Renewable Energy's Comparative Edge over Non-Renewable Energy in Today's Era and Its Role in the Greenhouse Effect

Nazvar Ashfakusen Ghanchi[1], Haresh B. Tank[2], Ankur Bhupendrakumar Pachani[3]

[1] Correspondence Author, nikag@vaidehibackbone.org, Orcid Id: 0009-0006-2832-0083

[2] Associate Professor, hareshtank@yahoo.com, Orcid Id: 0000-0002-9029-9928

[3] Strategic And Financial Director, ITL Group of Companies. pachaniankur@gmail.com, Orcid Id: 0009-0001-7796-5877.

Abstract

This paper asks whether renewable energy now holds a demonstrable advantage over fossil-fuel energy and evaluates what that advantage means for the enhanced greenhouse effect. The study responds to a specific gap in the literature. Existing work tends to examine emissions, generation costs, system integration, energy security, and employment in isolation, and much of it predates the 2024–2025 cost and deployment data. Few studies bring these dimensions together in a single transparent comparative framework using the most recent international benchmarks, and fewer still connect that framework to technology innovations, such as floating solar photovoltaics, that are actively relaxing the constraints on renewable deployment. The paper fills that gap through a descriptive comparative design built from recent authoritative datasets: the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), Ember, the Intergovernmental Panel on Climate Change (IPCC), and the U.S. National Renewable Energy Laboratory (NREL), supplemented by the Indian literature on floating solar. The transition context is documented first: in 2024, renewables added 585 GW globally and accounted for 92.5% of net power-capacity expansion; renewables supplied a record 32% of world electricity, while clean power including nuclear reached 40.9%. Technology-level comparisons then follow. Renewable electricity technologies in the sample show a median harmonized life-cycle emissions estimate of 28 gCO2e/kWh, against a fossil median of 840 gCO_2e/kWh, a thirty-fold gap that no reasonable adjustment of assumptions can close. On cost, the global weighted average levelized cost of electricity (LCOE) of mainstream renewables, meaning utility-scale solar PV, onshore wind, hydropower, and geothermal, averaged USD 0.0485/kWh in 2024, well below representative benchmarks for new coal and gas generation. Supplementary statistical checks, reported with explicit caveats about the small purposive

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sample, are consistent with these descriptive gaps. The paper also examines what LCOE cannot capture. Drawing on the system-cost literature, it discusses integration, balancing, and grid costs at high renewable penetration, and it argues that these costs qualify rather than reverse the renewable advantage. The conclusion is that renewable energy now leads fossil generation on emissions intensity, mainstream generation economics, energy security, employment, and adaptability, while grids, storage, financing, and institutions remain the binding constraints on translating that lead into faster decarbonization.

Keywords: renewable energy; fossil fuels; greenhouse effect; energy transition; life-cycle emissions; LCOE; system integration costs; floating solar; decarbonization

Highlights

- Renewables supplied a record 32% of global electricity in 2024, while clean electricity including nuclear reached 40.9%.
- Renewable technologies in the comparative sample show a median life-cycle emissions estimate thirty times lower than the fossil sample median.
- Mainstream renewables now undercut representative new coal and gas benchmarks on a global weighted average LCOE basis.
- System-level integration costs qualify, but do not reverse, the renewable cost advantage at current penetration levels.
- Floating solar illustrates how renewable innovation is relaxing land constraints and widening the gap with fossil generation.

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Visual Snapshot

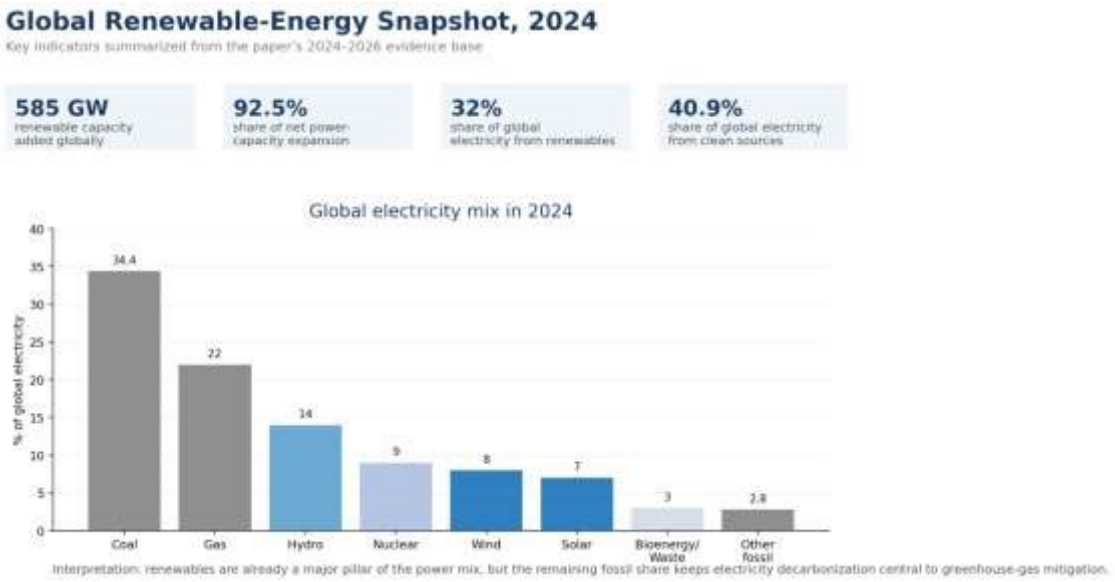


Figure 1. Executive snapshot of the renewable-energy transition and the current global electricity mix.

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1. Introduction

The energy transition has moved from a largely normative debate into a strategic, economic, and geopolitical one. For decades, the conventional view was that renewable energy was environmentally superior but commercially weaker than fossil-fuel generation, especially when judged by reliability, dispatchability, capital intensity, and the need for supportive policy. That framing no longer describes the electricity sector accurately. In 2024 the world added renewable capacity at unprecedented scale, and the pace of clean power deployment increasingly shaped markets, industrial policy, supply chains, and security planning. At the same time, energy-related carbon dioxide emissions still reached a record 37.8 Gt in 2024, confirming that the transition, while unmistakable, remains incomplete (IEA, 2025a).

This coexistence of rapid renewable growth and still-rising global emissions makes the present moment analytically important. It is not enough to state that renewable energy is good for the climate. The more demanding question is whether renewable energy holds a demonstrable advantage over fossil-fuel energy when the comparison covers emissions, cost, security, scalability, employment, and long-run climate relevance together. Related to that, how exactly does the renewable transition alter the greenhouse effect, which remains the physical basis of anthropogenic warming? The answer matters for policy design, public finance, infrastructure planning, and for the political economy of coal, oil, and gas phase-down.

A note on terminology is useful at the outset. The title of this paper contrasts renewable with non-renewable energy. In the text, the comparison group is described consistently as fossil fuels or fossil-fuel generation, meaning coal, oil, and natural gas used for electricity. Nuclear power is treated separately: it is non-renewable but low-carbon, and it enters the analysis only as part of the clean-electricity aggregate reported by Ember and the IEA.

The greenhouse effect itself is not harmful in principle; without it, Earth would be too cold for current forms of life. The problem is the enhanced greenhouse effect produced by the accumulation of anthropogenic greenhouse gases, above all carbon dioxide, methane, and nitrous oxide, which trap more outgoing infrared radiation and disturb the planet's radiative balance. The energy system is central to this problem. The United Nations' global stocktaking of the energy transition identifies the energy sector as the source of around three-quarters of greenhouse gas emissions, while the IPCC identifies the global energy system as the largest source of carbon dioxide emissions (United

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Nations, 2021; IPCC, 2022). The comparison between renewable and fossil energy is therefore not a sectoral side issue. It is a direct test of how societies can reduce the flow of new greenhouse gases into the atmosphere.

Research gap and contribution. The literature on this comparison is large but fragmented. Lifecycle assessment studies establish the emissions gap between renewable and fossil electricity but rarely engage with cost or deployment data (NREL, 2021). Cost studies track the fall in renewable LCOE but are frequently criticized for ignoring system-level integration costs (Joskow, 2011; Ueckerdt et al., 2013). The system-cost literature, in turn, is technically rich but seldom connected back to the emissions and development dimensions that motivate the transition in the first place (Heptonstall & Gross, 2021). Policy-oriented reviews often predate the sharp cost and deployment shifts recorded in 2024–2025, when renewables came to dominate global capacity additions and mainstream technologies moved decisively below fossil cost benchmarks. Finally, technology innovations such as floating solar photovoltaics (FPV) are usually studied as engineering subjects rather than as evidence about the direction of comparative advantage. This paper addresses that fragmentation. Its contribution is integrative and current rather than econometric: it assembles the 2024–2025 evidence on emissions, generation costs, system costs, security, and employment into one comparative framework; it makes the limits of LCOE explicit and incorporates the system-cost critique directly rather than treating it as an afterthought; and it uses FPV as a structured case of how innovation is enlarging the renewable advantage on precisely the dimension, land, where fossil generation was once thought to hold an edge. To the authors' knowledge, no recent study combines these elements around the 2024 benchmark year. This paper argues that renewable energy now holds a strong advantage over fossil-fuel energy, but that the advantage is uneven across dimensions and technologies. The strongest lead lies in life-cycle emissions performance and in the rapidly improving economics of solar PV, onshore wind, hydropower, and geothermal power. Additional advantages include energy security, modularity, faster deployment at distributed scales, reduced exposure to fuel-price volatility, and rising employment. The paper also emphasizes that this advantage should not be romanticized. Grid integration, seasonal balancing, storage requirements, financing costs in emerging markets, critical mineral supply chains, curtailment, land and water conflicts, and bioenergy sustainability remain

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serious challenges. A credible comparative assessment must account for these frictions rather than assume a frictionless clean-energy transition.

