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RENEWABLE POWER GENERATION COSTS IN 2024

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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EXECUTIVE SUMMARY

HIGHLIGHTS

- On a levelised cost of electricity (LCOE) basis, renewables remained the most cost-competitive option for new electricity generation in 2024, with 91% of newly commissioned utility-scale capacity delivering power at a lower cost than the cheapest, newly installed fossil fuel-based alternative.
- In 2024, new utility-scale onshore wind projects remained the cheapest source of renewable electricity, with a global weighted average LCOE of USD 0.034/per kilowatt hour (kWh),[1] followed by new solar photovoltaic (PV) (USD 0.043/kWh) and new hydropower (USD 0.057/kWh).
- Between 2010 and 2024, total installed costs (TIC) declined sharply across major renewable technologies. By 2024, TIC fell to USD 691/kW for solar PV, USD 1 041/kW for onshore wind, and USD 2 852/kW for offshore wind.
- LCOE increased slightly for some technologies over 2023: solar PV by 0.6%, onshore wind by 3%, offshore wind by 4%, and bioenergy by 13%. Meanwhile, costs declined for CSP (-46%), geothermal (-16%), and hydropower (-2%).
- Battery storage costs declined by 93% from 2010 to 2024, falling from USD 2 571/kWh to USD 192/kWh.
- For onshore wind, China (USD 0.029/kWh) and Brazil (USD 0.030/kWh) recorded LCOEs below the global average, reflecting the maturity of these top markets. For solar PV, China and India reported below-average LCOEs, at USD 0.033/kWh and USD 0.038/kWh, respectively. For offshore wind, Asia's average (USD 0.078/kWh) was slightly below Europe's (USD 0.080/kWh).
- Over the next five years, global total installed costs are expected to reach approximately USD 388/kW for solar PV, USD 861/kW for onshore wind, and USD 2 316/kW for offshore wind.
- While long-term cost reductions are expected from continued technological learning and supply chain maturity, emerging geopolitical risks – notably trade tariffs on renewable components and materials and Chinese manufacturing sector dynamics – could raise costs in the short term.
- Financing costs remain a key determinant of renewable project viability, with capital costs shaped by factors such as revenue certainty, capital structure and macroeconomic conditions.
- Integrating more variable renewables into the grid may lead to higher short-term costs; but a growing number of projects are combining solar, wind, storage, and digitalisation - enhancing economic performance and facilitating integration.
- In 2024, renewables helped avoid USD 467 billion in fossil fuel costs, reinforcing their role not only as the lowest-cost source of new power but also as a key driver of energy security, economic stability, and resilience in a volatile global energy landscape.

[1] *All total installed cost (TIC) and levelised cost of electricity (LCOE) values presented in this report are expressed in 2024 USD.*

[2] *Excluding African Union (AU) countries.*

Table S1 Total installed cost, capacity factor and LCOE trends by technology, 2010 and 2024

	Total installed costs (2024 USD/kW)			Capacity factor (%)			Levelised cost of electricity (2024 USD/kWh)		
	2010	2024	Percent change	2010	2024	Percent change	2010	2024	Percent change
Bioenergy	3 082	3 242	5%	72	73	1%	0.086	0.087	1%
Geothermal	3 083	4 015	30%	87	88	1%	0.055	0.060	9%
Hydropower	1 494	2 267	52%	44	48	9%	0.044	0.057	30%
Solar PV	5 283	691	-87%	15	17	13%	0.417	0.043	-90%
CSP	10 703	3 677	-66%	30	41	37%	0.402	0.092	-77%
Onshore wind	2 324	1 041	-55%	27	34	26%	0.113	0.034	-70%
Offshore wind	5 518	2 852	-48%	38	42	11%	0.208	0.079	-62%

Notes: CSP = concentrated solar power; kW = kilowatt; kWh = kilowatt hour; USD= United States dollars.

ANNUAL RENEWABLE POWER CAPACITY ADDITIONS SET A NEW RECORD IN 2024, WITH TOTAL INSTALLED CAPACITY INCREASING 15% YEAR-ON-YEAR[3]

In 2024, global renewable power capacity[4] additions reached an unprecedented 582 gigawatts (GW), representing a 19.8% increase compared to the capacity additions delivered in 2023 and marking the highest annual expansion since records began in 2000. Solar photovoltaics (PV) led this surge, accounting for 452.1 GW (77.8%) of the total, followed by wind, with 114.3 GW. These additions brought the total global installed renewable capacity to 4 443 GW by the end of the year.

Capacity additions for other technologies - concentrated solar power (CSP), geothermal, bioenergy and hydropower - remained modest in 2024, collectively adding approximately 15.4 GW, up from 13.7 GW in 2023. Hydropower alone accounted for 9.3 GW. Additions for CSP and geothermal continued to stagnate, while bioenergy saw a slight increase compared to 2023.

In 2024, Asia added 413.2 GW of renewable capacity – a 24.9% increase that brought the region's total to 2 374 GW. China alone accounted for 61.2% of global PV additions (276.8 GW) and 69.4% of new wind installations (79.4 GW). Other notable contributors included the United States, India, Brazil and Germany, all of which added substantial volumes of new renewable capacity, highlighting the continued global diversification of renewable investment.

