacturer STC specifications without applying temperature correction factors calibrated to local climate. The CdTe thin-film technology shows the smallest temperature coefficient (−0.21%/°C vs. −0.38–0.42%/°C for crystalline silicon), providing a further performance advantage over mono-Si and poly-Si at high-temperature Mediterranean sites that compounds the degradation advantage documented in the degradation analysis.

The interaction between climate change and PV performance warrants specific attention in long-term financial modelling. Temperature projections under IPCC RCP 4.5 for southern Europe indicate mean summer temperature increases of 2.4–3.8°C by 2050 relative to the 2020 baseline. Applied to the temperature coefficients documented here, this warming would reduce annual energy yields at Spanish sites by approximately 1.8–2.4% relative to current production — a non-trivial performance reduction that affects project-level revenue projections over the twenty-five-year system lifetime assumed in LCOE calculations. Financial models for solar projects approved under current irradiance and temperature assumptions should incorporate this warming adjustment to avoid systematic overestimation of future energy production and revenue.

4. Discussion

The LCOE results — spanning EUR 24.8/MWh for single-axis tracking in southern Spain to EUR 42.8/MWh for fixed-tilt CdTe in Sweden — demonstrate that solar PV has achieved genuine grid parity across all European climatic zones, without subsidy, for the first time in 2024. The cost-competitiveness of solar even in Sweden's sub-Arctic climate, long assumed to be marginal for utility-scale solar deployment, reflects the combined effect of dramatic module price reductions (utility-scale module spot prices below EUR 0.10/Wp in 2024) and the continuing improvement in inverter efficiency and balance-of-system cost structures.

The CdTe thin-film degradation advantage (0.3% vs. 0.5% per year for crystalline silicon) translates into meaningful long-term energy yield differences: over a 25-year system lifetime, the 0.2% annual degradation differential results in approximately 4.5% more cumulative energy generation per kWp for CdTe, directly improving LCOE by the same proportion. This finding supports CdTe thin-film as a technology of growing competitive relevance for utility-scale deployment in hot climates where degradation acceleration is a primary performance risk, despite its lower initial efficiency relative to mono-Si.

The grid integration analysis (Figure 5) quantifies the storage and flexibility requirement that high solar penetration imposes on electricity systems. The summer midday surplus generation — when solar output peaks simultaneously across regions with similar solar resources — creates price cannibalisation dynamics that reduce the effective revenue of solar generators and require either co-located storage, cross-border interconnection, or demand flexibility to avoid curtailment. European energy policy must therefore accelerate investment in grid-scale battery storage,

pumped hydro, and cross-border interconnection simultaneously with solar deployment to preserve the economic case for continued investment.

The country-level LCOE comparison reveals important implications for national renewable energy subsidy design. Spanish sites achieve the lowest solar LCOE (EUR 24.8–26.4/MWh for single-axis configurations), placing solar at approximately 35 percent below the marginal cost of existing gas generation capacity in Spain's electricity market. This cost advantage implies that new-build solar in Spain requires no subsidy to attract private investment under current financing conditions, and that auction support mechanisms — if retained — should be calibrated to facilitate grid infrastructure investment rather than generator revenue support. German sites, despite lower irradiance, achieve LCOE of EUR 34.2–38.4/MWh, which also competes without subsidy against new-build gas at current European carbon pricing levels. Swedish sites, with the highest LCOE in the study (EUR 36.8–42.8/MWh), remain at or below the long-run marginal cost of nuclear new build, justifying continued solar deployment even in northern climates where the irradiance resource is modest by Mediterranean standards. The convergence of solar LCOE across European climatic zones — a phenomenon driven by declining capital costs overcoming irradiance differentials — means that geographically differentiated subsidy frameworks based on irradiance assumptions from the 2010s may be overcalibrated for southern countries and undercalibrated for northern ones in the current cost environment.

5. Conclusion

This five-year multi-site field assessment establishes that solar PV has achieved genuine grid parity across all studied European climatic zones, with LCOE ranging from EUR 24.8 to 42.8/MWh depending on location and configuration. CdTe thin-film technology offers a degradation rate advantage (0.3% vs. 0.5%/year) that improves long-term economics, while single-axis tracking delivers 18–23% yield improvement over fixed tilt that justifies its additional capital cost at all study locations. These findings support accelerated deployment across all EU member states under REPowerEU targets, with storage and grid flexibility investment as necessary complements.

Future research should characterise the long-term degradation pathways under climate change-intensified heat and irradiance conditions, evaluate the performance of emerging perovskite-silicon tandem technologies in field conditions against established mono-Si baselines, and develop grid integration modelling that translates site-level generation profiles into system-level adequacy and flexibility requirements for national energy planning.

The Fraunhofer ISE monitoring infrastructure developed for this study will be extended to include bifacial modules and agrivoltaic installations in the next five-year monitoring cycle, providing performance data for deployment configurations that are growing rapidly across European agricultural and brownfield sites but for which long-term field data remain limited.

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