The paper makes four specific contributions. First, it synthesizes international facts and figures from 2024–2026 reporting to provide an up-to-date picture of the renewable transition. Second, it organizes the renewable-versus-fossil comparison around both climate and economic performance rather than around emissions alone, and it extends the economic comparison from generation costs to system-level costs. Third, it reports transparent technology-level comparisons of life-cycle greenhouse gas emissions and levelized costs, supported by supplementary statistical checks whose limits are stated openly. Fourth, it adds a focused discussion of floating solar photovoltaics, especially in the Indian context, and links that case explicitly to the paper's central argument about the changing direction of comparative advantage.

The rest of the paper is structured as follows. Section 2 reviews the literature and conceptual foundations. Section 3 explains the data sources and methodology. Section 4 presents the current global renewable transition context. Section 5 reports the comparative emissions and cost results, the system-cost discussion, and the floating-solar case. Section 6 interprets the findings for the greenhouse effect and for contemporary energy policy. Section 7 draws policy implications, Section 8 states limitations, and Section 9 concludes.

2. Literature Review and Conceptual Background

The literature on renewable energy has evolved through three broad stages. Early work centered on technological feasibility and environmental desirability: whether wind, solar, hydro, and biomass could contribute meaningfully to power systems traditionally dominated by coal, oil, gas, and large centralized infrastructure. A second phase of research focused on commercialization, policy support, and diffusion, examining feed-in tariffs, renewable purchase obligations, tax incentives, auctions, and deployment trajectories. The present phase is more integrated and more demanding. The question is no longer only whether renewables can grow. It is whether they can structurally outperform fossil alternatives in cost, risk, flexibility, and climate outcomes under real-world conditions.

At the climate level, the strongest and most stable finding in the literature is that renewable electricity generally has much lower life-cycle greenhouse gas emissions than fossil-fuel

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electricity. NREL's harmonized synthesis of life-cycle greenhouse gas emissions reports median estimates of 43 gCO2e/kWh for photovoltaic electricity, 13 gCO2e/kWh for wind, 21 gCO2e/kWh for hydropower, and 37 gCO2e/kWh for geothermal electricity, compared with 486 gCO2e/kWh for natural gas, 840 gCO2e/kWh for oil, and 1001 gCO2e/kWh for coal (NREL, 2021). This matters because climate policy increasingly evaluates technologies on a life-cycle rather than stack-emissions basis, which captures upstream extraction, transport, manufacturing, operation, and decommissioning. The IPCC likewise emphasizes that deep emission reductions in the energy system are indispensable to limiting warming (IPCC, 2023).

On the economic side, the literature has changed more dramatically over the last decade. Earlier studies often treated renewable electricity as structurally more expensive than fossil generation once intermittency, grid integration, and capital costs were considered. Contemporary evidence is less supportive of that view. IRENA's latest cost assessment reports that in 2024 the global weighted average LCOE of onshore wind was USD 0.034/kWh and of utility-scale solar PV USD 0.043/kWh, and that 91% of newly commissioned utility-scale renewable capacity produced electricity at lower cost than the cheapest newly installed fossil alternative (IRENA, 2025b). Hydropower and geothermal also remain competitive in many markets, while concentrated solar power, offshore wind, and bioenergy are improving but remain more locationsensitive and cost-variable. The economic literature therefore increasingly distinguishes between mainstream renewables that are already cost leaders and context-specific renewables that require stronger system or site advantages.

A parallel strand of research, however, warns against reading generation-cost comparisons as complete cost comparisons. Joskow (2011) showed early that LCOE comparisons between dispatchable and intermittent technologies are economically incomplete because they ignore when electricity is produced and what it is worth at that time. Ueckerdt et al. (2013) formalized the idea of a system LCOE that adds integration costs, comprising balancing, grid reinforcement, and the reduced utilization of conventional plants, to plain generation costs, and Hirth, Ueckerdt and Edenhofer (2015) estimated that these integration costs rise with the share of variable renewables in the system. Heptonstall and Gross (2021), reviewing the empirical evidence systematically, find that integration costs are real and penetration-dependent but generally modest at low and moderate shares, and highly sensitive to system flexibility. Sepulveda et al. (2018) add that deep

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decarbonization becomes markedly cheaper when variable renewables are complemented by firm low-carbon resources. On the infrastructure side, the IEA has documented that grids themselves are becoming a bottleneck, with large volumes of renewable capacity waiting in connection queues and grid investment lagging generation investment (IEA, 2023). This paper takes that strand seriously. Rather than treating LCOE as a verdict, Section 5.3 uses it as one input into a broader comparison that acknowledges system-level costs explicitly.

A third branch of literature stresses energy security. Fossil-fuel systems depend on extraction, transport corridors, refineries, shipping routes, pipeline systems, and fuel-price exposure. By contrast, once renewable assets are installed, their primary energy input is domestic and noncombustible: sunlight, wind, water flow, geothermal heat, or organic residue. This does not make renewable systems geopolitically neutral, because critical minerals, manufacturing concentration, and technology dependencies create new forms of exposure. But it does change the risk structure from recurring fuel dependence toward upfront capital and industrial capability. The rise in domestic renewable generation during periods of fuel-price volatility has therefore strengthened the argument that renewable energy is not only a climate strategy but also a resilience strategy. The literature also documents a broader socio-economic dimension. IRENA's employment review reports at least 16.6 million renewable energy jobs worldwide in 2024, showing that the sector has become a major labor market in manufacturing, project development, construction, operations, maintenance, and decentralized energy services (IRENA, 2026). Although job quality, supply-chain concentration, automation, and just-transition issues remain uneven, the overall employment base of renewables has become too large to treat as a marginal co-benefit. This is particularly relevant in emerging economies where distributed generation, rooftop solar, mini-grids, and renewable manufacturing can align industrial policy with climate policy. System integration deserves emphasis in its own right. Critics of renewables rightly note that low marginal cost does not automatically guarantee low system cost, because a high-renewable power system needs transmission reinforcement, balancing resources, storage, digital controls, flexibility, and market redesign. This is one reason why simplistic renewables-versus-fossil comparisons can mislead. Yet recent evidence from IRENA and the IEA suggests that enabling technologies are improving quickly. Battery storage costs fell by 93% between 2010 and 2024, reaching USD 192/kWh for utility-scale systems, and hybridization of solar or wind with

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storage is increasingly standard in major markets (IRENA, 2025b). What the literature now suggests is not that integration is trivial, but that the supporting technologies and market practices are catching up fast enough to protect the long-run position of renewables.

A more specialized but increasingly important literature examines the land-water-energy nexus and floating solar photovoltaics. Conventional large-scale solar deployment often encounters land acquisition problems, competing land uses, biodiversity issues, and social conflict. Floating PV offers an institutional and engineering response. Indian studies indicate that the country may have around 18,000 square kilometers of suitable water surface and an FPV potential of approximately 280 GW (Kumar, 2021). TERI (2020) describes FPV as effectively land-neutral and notes reported energy-yield gains linked to lower module temperature and the cooling effect of water bodies, while Misra (2021) argues that floating systems can reduce evaporation and, in some cases, improve output relative to land-based PV. The World Bank's global market assessment reaches similar conclusions about the scale of the opportunity (World Bank, ESMAP, & SERIS, 2019). Although these estimates are context dependent, the broader literature is clear that renewable innovation is now working precisely on the constraints that once favored fossil alternatives. This paper reads the FPV literature through that comparative lens rather than as a standalone technology review.

The literature, however, also contains several warnings. First, not all renewables are equally lowcarbon under all conditions. Hydropower reservoirs can generate methane; poorly governed biomass can create high land-use and supply-chain emissions; and solar or wind deployment without recycling and responsible sourcing can externalize environmental burdens. Second, financing costs matter enormously. IRENA's 2024 cost review emphasizes that high weighted average costs of capital can overwhelm technology-cost advantages in many emerging markets (IRENA, 2025b). Third, the decarbonization effect of renewables depends on the fossil generation they displace, the flexibility of the thermal fleet, and grid operating rules. Recent analytical work shows that renewable electricity typically reduces carbon emissions, but the magnitude of reduction depends on coal reliance, plant cycling, and storage deployment.

The literature thus supports a strong but qualified proposition: renewable energy now holds an advantage over fossil energy, yet the strength of that advantage depends on whether one is analyzing climate damage, direct generation cost, system cost, macroeconomic resilience, or

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institutional readiness. This paper builds on that literature by integrating the dimensions instead of treating them separately.