The growth in renewable power capacity additions reflects the accelerating global momentum to increase the share of renewables in electricity generation. However, current deployment levels fall short of that required to triple renewable energy capacity by 2030 – the goal set out in the First Global Stocktake, known as the "UAE Consensus", at COP28. Although installed capacity reached 4 443 GW in 2024, achieving the 11 000+ GW target by 2030 requires annual additions well over 1 000 GW in the latter half of the decade. Meeting this goal will require not only a rapid scale-up in deployment but also substantial investment in enabling infrastructure – particularly grid expansion and energy storage.

[3] *This section reflects the latest capacity data presented in: (IRENA, 2025d).*

[4] *In this report, "renewable power capacity" is expressed in AC and refers to the net generating capacity of power plants and other installations utilising renewable energy sources to produce electricity, commissioned within the respective year.*

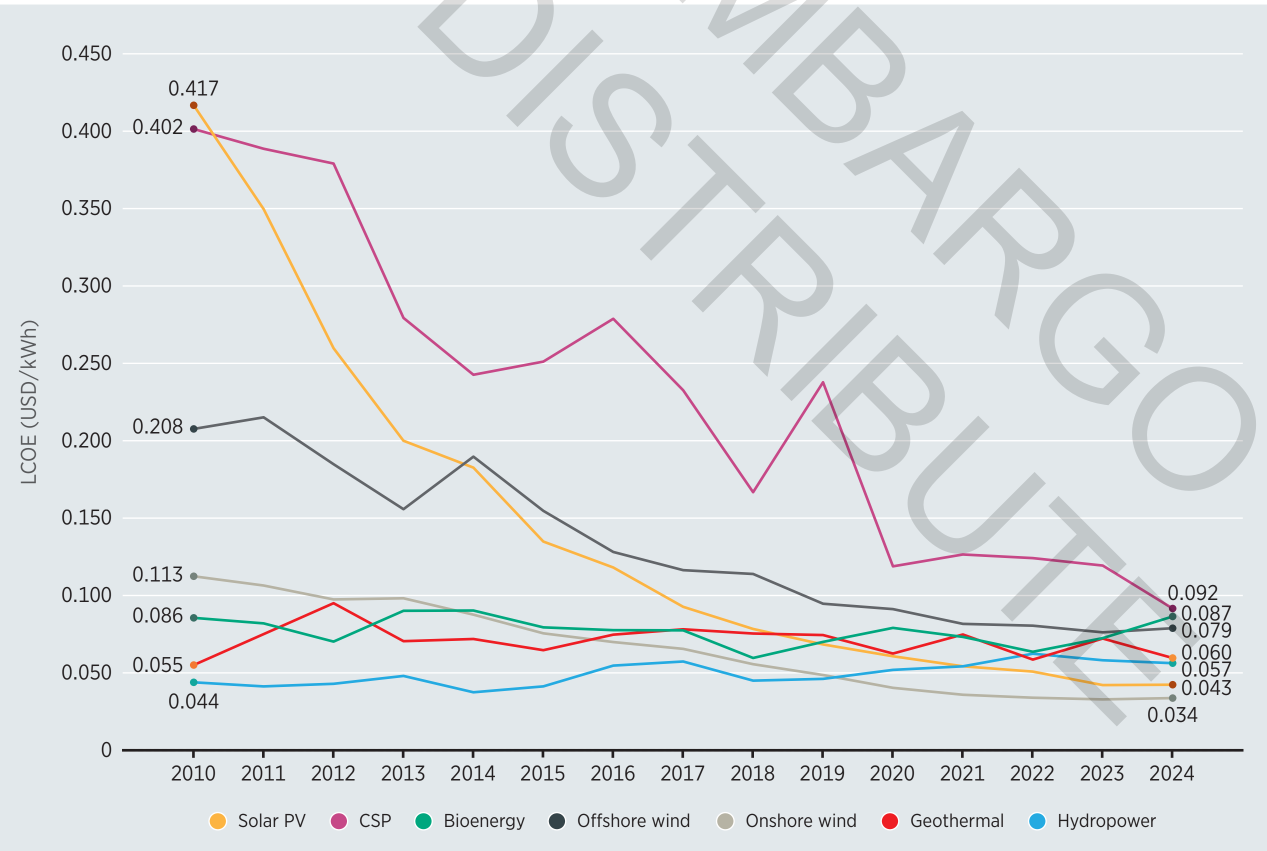
Data from IRENA's renewable cost database, paired with an analysis of recent power sector trends, nevertheless reaffirm renewables' central role in achieving climate objectives while underscoring their growing cost-competitiveness relative to all fossil fuel alternatives.

The rapid deployment of renewables is beginning to reshape the electricity mix in key economies. In the European Union, solar generation surpassed coal for the first time in 2024, while clean sources overall accounted for more than two-thirds of total generation. In the United States, solar and wind generation combined grew at an average compound rate of 12.3% per year in 2018-2023, while coal and peat generation declined by an average of 10.2% each year, compounded over the same period. These trends point to a structural decoupling from fossil fuel-based power generation, enabled by supportive policies, falling technology costs and rising electrification.

LCOE FROM RENEWABLES: A RISING COST ADVANTAGE

Renewable energy technologies have experienced spectacular cost declines since 2010, driven by technology improvement, competitive supply chains and economies of scale (Figure S1). Notably, 91% of new renewable power projects commissioned in 2024 were more cost-effective than any fossil fuel-fired alternative.

Figure S1 Renewable energy LCOE decline, 2010-2024

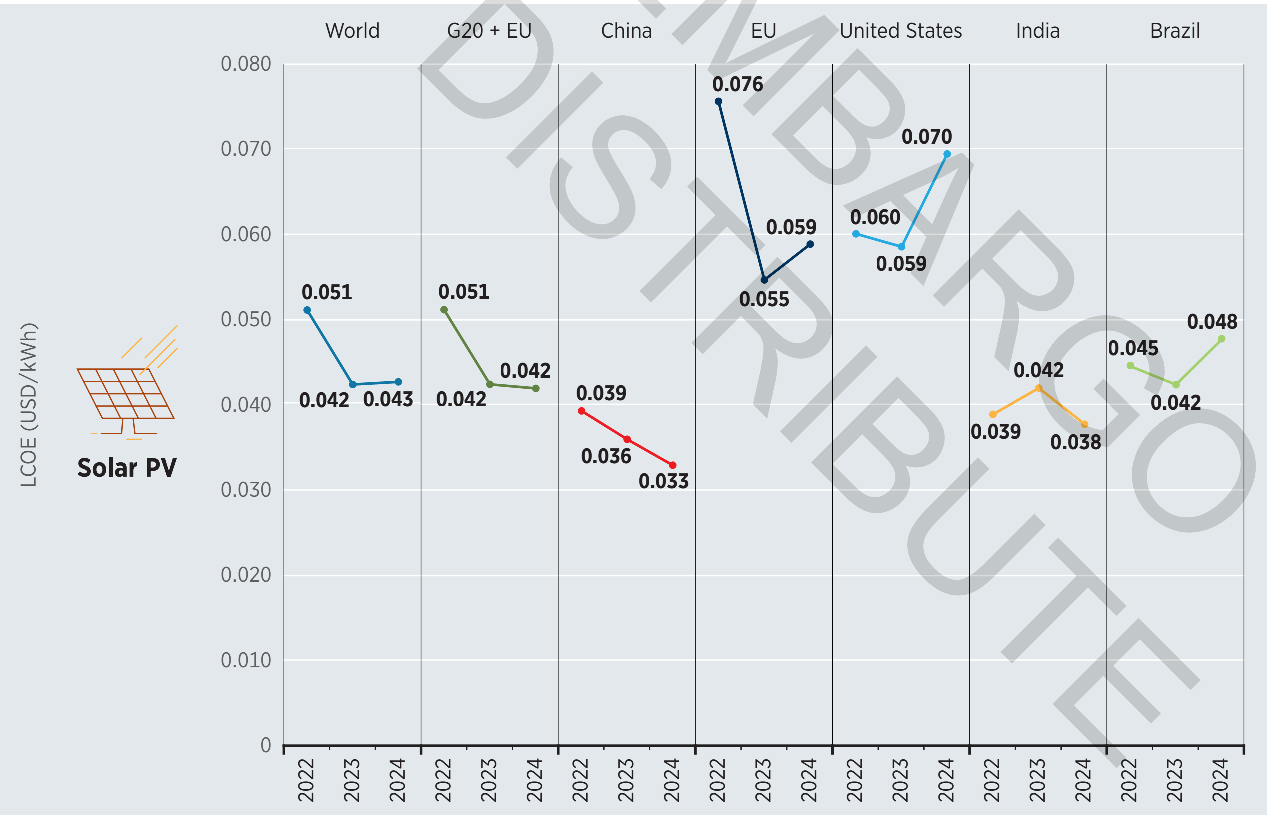


Notes: CSP = concentrated solar power; kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; USD = United States dollar.

Solar PV LCOE has dropped further in China and stabilised on a global level

By 2024, the global weighted average LCOE for utility-scale solar PV stabilised at USD 0.043/kWh, making it 41% cheaper than the least-cost fossil fuel-fired alternative (Figure S2).[5] In China, where vertically integrated supply chains and abundant domestic manufacturing capacity continue to exert downward pressure on costs, LCOE fell to USD 0.033/kWh. India also reported competitive values at around USD 0.038/kWh. In contrast, PV LCOE increased in the United States and the European Union, where permitting delays, interconnection bottlenecks and higher balance-of-system costs limited further cost reductions.

Figure S2 Solar PV weighted average LCOE: Global, G20, EU and selected countries, 2022–2024