3. Data Sources and Methodology

This study adopts a descriptive comparative review design. It does not construct an econometric panel of countries, and it does not claim inferential generalization from its technology samples to the global electricity system. The objective is different: to combine up-to-date global evidence with transparent technology-level comparisons whose data can be traced directly to internationally recognized benchmark sources. The empirical core therefore relies on recent secondary datasets and authoritative reviews. The main sources are: (i) IRENA's Renewable Capacity Statistics 2025 and Renewable Power Generation Costs in 2024; (ii) Ember's Global Electricity Review 2025; (iii) the IEA's Global Energy Review 2025 and Renewables 2025; (iv) the IPCC AR6 Synthesis Report and IPCC Working Group III material on energy systems; (v) NREL's harmonized life-cycle greenhouse-gas emissions synthesis; and (vi) the Indian floatingsolar literature, including Misra (2021), Kumar (2021), and TERI (2020).

The paper uses two compact comparative datasets. Dataset A is a technology-level life-cycle emissions sample derived from NREL (2021). Renewable technologies include biomass, photovoltaic, concentrated solar power, geothermal, hydropower, ocean energy, and wind. Fossil technologies include natural gas, oil, and coal. The dependent measure is the median harmonized life-cycle greenhouse gas emissions estimate per unit of electricity generated, expressed in gCO2e/kWh. Dataset B is a 2024 cost sample derived from IRENA (2025b), using the global weighted average levelized cost of electricity. Renewable observations include solar PV, concentrated solar power, bioenergy, offshore wind, onshore wind, geothermal, and hydropower. Fossil benchmarks are IRENA's reported global average LCOE of new coal power and combined-cycle gas turbine (CCGT) generation. Throughout the paper, emissions values are median harmonized estimates and cost values are global weighted averages unless explicitly stated otherwise.

The analytical strategy is descriptive first. The paper reports means, medians, ranges, and ratios, and it interprets the comparison on the basis of these descriptive magnitudes. Statistical tests are then reported as supplementary robustness checks, not as the basis of the paper's claims. The

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reason for this ordering is methodological honesty. The technology categories in Datasets A and B form a small, purposive sample of benchmark values rather than a random sample from a defined population, so classical inferential assumptions are only partially met. Reporting the tests still has value: they discipline the descriptive claims by showing that the observed gaps are far too large to be attributed to chance variation within the benchmark set, and the nonparametric results do not depend on distributional assumptions. But the reader should interpret the p-values as indicative checks on the benchmark comparison, not as population inference. Concretely, the supplementary checks are: a Welch unequal-variance t-test and a Mann-Whitney U test for the emissions comparison, with Hedges' g as a small-sample corrected effect size; and one-sample ttests comparing renewable LCOE values against the fossil benchmark mean, including a sensitivity variant restricted to the mainstream technologies that dominate current deployment (solar PV, onshore wind, hydropower, and geothermal).

The cost comparison also requires a caution that the paper treats as substantive rather than procedural. LCOE measures the average discounted cost of generating electricity over a plant's lifetime. It does not capture when that electricity is produced, what it is worth at that time, or what the surrounding system must spend on balancing, transmission, and backup to accommodate it (Joskow, 2011; Ueckerdt et al., 2013). At high shares of variable renewables, these integration costs grow and the gap between generation cost and system cost widens (Hirth et al., 2015; Heptonstall & Gross, 2021). For this reason, the paper does not present LCOE as a standalone verdict. Section 5.3 discusses system-level costs explicitly and states the conditions under which the generation-cost comparison remains informative.

A simple scenario model is also introduced to connect the technology comparison to the greenhouse effect. Using Ember's 2024 global electricity shares, comprising hydro 14%, wind 8%, solar 7%, bioenergy and waste 3%, nuclear 9%, coal 34.4%, gas 22%, and other fossil fuels 2.8%, the paper computes an indicative weighted average life-cycle carbon intensity for the global power mix using NREL's technology medians. It then compares that mix with a counterfactual in which the 32% renewable electricity share is replaced by coal. This is not presented as an official estimate; it is an illustrative analytical exercise to show how portfolio composition affects greenhouse-gas loading.

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The study has clear limitations. Technology-level benchmarks do not capture full nationalsystem costs, local environmental impacts, market design differences, or the time profile of variable renewable output. They do not resolve debates about firm capacity, seasonal storage, or the interaction between electricity and industry. Biomass and hydropower also involve wider sustainability questions that a narrow emissions benchmark can understate. Even with those caveats, the data are sufficiently robust to support a careful comparative argument about the present position of renewable energy relative to fossil energy.

3.1 Research Questions and Analytical Expectations

The comparative discussion is organized around three research questions. RQ1 asks whether renewable electricity technologies exhibit substantially lower life-cycle greenhouse-gas emissions than fossil-fuel electricity technologies when compared on a common grams-of-CO2equivalent-per-kWh basis. RQ2 asks whether renewable electricity technologies are, on average, more cost-competitive than new fossil alternatives when compared using recent LCOE benchmarks, and how far that comparison survives once system-level costs are considered. RQ3 asks whether the strategic value of renewables extends beyond climate and cost to include resilience, resource security, and institutional compatibility with contemporary low-carbon development, and whether ongoing innovation, illustrated here by floating solar, is widening or narrowing the gap.

From these questions, the study derives four directional expectations. E1 expects the mean lifecycle emissions intensity of renewable electricity technologies to be lower than that of fossil technologies. E2 expects the same for the medians. E3 expects the average LCOE of mainstream utility-scale renewables, particularly solar PV, onshore wind, hydropower, and geothermal, to be lower than the benchmark cost of new coal and combined-cycle gas generation. E4 expects renewable energy to hold a systems-level advantage in the current period because its low operating emissions, modular deployment profile, and fuel-free generation model better fit the requirements of climate-constrained, import-exposed, and infrastructure-modernizing economies. The first three expectations are examined directly against the compact technology-level datasets described above, with the statistical checks in a supplementary role, while the fourth is evaluated through structured synthesis of the broader evidence base. This mixed logic is deliberate. A smaller comparative design can still be rigorous when the units of analysis are clearly defined, the data sources are

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authoritative, the claims are proportionate to the evidence, and the limits of generalization are acknowledged explicitly. The statistical checks are not a substitute for system modelling; they discipline the core proposition that renewables are not only environmentally preferable in theory but measurably ahead across key observable indicators in the current period.

4. Global Context: Where the Energy Transition Stands in 2024–2025

The empirical context for this paper is unusually dynamic. According to IRENA's Renewable Capacity Statistics 2025, the world added 585 GW of renewable power capacity in 2024, taking total global renewable power capacity to 4,448 GW. Renewables accounted for 92.5% of total power-capacity expansion in that year, and the annual growth rate reached 15.1% (IRENA, 2025a). These are not marginal numbers. They indicate that, at the level of new capacity, renewable energy has become the default expansion pathway for the global power sector.

Electricity generation data show a similarly important structural shift. Ember's Global Electricity Review 2025 reports that renewables generated a record 32% of global electricity in 2024, up from 30% in 2023. Clean electricity including nuclear reached 40.9% of total generation, the first time in the modern era that two-fifths of world electricity came from low-carbon sources (Ember, 2025). The IEA reports a compatible pattern, noting that renewables collectively accounted for about one-third of electricity generation in 2024 and that renewables plus nuclear covered two-fifths of total generation (IEA, 2025b). At source level, hydropower remained the largest renewable contributor at about 14%, wind supplied around 8%, solar PV around 7%, and bioenergy and waste around 3%. Coal still supplied about 34.4% and gas 22%, which shows both the scale of the transition and the scale of the task ahead.

These power-sector gains did not yet deliver absolute decoupling in global energy emissions. The IEA reports that total energy-related CO2 emissions increased by 0.8% in 2024 to a record high of 37.8 Gt CO2, contributing to atmospheric concentrations of 422.5 ppm (IEA, 2025a). Yet the same report emphasizes that the rapid adoption of clean-energy technologies is restraining the growth of emissions. Without the continued expansion of clean technologies such as solar PV, wind, nuclear power, electric vehicles, and heat pumps, global annual emissions would have been roughly 2.6 billion tonnes higher (IEA, 2025a). This is crucial for the greenhouse-effect argument:

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renewables are not merely a future promise but an already observable brake on the flow of additional greenhouse gases.

Cost and industrial indicators reinforce this structural shift. IRENA finds that 91% of newly commissioned utility-scale renewable capacity in 2024 delivered power at lower cost than the cheapest newly installed fossil-fuel alternative. The global weighted average LCOE of onshore wind was USD 0.034/kWh and of solar PV USD 0.043/kWh, while utility-scale battery storage costs fell to USD 192/kWh after a 93% decline since 2010 (IRENA, 2025b). These figures matter because they show that climate mitigation is no longer proceeding only through premiumpriced green choices. It is increasingly proceeding through technologies that are also industrially rational and cost effective.

The socio-economic dimension has expanded as well. IRENA and the ILO estimate at least 16.6 million jobs in renewable energy worldwide in 2024 (IRENA, 2026). The clean-energy transition has therefore moved beyond a narrow environmental sector and into the core of labor markets, industrial strategy, and trade competition. This does not mean that all countries are benefiting equally; the regional imbalance remains large, with China dominating manufacturing and a disproportionate share of deployment. Still, the employment scale strengthens the claim that renewable energy now holds a broader development advantage over fossil energy.