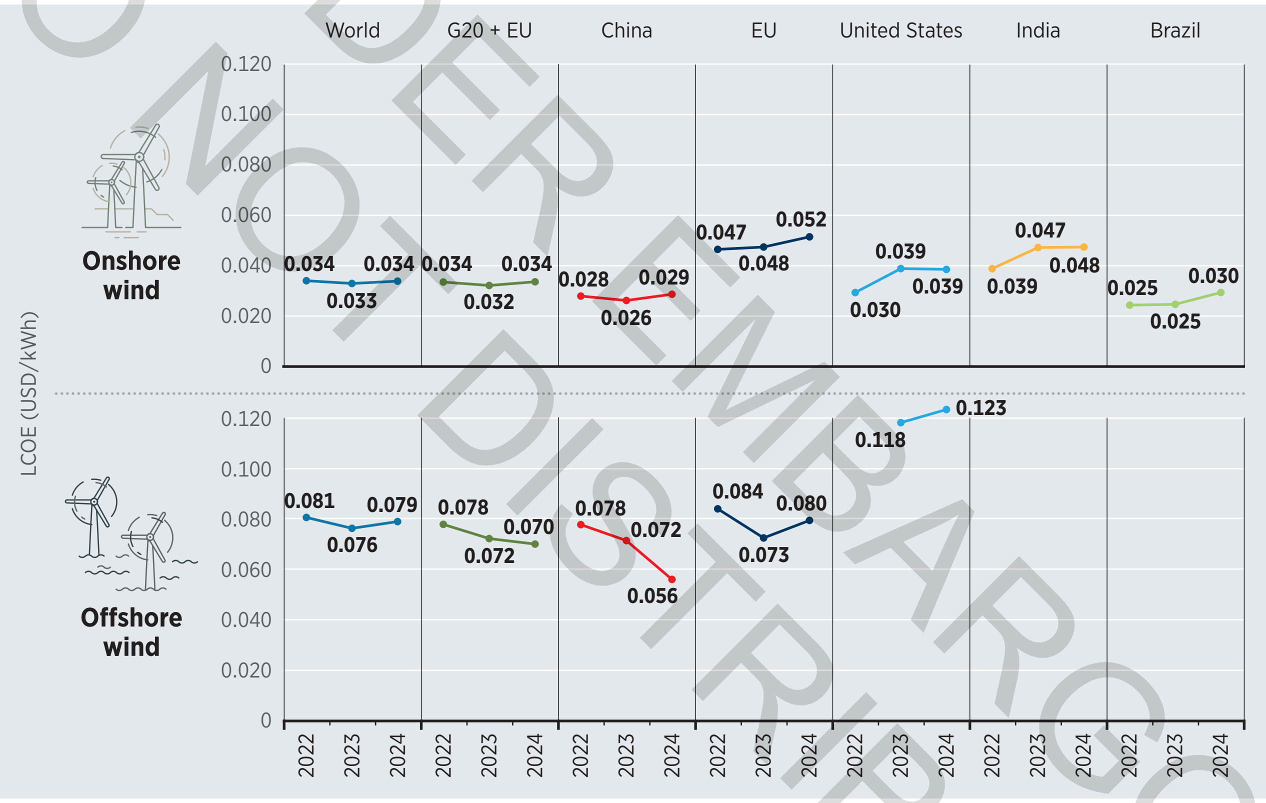
Notes: EU = European Union; G20 = Group of 20; kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; USD = United States dollar.

[5] The global average LCOE of coal power was USD 0.073/kWh, and for CCGT was USD 0.085/kWh.

Wind has become cheaper than fossil fuels in all major markets

Onshore wind continued reinforcing its cost advantage (Figure S3), with a global average LCOE of USD 0.034/kWh in 2024 – 53% lower than fossil fuel-based generation. China (USD 0.029/kWh) and Brazil (USD 0.030/kWh) recorded the lowest costs, benefitting from strong resource availability, domestic manufacturing and streamlined project execution. Offshore wind costs slightly increased from their 2023 levels (Figure S3), driven by a greater presence of projects in emerging markets with higher costs. Offshore wind global weighted average LCOE reached USD 0.079/kWh. In China, the LCOE fell to USD 0.056/kWh, significantly below levels in the EU and North America, where offshore wind remained substantially more expensive, exceeding USD 0.123/kWh in the United States.

Figure S3 Wind power weighted average LCOE: Global, G20, EU and selected countries, 2022–2024

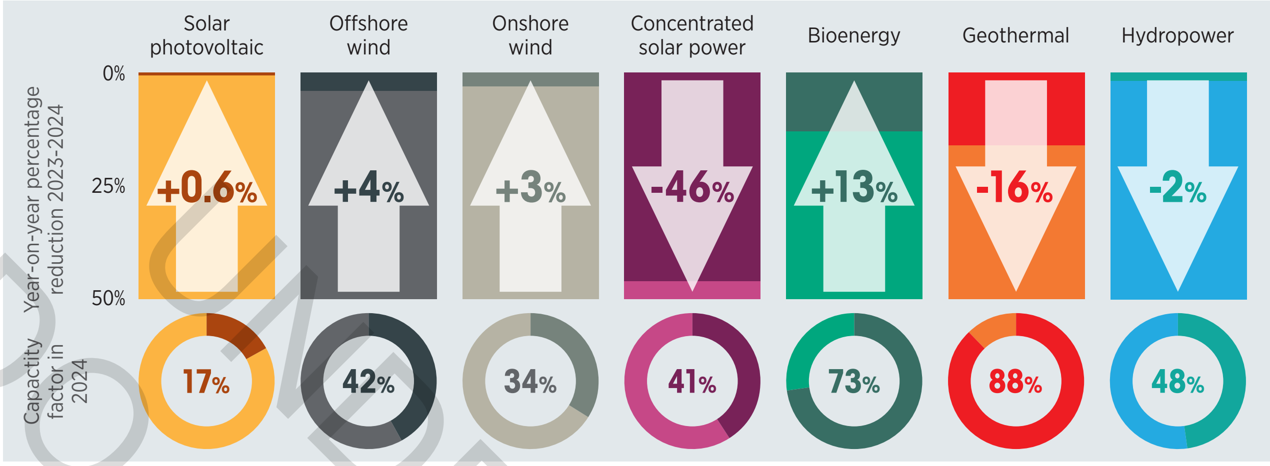


Notes: EU = European Union; G20 = Group of 20; kWh = kilowatt hour; LCOE = levelised cost of electricity; USD = United States dollar.

The economics of most dispatchable renewables are improving

The economics of new dispatchable hydropower, geothermal and CSP technologies improved in 2024. Hydropower achieved a global weighted average LCOE of USD 0.057/kWh, supported by better hydrological conditions and higher energy yields in China and Latin America. Geothermal power averaged USD 0.060/kWh, with particularly favourable outcomes in New Zealand and Indonesia. CSP saw its global LCOE fall by 77% since 2010, reaching USD 0.092/kWh, driven by longer thermal storage durations, reduced operation and maintenance (O&M) costs, and improved capacity utilisation in regions of high direct normal irradiance (DNI), such as in China and South Africa. By contrast, however, bioenergy faced upward pressure, with LCOE rising to USD 0.087/kWh due to volatile feedstock and logistics costs (Figure S4).

Figure S4 Global weighted-average LCOE reduction and capacity factor from newly commissioned utility-scale renewable power technologies, 2024

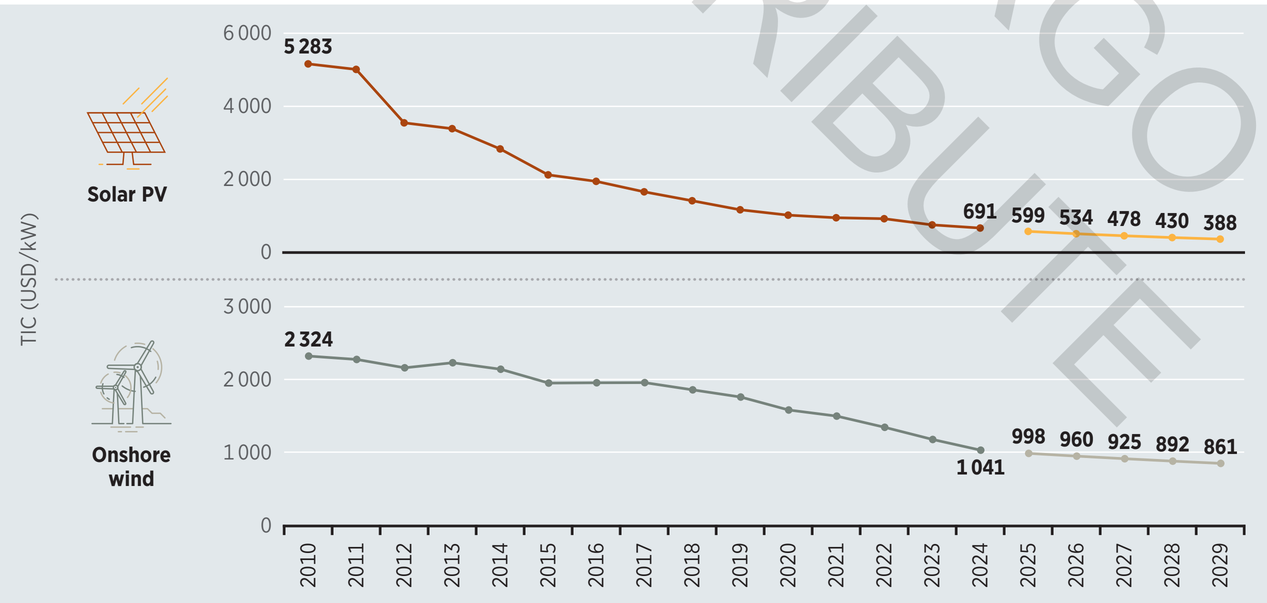


Note: The colour shading indicates the year-on-year percentage LCOE reduction (increase or decrease), starting from top (0%) to bottom (50%).

Future cost declines will slow but remain significant in high-growth regions

Looking ahead, total installed costs are projected to decline further – although at a slower pace – as learning rates and economies of scale continue to drive efficiency gains. Globally, solar PV is expected to fall below USD 600/kW by 2026, while onshore wind TICs are projected to stabilise at between USD 850 and 1 000/kW (Figure S5). For both technologies, Asia is set to retain a distinct cost advantage, with solar PV projected at around USD 500/kW and onshore wind, USD 850/kW. However, higher costs are likely to persist in Europe and North America, reflecting structural factors such as permitting delays and higher balance-of-system costs. Strong learning rates and high deployment sensitivity to costs – especially in Asia, Africa and South America – suggest that accelerated market growth could amplify cost reductions.

Figure S5 Global short-term TIC projections for solar PV and onshore wind



Notes: kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; TIC = total installed cost; USD = United States dollar.