Finally, the transition is expected to continue. The IEA's Renewables 2025 outlook projects that the share of renewables in global electricity generation will rise from 32% in 2024 to 43% by 2030, and that renewables will meet over 90% of global electricity demand growth over the period 2025–2030 (IEA, 2025c). The baseline direction of travel is already known. The main remaining question is how far, how fast, and with what institutional design the transition can displace the fossil share that still drives the greenhouse effect.

5. Results

This section presents the core comparative results. It is organized around four linked questions. Do renewables outperform fossil fuels on greenhouse-gas intensity? Do they outperform on generation cost? How does the picture change when system-level costs are considered? And how do these differences matter for the greenhouse effect in practical rather than purely conceptual terms?

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5.1 Life-Cycle Emissions: The Strongest Renewable Advantage

Table 2 and Figures 2 and 7 summarize life-cycle greenhouse-gas emissions by electricity technology. The contrast is stark. Renewable technologies in the NREL sample range from 8 gCO2e/kWh for ocean energy to 52 gCO2e/kWh for biomass, with solar PV at 43, hydropower at 21, geothermal at 37, and wind at 13. By contrast, natural gas stands at 486 gCO2e/kWh, oil at 840, and coal at 1001 (NREL, 2021). All values are median harmonized estimates. The renewable median is 28 gCO2e/kWh, while the fossil median is 840 gCO2e/kWh, a thirty-fold difference.

The descriptive gap is so large that it does not depend on any statistical procedure: the highest renewable value in the sample sits at roughly one-ninth of the lowest fossil value. The supplementary checks are nonetheless consistent with it. The Welch unequal-variance t-test yields $t = -4.91$ with $p = 0.039$, and the nonparametric Mann-Whitney U test yields $U = 0.00$ with $p = 0.017$, meaning that every fossil observation exceeds every renewable observation. The corrected effect size is extremely large (Hedges' $g = -5.09$). Given the small purposive sample described in Section 3, these results are read as indicative confirmation that the benchmark gap is not an artifact of chance variation or distributional assumptions, rather than as population inference.

From the perspective of the greenhouse effect, this finding is the most important result in the paper. Fossil electricity, especially coal and oil, intensifies the greenhouse effect largely through combustion emissions during operation. Renewable electricity, by contrast, shifts most emissions upstream into manufacturing, construction, and supply chains. That means renewable power does not eliminate greenhouse-gas emissions entirely, but it radically changes their scale and timing. The climate relevance is therefore cumulative. Every additional unit of coal- or oil-based electricity contributes a large ongoing stream of greenhouse gases; every additional unit of renewable electricity contributes a much smaller life-cycle burden and avoids future combustionbased emissions.

The result also clarifies a frequent public misunderstanding. It is sometimes argued that because renewable infrastructure is built using steel, concrete, mining, transport, and industrial supply chains, renewables are not really clean. That statement is true only in a trivial sense. No large energy technology has zero life-cycle impact. The relevant analytical question is comparative magnitude, not absolute purity. On that criterion, renewables are unambiguously cleaner. Even the higher-emission renewables in the benchmark sample remain far below gas, oil, and coal.

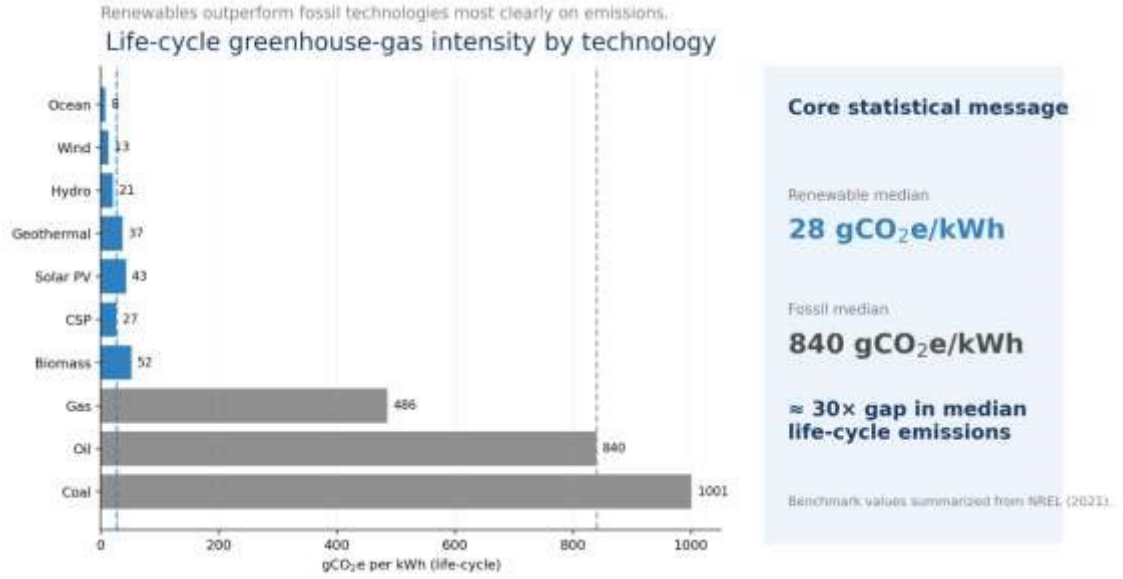
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To connect the benchmark comparison with the global power mix, the paper computed an indicative weighted average life-cycle intensity for the 2024 world electricity portfolio using Ember's source shares and NREL's technology medians. The resulting illustrative value is approximately 485 gCO2e/kWh. A counterfactual case in which the 32% renewable share of 2024 electricity were replaced by coal raises that portfolio intensity to roughly 796 gCO2e/kWh. Replacing the existing renewable share with coal would therefore increase indicative life-cycle carbon intensity by about 64%. The exercise is simple, but it helps show why even partial renewable penetration already matters for the enhanced greenhouse effect.

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444 The life-cycle result also aligns with the broader climate literature. The IPCC's synthesis makes 445 clear that rapid and deep reductions across the energy system are required to limit warming, 446 while the IEA documents that the clean-energy build-out is already restraining annual emissions 447 growth (IPCC, 2023; IEA, 2025a). The present comparison therefore supports a stronger claim 448 than the standard formulation that renewables are cleaner. Renewable energy now provides one

449 of the clearest measurable ways to reduce the marginal climate intensity of electricity production.



450

451 Figure 2. Renewable-versus-fossil contrast in life-cycle greenhouse-gas intensity.

452

453 **5.2 Generation Costs: A More Nuanced but Still Favorable Result**

454 The cost evidence is more nuanced than the emissions evidence, which is exactly why it deserves

455 careful treatment. Table 2 and Figures 3 and 8 report the 2024 global weighted average LCOE 456 values compiled by IRENA. Onshore wind averaged USD 0.034/kWh, solar PV USD 457 0.043/kWh, hydropower USD 0.057/kWh, geothermal USD 0.060/kWh, offshore wind USD 458 0.079/kWh, CCGT USD 0.085/kWh, bioenergy USD 0.087/kWh, and concentrated solar power 459 USD 0.092/kWh. New coal power averaged USD 0.073/kWh (IRENA, 2025b).

460 These values illustrate a critical contemporary shift. The leading renewable technologies are not 461 simply approaching fossil competitiveness; they have already crossed it. On these global 462 weighted averages, solar PV is 41% cheaper than the least-cost fossil alternative and onshore 463 wind is 53%

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cheaper (IRENA, 2025b). Hydropower and geothermal also compare favorably. 464 However, the comparison is not uniformly favorable across all renewable technologies. Offshore

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wind, bioenergy, and CSP remain more expensive than coal on the 2024 global average, although offshore wind sits below the gas benchmark and can be attractive in strong-resource locations or where policy values firm decarbonization and local industrial content.

This variation appears in the supplementary checks. When all seven renewable technologies are compared with the mean fossil benchmark of USD 0.079/kWh, the renewable mean is lower at USD 0.0646/kWh, but the one-sample t-test does not reach the 5% level ($t = -1.72$, $p = 0.068$, one-tailed). That result is analytically useful because it prevents overstatement. It shows that the renewable cost lead is not universal across the entire technology set.

The sensitivity check is more revealing for current deployment realities. When the comparison is restricted to the mainstream renewables that dominate new global build-out, meaning solar PV, onshore wind, hydropower, and geothermal, the mean LCOE falls to USD 0.0485/kWh. Against the same fossil benchmark mean of USD 0.079/kWh, the one-sample t-test is clearly consistent with a lower renewable mean ($t = -5.01$, $p = 0.008$, one-tailed). In substantive terms, the mainstream renewable portfolio is about 39% cheaper than the representative fossil mean and about 34% cheaper than the coal benchmark. As with the emissions tests, these results are indicative checks on benchmark values rather than population inference; the descriptive gap carries the argument.

The distinction between mainstream renewables and all renewables matters. It avoids the error of claiming that every renewable technology outperforms every fossil technology in every market. That is not currently true. What is true is more strategically important: the renewable technologies that now drive most global capacity additions, solar PV and onshore wind above all, with hydro and geothermal in appropriate contexts, have become durable cost leaders. This is the part of the renewable sector that matters most for the present decade.

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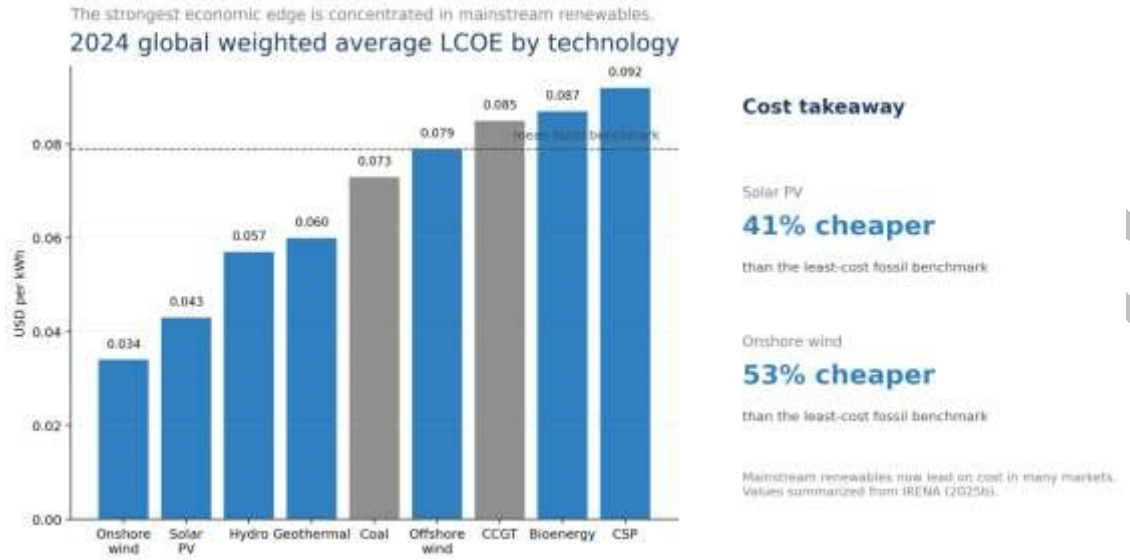


Figure 3. Relative cost position of mainstream renewables in 2024 global weighted average LCOE terms.

5.3 Beyond Generation Costs: System-Level Costs and the Limits of LCOE

The generation-cost comparison in Section 5.2 must be qualified before it can support policy conclusions, because LCOE has known limits as a standalone metric. Three limits matter most. First, LCOE ignores the timing and market value of output. Solar generation is concentrated in daylight hours, so as solar penetration rises, additional solar output arrives when prices are already depressed, a value-decline effect that plain LCOE cannot see (Joskow, 2011; Hirth et al., 2015). Second, LCOE excludes integration costs: short-term balancing, additional reserves, transmission and distribution reinforcement, and the reduced utilization of the residual thermal fleet (Ueckerdt et al., 2013). Third, LCOE says nothing about firmness. A power system needs dependable capacity through windless weeks and monsoon cloud cover, and the cost of providing that firmness belongs in any honest comparison (Sepulveda et al., 2018).

The empirical question is how large these system-level costs are. The systematic review evidence suggests three regularities (Heptonstall & Gross, 2021). Integration costs rise with the penetration of variable renewables. They are modest at low and moderate shares, typically small relative to the generation-cost gap documented in Section 5.2. And they depend heavily on system flexibility: grids with strong interconnection, demand response, flexible hydro, and storage absorb variable renewables far more cheaply than rigid, coal-heavy systems. The direction of technological change

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is also relevant. The 93% decline in battery storage costs since 2010 (IRENA, 2025b) directly attacks the balancing component of integration costs, and hybrid solar-plus-storage and wind-plus-storage projects internalize part of the integration burden within the project itself.

Two implications follow for this paper's argument. The first is a genuine concession: at very high renewable penetration, the relevant comparison is no longer technology LCOE versus technology LCOE but decarbonized system cost versus fossil system cost, and that comparison requires system modelling beyond the scope of a benchmark review. The second, however, protects the core conclusion. At the penetration levels that describe most of the world today, with renewables at 32% of global generation and far less in many national systems, the measured integration costs do not come close to erasing a 34–53% generation-cost advantage for mainstream renewables. The fossil comparison also has its own hidden costs that LCOE omits, including fuel-price risk, import exposure, and unpriced climate and health damages. The system-cost critique therefore disciplines the renewable case; it does not overturn it. What it changes is the location of the policy problem, which has shifted from generation technology to grids, storage, flexibility, and market design. Section 6 develops that point.

5.4 Energy Security, Employment, and Strategic Resilience

The renewable advantage is not exhausted by emissions and cost. A major non-price advantage is the change in risk exposure. Fossil power is structurally dependent on continuous fuel extraction, transport, and often imports. Coal logistics, liquefied natural gas contracts, pipeline disputes, refinery disruptions, and shipping bottlenecks all enter the delivered cost and security profile of fossil energy. Renewables front-load cost into equipment and construction, but their primary energy input is not purchased repeatedly in commodity markets. This means that highrenewable systems are typically less exposed to recurrent fuel-price shocks, even if they remain exposed to equipment, mineral, and financing risks.

IRENA estimates that renewables avoided USD 467 billion in fossil-fuel costs in 2024 alone (IRENA, 2025b). That figure reframes energy security. Avoided fuel expenditure is not just a climate dividend; it is a macroeconomic stabilization mechanism. In many importing economies, particularly after the energy-price volatility of recent years, domestic renewable generation has become a hedge against external fossil-market turbulence. This does not make renewables geopolitically frictionless, but it changes the structure of dependency in a favorable direction.

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Employment adds another strategic dimension. The renewable sector supported at least 16.6 million jobs worldwide in 2024 according to IRENA and the ILO (IRENA, 2026). These jobs are unevenly distributed, and automation is beginning to slow employment growth in some manufacturing segments, but the scale itself is a structural finding. A technology set that combines lower emissions, falling generation costs, and multi-million-job industrial ecosystems is no longer a niche environmental agenda. It becomes part of industrial development strategy, regional manufacturing policy, and labor-market planning.

Renewables also offer modularity and decentralization advantages that fossil generation often lacks. Solar PV can be deployed at utility scale, commercial rooftop scale, household scale, and in mini-grid or off-grid applications. Wind can be distributed across onshore and offshore geographies. Small hydro, biomass residues, and hybrid systems allow context-sensitive deployment. This modularity creates adaptation benefits in countries with weak grids, rural energy-access deficits, or fragmented geography. Fossil systems can also be distributed, but large-scale fossil generation has historically favored centralized infrastructure and long fuel chains.

5.5 Case Illustration: Floating Solar and the Expanding Renewable Advantage

The floating-solar case belongs in this paper for a precise analytical reason, not as an aside. The comparative framework developed above rests on four dimensions: emissions, cost, security, and adaptability. The fourth dimension is dynamic. If the constraints that limit renewable deployment are fixed, the renewable position documented in Sections 5.1–5.4 is a snapshot that could erode. If renewable innovation is actively relaxing those constraints while fossil technologies face a constraint, combustion emissions, that cannot be engineered away, then the gap between the two technology families should widen over time. Floating photovoltaics test exactly that proposition, on the constraint most often cited against solar energy: land.

India is particularly relevant here because the country faces rapid electricity demand growth, land-acquisition complexity, water-stress pressures, and strong solar resource endowments. Kumar's review from the Indian Institute of Technology Roorkee reports approximately 18,000 square kilometers of suitable water surface and a floating-solar potential of around 280 GW in India (Kumar, 2021). TERI's report similarly argues that FPV can function as a third pillar of solar deployment by exploiting reservoirs, lakes, and other water bodies rather than competing for scarce land (TERI, 2020).

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The Indian literature points to several reasons why floating solar strengthens the renewable position on each dimension of the framework. On adaptability, FPV is land neutral or at least land sparing, which for densely populated and agrarian regions is an institutional advantage over both ground-mounted solar and many conventional power projects. On cost, the thermal environment over water can improve module efficiency: TERI (2020) reports observed gains of up to about 10% in some studies, while Misra (2021) describes output improvements that may reach around 25% under favorable design and climatic conditions. These figures are contextspecific rather than universal, but they confirm the technological logic of module cooling and feed directly into the LCOE comparison of Section 5.2. On security and co-benefits, FPV can reduce water evaporation and can be co-located with reservoirs, including hydropower systems, which opens possibilities for hybrid renewable generation and eases the integration challenges discussed in Section 5.3.

The Indian literature also illustrates how renewable innovation can be tailored to local bottlenecks. Misra (2021) reports theoretical floating-solar potential across major Indian reservoirs and lists Gujarat's Sardar Sarovar among the promising water bodies. The significance is straightforward: renewable technology is no longer limited to generic wind farms or landbased solar parks. It is diversifying into forms that fit regional land, water, and infrastructure conditions more intelligently than the fossil-centered paradigm.

FPV is not without risks. Mooring, corrosion, water-body ecology, maintenance access, biodiversity concerns, higher upfront capital costs, and reservoir-use conflicts all matter. Yet as a case study it demonstrates the wider point that motivates its inclusion: the renewable sector is not static, and its position relative to fossil generation is being enlarged through ongoing technical adaptation. Fossil technologies can improve at the margin, but they do not solve the core problem that combustion-based electricity remains greenhouse-gas intensive. Renewable innovation, by contrast, often improves deployment while retaining low-carbon fundamentals. In terms of the paper's expectations, the FPV case is direct evidence for E4.