ENABLING TECHNOLOGIES ARE IMPROVING THE ECONOMICS OF RENEWABLES

Battery storage, hybrid systems and digitalisation are all critical enablers of the energy transition and the integration of variable renewables (solar PV and wind). Battery deployment must expand significantly to support a renewables-based power system, with storage technologies expected to provide the majority of short-duration flexibility needs (IRENA, 2024a). Batteries also play a central role in enabling sector coupling and electrification, contributing to emissions reductions both directly and indirectly. China dominates supply, producing over 75% of global batteries at costs 20–30% lower than in European and North American markets (IEA, 2025a), driven by scale and vertical integration. AI-enabled digital tools are improving asset performance and grid responsiveness, yet digitalisation and grid-readiness gaps remain acute in many emerging markets.

Battery storage costs have fallen 93% since 2010

From 2010 to 2024, the total installed cost of utility-scale battery energy storage systems (BESS) dropped by 93%, falling from USD 2 571/kWh to USD 192/kWh. This sharp decline has been driven by manufacturing scale-up, improved materials efficiency and optimised production processes. Lithium-ion batteries – particularly lithium iron phosphate (LFP) chemistries – dominate utility-scale deployment. BESS installations are increasingly co-located with variable renewable energy sources, especially solar PV, to provide peak shaving, frequency regulation and grid balancing. In 2024, the United States and China led global BESS growth, supported by national policy incentives and grid integration mandates.

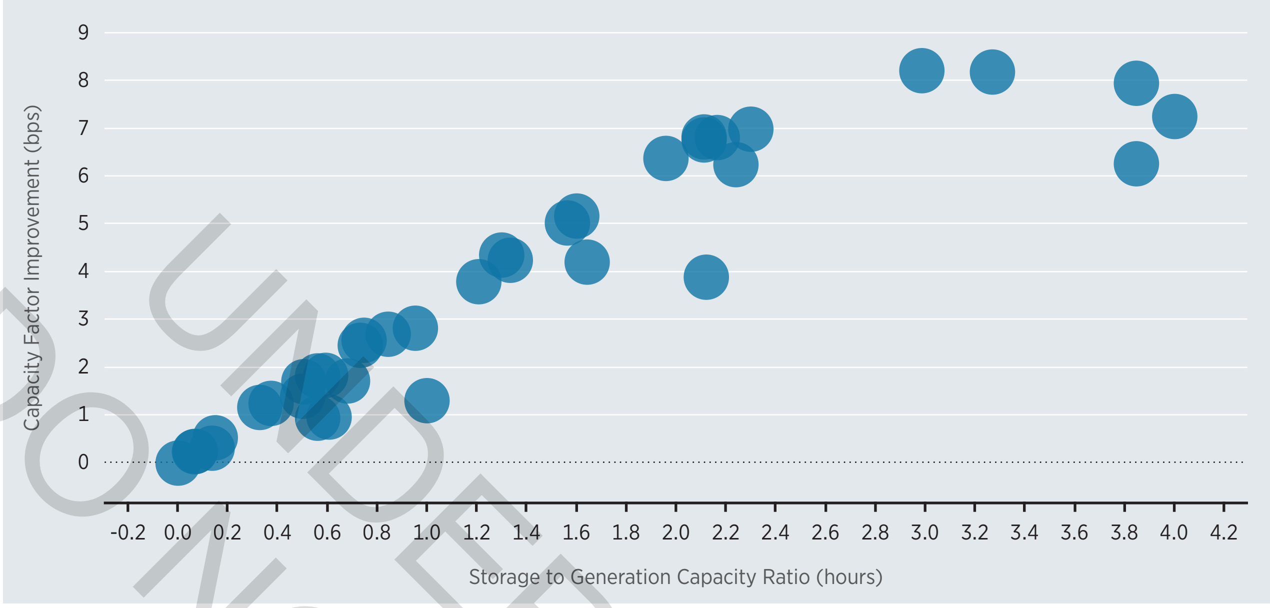
Hybridisation is enhancing grid integration

Hybrid systems,[6] combining solar PV or wind with battery storage, are becoming standard in many markets, offering firmer output profiles, improved capacity factors (Figure S6) and enhanced grid reliability. In China, solar-plus-storage systems have helped mitigate curtailment risks in provinces with high renewable penetration. In the United States, the integration of BESS with new solar capacity has accelerated, enabling dispatch during peak demand and deferring investments in peaking gas plants. Hybridisation is also being explored with geothermal and CSP, particularly for long-duration storage applications.

Figure S6 illustrates the relationship between storage capacity and capacity factor improvement for a sample of hybrid wind and solar projects. Using a linear optimisation approach (described in Box 1.7), gains in terms of capacity factor increase are estimated from adding storage. As expected, the larger the battery (measured by the storage-to-generation capacity ratio), the greater the improvement. However, this comes at a cost (investing in a BESS) and must be weighed against the increased revenue or reliability benefits storage may provide.

[6] *This report refers to "hybrid systems" as configurations that combine renewable generation (e.g. solar PV or wind) with battery storage to improve dispatchability, reliability or grid alignment. We acknowledge that international work – notably under the IEA Wind Task 50 – is underway to develop a standardised taxonomy distinguishing between hybrid systems and hybrid power plants. In this framework, hybrid systems encompass broader energy conversion applications (e.g. power-to-hydrogen), whereas hybrid power plants are defined as co-located and/or integrated generation and storage resources connected at a single grid interconnection point.*

Figure S6 Impact of adding storage capacity on the capacity factor for selected wind and solar projects



Note: bps = basis points.