5.6 Greenhouse-Effect Counterfactual: What If Renewables Were Replaced by Fossil Power?

The technology-level comparisons can be connected more directly to the greenhouse effect through a portfolio counterfactual. The enhanced greenhouse effect is driven not by a single plant or a single year of emissions, but by the cumulative atmospheric stock that results when high-emissions

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energy systems remain dominant over time. To illustrate the aggregate relevance of current electricity choices, this paper constructs an indicative weighted-average life-cycle carbon intensity for the actual 2024 global electricity mix using Ember's reported shares for hydro, wind, solar, bioenergy and waste, coal, gas, other fossil generation, and nuclear, together with NREL's median life-cycle emissions estimates. The resulting illustrative portfolio intensity is approximately 485 gCO2e/kWh. This figure is not presented as an official global accounting estimate; it is a transparent analytical device that links the technology comparisons to the structure of the power mix.

A second scenario then asks what would happen if the renewable share of the 2024 electricity mix were counterfactually replaced by coal generation while all other shares remained unchanged. Under that simplifying assumption, the indicative portfolio intensity rises to roughly 796 gCO2e/kWh, an increase of about 64%. The point of the exercise is not to claim that coal is the only plausible substitute, or that real-world dispatch would behave in such a mechanical way. The point is that the existing renewable share is already suppressing the carbon intensity of the power sector at a system level. Renewables are not merely a future climate solution. They are a present-tense brake on greenhouse forcing relative to a plausible fossil-heavy baseline.

This counterfactual also clarifies why the greenhouse-effect argument should be framed in stockflow terms. The natural greenhouse effect makes life on Earth possible, but the enhanced greenhouse effect arises when annual emissions continue adding to atmospheric concentrations faster than natural sinks can absorb them. Electricity technologies that produce hundreds of grams of CO_2-equivalent per kilowatt-hour accelerate that accumulation; technologies that produce only a few tens of grams slow it dramatically. Because the power sector is deeply upstream of industrial production, building operations, mobility, digital infrastructure, and household welfare, the emissions profile of electricity has multiplier effects across the broader economy. Cleaner electricity lowers not only direct power-sector emissions but also the emissions attached to electrification pathways such as electric vehicles, heat pumps, green hydrogen production, and digitally managed public services.

The counterfactual is therefore conceptually important even though it is deliberately simple. It demonstrates that renewable deployment changes the greenhouse-effect trajectory through displacement. Every percentage point of generation shifted from coal and gas toward low-carbon sources reduces the rate at which anthropogenic greenhouse gases accumulate in the atmosphere.

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Since the climate system responds to cumulative concentrations rather than rhetorical commitments, displacement remains the central metric of seriousness in climate policy. On that metric, the renewable lead over fossil generation is not abstract. It is measurable, cumulative, and directly connected to the physics of radiative forcing.

6. Discussion: Why Renewable Energy Leads in the Current Period

The results support the proposition that renewable energy now leads fossil energy, but the strongest formulation of that claim must be carefully specified. The lead is decisive in life-cycle greenhouse-gas emissions, increasingly decisive in mainstream generation costs, strong in energy security and modularity, and important in employment and industrial development. It is less automatic in full-system cost, firm capacity provision, and institutional readiness, for the reasons developed in Section 5.3. Once stated this way, the contemporary energy transition becomes easier to understand: renewables win at the technology level more often than they fail, but systems and institutions have not yet fully caught up to the technologies.

The climate implication is especially strong. The greenhouse effect responds to atmospheric concentrations, which in turn depend on the cumulative flow of new greenhouse gases. Coal, oil, and gas based electricity add to that stock at far higher rates than renewable electricity. Because the fossil share of the global power system is still large, fossil energy continues to play a disproportionate role in reinforcing the enhanced greenhouse effect. Every percentage point of fossil generation displaced by low-lifecycle renewable generation therefore has a dual effect: it reduces current emissions and lowers future cumulative warming pressure. This is why the IEA's finding that clean technologies avoided roughly 2.6 Gt of additional annual CO2 emissions is so consequential. It shows that renewable expansion is already altering the trajectory of greenhousegas accumulation, even if not yet fast enough to reverse total global emissions growth.

The economic interpretation is equally significant. The old claim that climate action requires societies to choose between ecological responsibility and affordable electricity is increasingly untenable. For mainstream renewable technologies, the climate-optimal choice and the costeffective choice are converging. This does not mean that every renewable project is cheap or that electricity bills automatically fall as renewable shares rise. Network charges, storage, balancing, market design, and legacy asset costs can all complicate the pass-through to final consumers, and the system-cost literature reviewed in Section 5.3 explains why. But the

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generation-cost frontier has shifted. It is now often more accurate to say that fossil dependence is the expensive choice because it preserves fuel-price exposure, carbon intensity, and long-run lock-in.

The advantage is also institutional. Renewable energy aligns well with a world of digitalized grids, distributed assets, electrification of end uses, and modular infrastructure. Fossil systems were built around extractive supply chains, centralized thermal plants, and combustion. Renewable systems are built around equipment manufacturing, grid intelligence, storage, flexibility, and power electronics. The strategic implication is that countries that invest early in grids, storage, domestic manufacturing capacity, and clean-technology skills may secure advantages beyond climate mitigation alone. The renewable transition therefore intersects with industrial policy in ways that older environmental debates often underestimated.

That said, the limits must remain visible. High renewable shares require more than cheap solar panels and turbines. They require transmission expansion, distribution upgrading, short-duration and eventually long-duration storage, market reforms that reward flexibility, improved forecasting, demand response, interconnection, and social acceptance. The IEA's grid analysis shows that connection queues and under-investment in networks are already delaying renewable projects at scale (IEA, 2023). Financing costs remain a major barrier in lower-income and emerging markets. Renewable manufacturing is also geographically concentrated, creating exposure to trade disputes and supply-chain shocks. Finally, not every low-carbon technology is equally benign. Large hydro can have ecological and methane impacts; biomass can be unsustainable if feedstocks are poorly governed; and renewable build-out without recycling policy can create waste burdens.

These caveats do not weaken the main conclusion. They refine it. Renewable energy does not need to be perfect to lead fossil energy. It needs to be systematically better on the dimensions that matter most for the twenty-first century: greenhouse-gas intensity, long-run affordability, strategic resilience, and scalability under carbon constraints. The evidence assembled in this paper shows that it is.

6.1 From the Natural Greenhouse Effect to the Enhanced Greenhouse Effect

Because the title of this paper explicitly invokes the greenhouse effect, it is useful to distinguish the climatic mechanism from the policy conclusion. The greenhouse effect in its natural form is an atmospheric process in which gases such as water vapor, carbon dioxide, methane, and nitrous

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oxide trap part of the outgoing longwave radiation emitted by Earth's surface. Without this process, global average temperature would be far lower and contemporary ecosystems would not exist in their present form. The problem is not the greenhouse effect as such; the problem is its anthropogenic intensification. Since the industrial era, the combustion of coal, oil, and gas, together with land-use change and industrial processes, has raised atmospheric concentrations of key greenhouse gases and increased radiative forcing. The result is the enhanced greenhouse effect: a warming of the Earth system that manifests in rising temperatures, altered precipitation, more intense heat extremes, sea-level rise, ecosystem stress, and growing risks to food, water, health, and infrastructure.

Renewable energy matters to this process because the power sector sits at the center of modern carbon metabolism. Electricity is not only a final good consumed by households and firms; it is also an enabling input into nearly every other domain of development. If electricity is generated from high-carbon fuels, then growth in electrification can merely shift emissions from one sector to another. If electricity is generated from low-carbon sources, however, electrification becomes a decarbonization strategy rather than an accounting illusion. This distinction is essential in the present decade, when many countries are planning to expand electric mobility, cooling, digital services, desalination, manufacturing automation, and electric cooking at the same time that they are attempting to comply with climate goals. Renewable power therefore weakens the enhanced greenhouse effect through both direct substitution and indirect enabling effects.

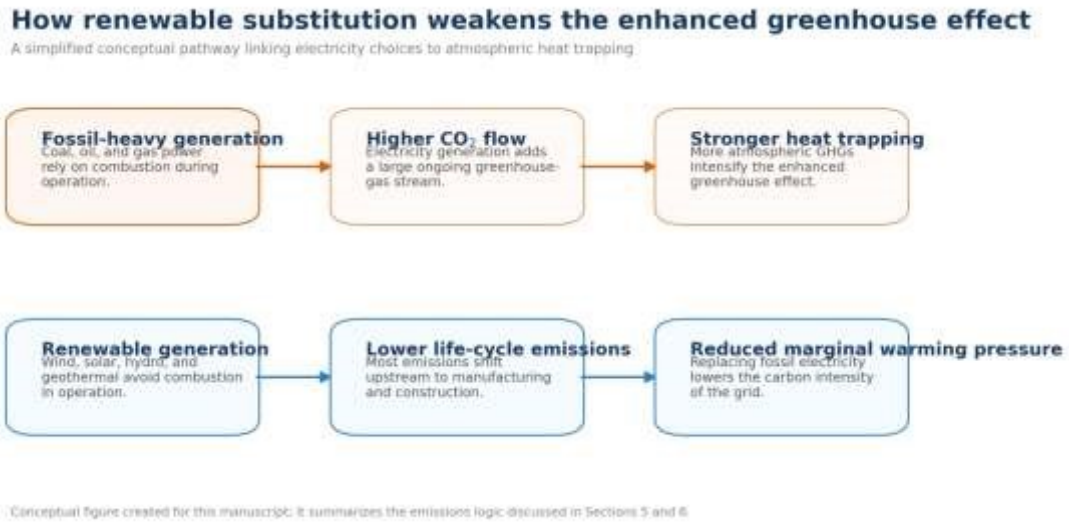


Figure 4. Conceptual pathway linking electricity choices to the enhanced greenhouse effect.