Although comprehensive LCOE estimates for hybrid systems remain scarce, available data indicates that renewables coupled with battery storage are increasingly approaching cost parity with fossil fuel-based generation in key markets. In the United States, IRENA data for 2024 show that 17 operational hybrid projects (combining 4 486 MW of solar PV and 7 677 MWh of battery storage) achieved a weighted average LCOE of USD 0.079/kWh, which is aligned with the midpoint of the LCOE range for combined-cycle gas turbines (USD 0.077/kWh) and below that of coal (USD 0.119/kWh). In Australia, eight hybrid projects combining solar, wind and battery storage (totalling 412.2 MW of generation and 188.4 MWh of storage) report a significantly lower weighted average LCOE of USD 0.051/kWh.

Digitalisation is driving operational efficiency

Digital technologies – predictive maintenance, real-time performance monitoring, AI-enabled asset management, *etc.* – are improving operational efficiency across renewable assets, allowing for lower O&M costs and extended asset lifetimes. For solar PV and onshore wind, in particular, digitalisation enables granular optimisation of performance, enhancing competitiveness in merchant and auction-based markets. Innovations in digital platforms are also supporting advanced forecasting and grid services, helping to align variable generation with system needs.

Beyond the asset level, digitalisation is increasingly being deployed across power systems to improve forecasting, grid operation and demand-side participation. Smart meters, dynamic pricing systems and Internet of Things (IoT) enabled appliances support demand response programmes, allowing consumers to shift or reduce their electricity use in response to price signals. At the power system level, such capabilities can help smooth out peaks, reduce system stress and facilitate the integration of renewable energy sources. Advanced grid management systems also use digital twins and AI algorithms to forecast congestion, co-ordinate distributed energy resources and optimise dispatch in near real-time.

Integration costs must be recognised and addressed

While the plant-level solar and wind costs continue to fall, grid constraints are increasingly limiting their deployment. A substantial volume of wind and solar projects worldwide are facing delays due to grid connection bottlenecks, while long procurement lead times for key components such as transformers and high-voltage cables are further affecting project timelines. These delays contribute to rising integration costs, including expenditures associated with storage, curtailment and transmission infrastructure. Although often triggered by renewable expansion, investments in such assets enhance grid flexibility and benefit the entire power system – including non-renewable generators. Recognising and addressing these costs is essential, particularly in emerging markets, where grid investment must keep pace with rising demand. In Australia, for example, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) estimates that integration costs can add USD 0.028–0.032/kWh to the cost of variable renewables at high penetration levels.[7] These integration costs vary significantly depending on project location, grid distance and infrastructure availability, and are often higher for projects requiring long-distance transmission or that are located in remote areas.

STRUCTURAL COST DRIVERS AND MARKET CONDITIONS

Supply chain integration keeps Chinese costs low

China's vertically integrated supply chains continue to deliver structural cost advantages across solar PV components, wind turbines and batteries. This integration reduces procurement delays, compresses margins and enables efficient scaling of gigawatt-scale projects. In 2024, Chinese manufacturers remained dominant across global supply chains for solar PV, wind and battery technologies, supplying a substantial share of key components.[8] However, this concentration also introduces vulnerabilities, including exposure to geopolitical tensions and emissions intensity. Although renewable capacity additions in China have grown rapidly in recent years, a significant share of PV manufacturing in China is still powered by coal, raising concerns about lifecycle carbon footprints.

[7] *These figures are based on system modelling, not direct project-level adders. The cost range reflects total integration costs - including storage, transmission, and curtailment - under scenarios with 60-90% shares of variable renewable energy (VRE).*

[8] *China accounted for 79% of global polysilicon production, 97% of wafer production, 85% of cell production, and 75% of module production in 2021 (IEA, 2022). China also holds nearly 85% of global battery cell production capacity and a leading share of anode and cathode active material production (IEA, 2024a). On the other hand, the 2025 edition of the GWEC Global Wind Report indicates that China accounted for 70% of global onshore wind installations in 2024, supported by domestic original equipment manufacturers that are increasingly expanding their presence in international markets (GWEC, 2025a).*

Cost of capital remains a key barrier in high-risk markets

Renewable energy projects are capital-intensive, with most costs incurred up front and recovered over long operating lifetimes. As a result, the LCOE is highly sensitive to financing conditions. In 2024, financing costs[9] represented an important share of LCOE, particularly in markets with elevated risk premiums, as indicated by sovereign credit ratings (*e.g.* Moody's) and illustrated in Figure S7. For example, while the average LCOE for onshore wind was similar in Africa and Europe – USD 0.051/kWh and USD 0.052/kWh, respectively – the underlying cost structures differed markedly. In Europe, LCOE were driven primarily by capital expenditure, whereas in Africa, financing costs accounted for the majority share. In 2024, IRENA's weighted average costs of capital (WACC) assumptions ranged from 3.8% in Europe to 12% in Africa, reflecting country risk and macroeconomic conditions prevailing in 2023.[10]

Figure S7 Share of financing in LCOE vs. cost of capital (WACC) for selected countries (with Moody's ratings), 2024

Notes: AGO = Angola; ARG = Argentina; AUT = Austria; BFA = Burkina Faso; BIH = Bosnia and Herzegovina; BRA = Brazil; CHN = China; CYP = Cyprus; DNK = Denmark; EGY = Egypt; EST = Estonia; JPN = Japan; LCOE= levelised cost of electricity; LUX = Luxembourg; MDA = Moldova; NIC = Nicaragua; PAK = Pakistan; PV = photovoltaic; RUS = Russia; TUN = Tunisia; TUR = Türkiye; WACC = weighted average cost of capital; ZAF = South Africa.