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The comparative results reported in this paper reinforce that mechanism. When median life-cycle emissions for renewable technologies are around 28 gCO2e/kWh and the fossil median is 840 gCO2e/kWh, the difference is not marginal. It is a categorical divergence in climatic consequence. Even the highest-emitting renewable option in the sample lies far below the fossil range. This means that the energy transition cannot be understood merely as a preference for cleaner branding or technological novelty. It is a change in the carbon intensity of the energy foundations of society. Once that point is recognized, renewable deployment acquires a significance beyond simple energy supply expansion: it becomes an intervention into the rate at which human activity amplifies the atmospheric blanket that is overheating the planet.

7. Policy Implications

Several policy implications follow from the analysis. First, electricity policy should shift from a narrow project-approval focus toward a system-enabling focus. In many jurisdictions, the cheapest generation technologies are already renewable, but the bottlenecks now lie in transmission access, interconnection queues, grid modernization, storage, flexibility procurement, and local permitting. A policy framework designed for centralized fossil plants is poorly matched to a high-renewable system. This follows directly from the system-cost analysis in Section 5.3: since integration costs are the residual weakness in the renewable case, integration infrastructure is the highest-value policy target.

Second, cost of capital has become a critical climate-policy variable. IRENA's cost analysis makes clear that financing conditions can erase otherwise strong technological advantages. Derisking instruments, public guarantees, concessional finance, blended finance, and stable auction design are therefore not peripheral financial tools; they are core decarbonization instruments, especially in the Global South.

Third, coal retirement strategy matters. Since coal remains the most emissions-intensive mainstream electricity source, replacing coal generation yields the largest greenhouse-effect benefit per unit of displacement. Policies that combine renewable build-out with planned coal phase-down, grid upgrades, worker transition packages, and local industrial alternatives will have the highest climate payoff.

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Fourth, innovation policy should support renewable forms that overcome local deployment barriers. Floating solar, hybrid renewable-plus-storage systems, agrivoltaics, distributed rooftop models, and digital demand-response platforms all represent ways to extend the renewable lead into land-constrained, water-stressed, or weak-grid environments. The Indian FPV literature is especially relevant for countries where land conflict is a major obstacle to solar expansion.

Fifth, renewable policy must be linked to material governance and circularity. A successful renewable transition cannot simply replace fossil extraction with unmanaged mining for lithium, cobalt, rare earths, copper, and other critical materials. Recycling, design-for-repair, supplychain transparency, local value addition, and environmental standards are essential if the renewable advantage is to remain durable and ethically credible.

7.1 Implications for Developing Economies and the Indian Energy Transition

The renewable advantage is particularly salient for developing economies, where three constraints often coincide: rapidly growing electricity demand, sensitivity to imported fuel prices, and limited fiscal space for locking in expensive long-lived infrastructure. In such contexts, the renewable transition is not merely an environmental aspiration; it is a development strategy. Fossil-fuel dependence exposes governments and utilities to exchange-rate risk, freight volatility, global commodity shocks, and geopolitical disruption. Renewable energy reduces part of that vulnerability because sunlight, wind, and many hydro resources are domestic rather than imported. The fuel-free operating model of renewables can also improve long-run planning by replacing volatile fuel expenditure with more predictable capital recovery profiles. For states struggling to extend reliable power access while also meeting climate obligations, that shift has substantial macroeconomic significance.

India offers a particularly relevant case. It is one of the world's largest electricity systems and simultaneously one of the most important arenas for future renewable expansion. Earlier Indian floating-solar and renewable-transition literature already recognized the pressure created by rising electricity demand, land constraints, and fossil dependence. The IIT Roorkee lecture by Arun Kumar estimated India's floating solar potential at approximately 280 GW across around 18,000 square kilometres of water surface, while TERI's floating-solar analysis emphasized that deployment on reservoirs can reduce land conflict and in some settings raise energy yield through cooling effects. Misra's India-focused review further argued that floating photovoltaic systems

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may deliver water-conservation benefits alongside electricity generation and identified large reservoir opportunities across multiple states. These findings remain strategically relevant because they show that the renewable lead in a populous country is not confined to ordinary land-based wind and solar projects; it can be widened through innovations tailored to local resource constraints.

For Indian energy policy, this has at least four implications. First, renewable expansion should be planned as a portfolio rather than as a single-technology race. Utility-scale solar, wind, rooftop solar, hydro, storage, demand response, and floating solar each solve different parts of the decarbonization problem. Second, transmission planning must run ahead of generation additions. India's strongest renewable resources are unevenly distributed geographically, so grid investment is indispensable if low-cost renewable power is to displace coal at scale rather than simply add new capacity on top of existing fossil dependence. Third, concessional finance and risk reduction remain crucial, because the cost advantage of renewables can be weakened by high interest rates, delayed payments, and contractual uncertainty. Fourth, domestic manufacturing and circularity policy should be integrated with energy policy so that solar modules, inverters, batteries, and grid equipment are supported across their life cycle, including recycling and end-of-life management. The relevance of floating solar deserves special mention in this context. Land acquisition is among the most persistent barriers to utility-scale solar deployment in densely used regions.

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799 Floating systems partially relax that constraint by shifting part of the generation build-out to 800 reservoirs, lakes, and industrial water bodies. The literature cited in this paper notes several
801 ancillary benefits, including land neutrality, reduced water evaporation, and in some cases 802 improved panel performance due to lower operating temperatures. In a water-stressed and land803 constrained development setting, these co-benefits matter. They suggest that the renewable lead 804 over fossil generation can be widened through project design choices that simultaneously address 805 climate mitigation, land use, and water management. The Indian case therefore illustrates an 806 important general principle: renewable superiority is not static, but can be amplified when 807 deployment models are adapted intelligently to local ecological and institutional conditions.



808
809 Figure 5. Floating solar as an India-relevant extension of the renewable advantage discussed in 810 the manuscript.

811
812 More broadly, developing economies should resist the false binary between growth and
813 decarbonization. The evidence assembled here indicates that, when viewed through the lenses of
814 climate damage, operating economics, and strategic autonomy, renewable power increasingly
815 serves all three objectives at once. The challenge is implementation capacity rather than

conceptual viability. Countries that build bankable procurement systems, strengthen grids, invest in technical skills, and maintain transparent regulation are likely to capture not only emissions reductions but also industrial learning, job creation, and reduced exposure to fossil-price shocks. Those that delay may find themselves locked into high-carbon assets just as the global cost curve and regulatory environment shift decisively in favor of low-carbon electricity.

8. Limitations and Future Research

This paper is intentionally bounded. It uses benchmark technology data rather than a full country panel and therefore cannot capture the complete interaction among renewable penetration, curtailment, wholesale prices, grid congestion, and national regulatory design. Its comparative samples are small and purposive, which is why the statistical results are presented as supplementary checks on descriptive benchmark gaps rather than as inferential findings about a population of technologies. The cost comparison focuses on generation LCOE, with system-level costs treated through a structured review of the literature rather than through original system modelling. Future research could extend the present work in three directions: first, by building a country-level panel linking renewable electricity share to carbon intensity and power-sector emissions, which would also permit properly specified inferential testing; second, by integrating storage-adjusted and transmission-adjusted system costs into the cost comparison; and third, by testing sector-specific transition pathways in electricity, transport, and industry rather than in electricity alone.

A second avenue for research involves justice and distribution. Renewable energy may be economically advantageous in aggregate while still producing regional losers, stranded assets, or labor dislocation in fossil-dependent regions. Future work should therefore connect the comparative position of renewables with just-transition policy, public compensation, and regional development planning.

9. Conclusion

The evidence assembled in this paper supports a clear conclusion: renewable energy now holds a real and measurable advantage over fossil energy. That advantage is strongest in life-cycle greenhouse-gas emissions, where renewable technologies are dramatically less carbon intensive

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than coal, oil, and gas. It is increasingly strong in generation economics, where mainstream renewables now outperform representative fossil benchmarks, and it survives, in qualified form, the system-cost critique of LCOE-based comparisons. It is reinforced by strategic advantages in energy security, modularity, job creation, and technological adaptability, and it is being actively widened by innovations such as floating solar that relax the constraints on renewable deployment. Most importantly, renewable deployment matters directly for the greenhouse effect. The contemporary electricity transition is reducing the carbon intensity of power generation and constraining what would otherwise be even higher annual emissions. The world's climate problem is not solved, because fossil fuels still hold large shares in the global power mix and overall energy-related CO2 emissions remain at record levels. But the direction of comparative advantage has changed. Renewable energy is no longer merely the cleaner option; in many cases it is the more rational option economically and strategically as well.

The policy question, therefore, has shifted. It is not whether renewable energy can compete with fossil energy. It already does. The central task now is to build the grids, storage systems, financing structures, regulatory frameworks, and transition institutions required to translate that advantage into faster decarbonization and a weaker enhanced greenhouse effect over time.

Tables and Figures

The following tables and figures summarize the main quantitative evidence used in the comparative analysis. All emissions values are median harmonized life-cycle estimates from NREL (2021); all cost values are 2024 global weighted average LCOEs from IRENA (2025b) unless stated otherwise.

Table 1. Key global facts and figures relevant to the renewable-versus-fossil comparison

Indicator	**Value**	**Why it matters**	**Source**
Renewable capacity added in 2024	585 GW	Shows that renewables have become the dominant source of new power capacity	IRENA 2025a
Share of total powercapacity expansion	92.5%	Indicates that the global expansion path is overwhelmingly renewable	IRENA 2025a

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Indicator	Value	Why it matters	Source
Renewables share of global electricity	32%	Shows that renewables are now a central rather than marginal part of power supply	Ember 2025
Clean electricity share (renewables + nuclear)	40.9%	Signals a structural turning point in global electricity generation	Ember 2025
Global energy-related CO2 emissions in 2024	37.8 Gt	Demonstrates that transition progress is real but still insufficient	IEA 2025a
Solar PV global weighted average LCOE, 2024	USD 0.043/kWh	Solar now undercuts new fossil alternatives in most markets	IRENA 2025b
Onshore wind global weighted average LCOE, 2024	USD 0.034/kWh	Onshore wind remains the cheapest mainstream new power source	IRENA 2025b
Utility-scale battery storage cost, 2024	USD 192/kWh	Lower storage cost improves renewable system integration	IRENA 2025b
Renewable energy jobs in 2024	16.6 million	Shows broad economic and labor-market relevance of the transition	IRENA 2026

Figure 3. Global electricity mix in 2024

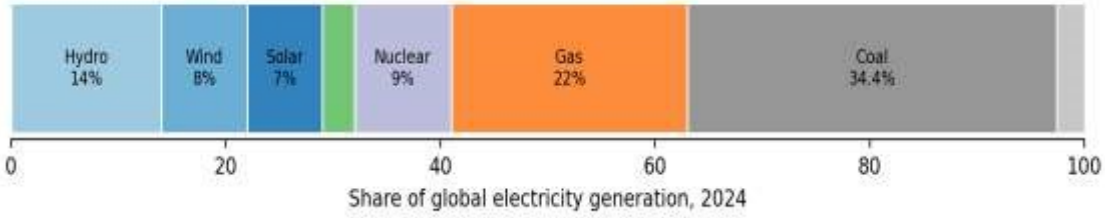


Figure 6. Global electricity mix in 2024. Source: constructed from Ember (2025) and IEA (2025b).

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886 Table 2. Comparative technology benchmarks for emissions and cost

Technology	Category	Life-cycle emissions, median (gCO_2e/kWh)	2024 global weighted average LCOE (USD/kWh)
Coal	Fossil	1001	0.073
Oil	Fossil	840	n.a.
Natural gas	Fossil	486	0.085 (CCGT)
Biomass	Renewable	52	0.087
Solar PV	Renewable	43	0.043
CSP	Renewable	28	0.092
Geothermal	Renewable	37	0.060
Hydropower	Renewable	21	0.057
Ocean	Renewable	8	n.a.
Wind	Renewable	13	0.034 (onshore)

887 Emissions source: NREL (2021), median harmonized estimates. LCOE source: IRENA (2025b),
888 global weighted averages.

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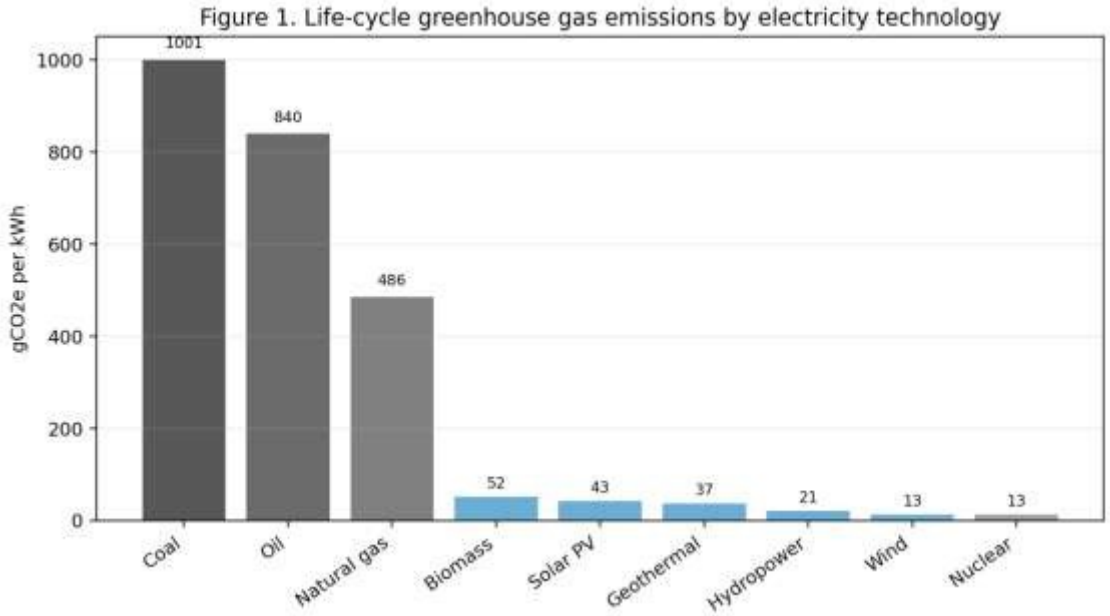


Figure 7. Life-cycle greenhouse gas emissions by electricity technology (median harmonized estimates). Source: plotted from NREL (2021).

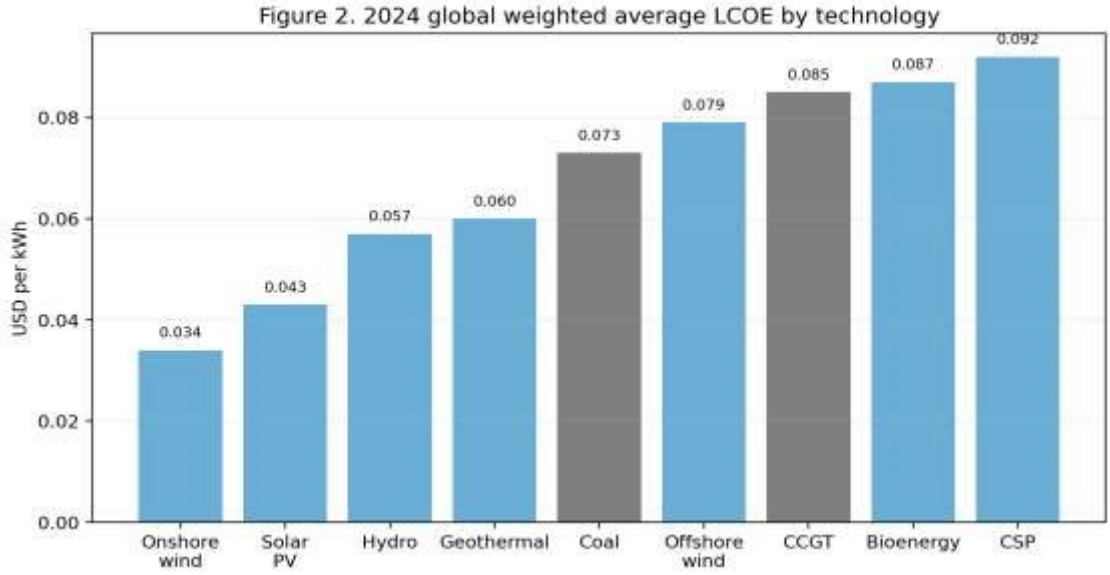


Figure 8. 2024 global weighted average LCOE by technology. Source: plotted from IRENA (2025b).

Table 3. Supplementary statistical checks (indicative; see Section 3)

Check	Sample compared	Statistic	pvalue	Interpretation

Welch t-test	Renewable vs fossil lifecycle emissions	t = -4.91	0.039	Consistent with a substantially lower renewable mean
Mann-Whitney U	Renewable vs fossil lifecycle emissions	U = 0.00	0.017	Complete separation of the two groups; robust to non-normality
Effect size	Renewable vs fossil lifecycle emissions	g = -5.09	n.a.	Very large substantive difference
One-sample t-test	All renewable LCOEs vs fossil mean benchmark	t = -1.72	0.068	Lower mean, but the gap is not uniform across technologies
One-sample t-test	Mainstream renewables vs fossil mean benchmark	t = -5.01	0.008	Mainstream renewables clearly cheaper on benchmark values

Note: these checks are reported as robustness support for the descriptive benchmark comparison, not as population inference; the samples are small and purposive. The illustrative 2024 global portfolio model gives approximately 485 gCO2e/kWh for the actual mix and 796 gCO_2e/kWh if the 32% renewable share were replaced by coal.

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