[9] *Financing costs are estimated as the difference between the LCOE at a given weighted average cost of capital (WACC) and the LCOE under a zero-discount rate scenario. For example, at a WACC of 5%, financing costs are calculated as LCOE(WACC=5%) minus LCOE(WACC=0%). Their share is then expressed as a proportion of the full LCOE. This approach isolates the effect of time on money from undiscounted cost components. WACC values account for country-specific parameters (e.g. sovereign credit ratings, risk premiums and tax rates).*

[10] *According to IRENA's methodology, the WACC for a given year (y) is based on macroeconomic data from the preceding year (y-1), reflecting the typical lag between shifts in financing conditions and investment decisions.*

Policy stability and market design influence competitiveness

Stable revenue frameworks are essential to lowering risk and attracting profit-driven investment. Revenue-securing instruments such as power purchase agreements (PPAs) and contracts-for-difference (CfDs) are key to accessing low-cost capital. Conversely, retroactive policy shifts and unclear procurement processes erode investor confidence. Strategic industrial policies – such as the United States (U.S.) Inflation Reduction Act and the EU's Green Deal Industrial Plan – have increased domestic investment and localisation despite introducing modest cost premiums for domestically manufactured technologies. However, effective implementation remains uneven, with many regions still grappling with permitting delays, grid bottlenecks and costlier local supply chains.

BEYOND COSTS: THE BROADER BENEFITS OF RENEWABLE ENERGY

Increased renewable energy integration is shifting fossil fuel generation to peak or residual demand, reducing thermal plant use and exposure to volatile fuel markets. By 2024, solar and wind comprised 46.4% of global installed electricity generation capacity, significantly displacing coal and gas in key markets like China, the United States and the EU, and reducing associated greenhouse gas emissions.

Renewables not only offer some of the lowest generation costs in LCOE terms but are also structurally advantageous. Their deployment can drastically reduce the need for costly infrastructure related to fossil fuel extraction, transport and backup generation while limiting dependence on international fuel markets and improving energy system resilience. As such, the full value of renewables extends far beyond the LCOE, encompassing long-term energy security as well as public health and environmental sustainability.

Crucially, renewable electricity displaces emissions of carbon dioxide (CO_2) and harmful air pollutants – including sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter ($PM_{2.5}$) – that are closely linked to respiratory and cardiovascular illnesses. These co-benefits, while not captured by the LCOE metric, are critical for public health and environmental integrity.

In 2024, the United States generated 1 057 terawatt hours (TWh) of electricity from renewables. Based on conservative assumptions about displaced fossil generation (30% coal; 70% gas), the estimated benefits include:

- USD 24.1 billion in avoided fossil fuel costs[11]
- USD 21.5 billion in avoided air pollution damages[12]

[11] *Based on avoided fossil fuel costs calculated using 2024 average U.S. fuel prices of USD 3.25/metric million British thermal unit (MBtu) for coal and USD 2.76/MBtu for gas, thermal efficiency assumptions (35% for coal, 48% for gas), and generation displacement shares (30% coal, 70% gas). Price data sourced from U.S. Energy Information Administration. These estimates are based on typical, average fossil fuel prices under long-term supply contracts, not temporary market spikes.*

[12] *Monetised air pollution damages estimated using flat damage rates of USD 50/megawatt hour (MWh) for coal and USD 10/MWh for gas, consistent with the World Health Organization (WHO) estimates and applied to the fossil generation displaced by renewable deployment*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This yields a total estimated benefit of USD 45.6 billion in a single year,[13] reinforcing the broader value proposition of renewables beyond their LCOE.

Table S2 complements this analysis by presenting comparable estimates for avoided fossil fuel costs and air pollution damages across several major economies.

Table S2 Estimated annual benefits from renewable power generation in selected countries, 2024

	China	Germany	Brazil	Australia
Avoided fossil fuel costs (USD billion)	179.8	16.4	28.3	5.0
Avoided air pollution damages (USD billion)	261.1	6.0	3.9	1.9
Total (USD billion)	**440.9**	**22.4**	**32.2**	**6.9**

While this example reflects the benefits in a specific national context, scaling such outcomes globally depends very much on the development of enabling infrastructure – including advanced grids, storage systems, critical material supply chains, *etc.* As deployment accelerates, it becomes increasingly important to move beyond plant-level metrics and fully assess renewables' system-wide impacts and co-benefits.

[13] *This assessment does not include avoided carbon dioxide (CO_2) emissions in the total benefit calculation. However, applying a carbon price of USD 190 per tonne of CO_2, as recommended by the High-Level Commission on Carbon Prices, the estimated 597 $MtCO_2$ avoided in 2024 would translate to an additional USD 113.5 billion in monetised climate benefits.*


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