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Green Energy Sources and Their Effects on the Environment: A Critical Review of Recent Advances, Environmental Impacts, and Future Perspectives

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ABSTRACT

Background. The simultaneous escalation of energy demand and climate disruption has made the transition from fossil to green energy one of the defining scientific and policy challenges of the twenty-first century. Global energy-related carbon dioxide emissions reached an all-time high of 37.8 Gt in 2024, yet renewable power capacity additions also set successive records, with 692 GW added in 2025 to reach a cumulative 5,149 GW. Understanding whether and under what conditions green energy delivers net environmental benefit is therefore urgent.

Objective. This review critically synthesises the recent (2022–2026) literature on the principal green energy sources solar, wind, hydropower, biomass, geothermal, ocean, and green hydrogen, together with emerging technologies and evaluates their full environmental footprint rather than their carbon benefits alone.

Methodology. A structured search of Scopus, Web of Science, ScienceDirect, SpringerLink, and IEEE Xplore was combined with authoritative grey literature from the IEA, IRENA, IPCC, and UNEP. Records were screened following the PRISMA 2020 framework, and a bibliometric analysis characterised publication and thematic trends across the review window.

Major findings. Across life-cycle metrics, wind and solar photovoltaics consistently emerge as the lowest-impact sources, with life-cycle carbon intensities roughly one to two orders of magnitude below those of fossil generation and energy payback times now below two years. However, every source carries non-trivial and frequently overlooked burdens land-use and habitat change, water consumption, critical-material demand, biodiversity disturbance, and end-of-life waste that are unevenly distributed across technologies and geographies. The review identifies persistent controversies, including the climate footprint of hydropower reservoirs, the carbon neutrality of biomass, and the material and recycling bottlenecks of the solar–storage–hydrogen value chain.

Research gaps. Key gaps include regionally disaggregated and harmonised life-cycle assessments, integrated water–energy–land nexus modelling, biodiversity-explicit

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impact metrics, and credible circular-economy pathways for end-of-life renewable infrastructure.

Future prospects. Realising a genuinely sustainable energy system will require co-optimising decarbonisation with biodiversity, water security, material circularity, and social equity, supported by artificial-intelligence-enabled system integration, robust storage, and policy frameworks that internalise full life-cycle externalities.

Keywords: renewable energy; environmental impact; life-cycle assessment; energy transition; sustainability; green hydrogen; decarbonisation; circular economy

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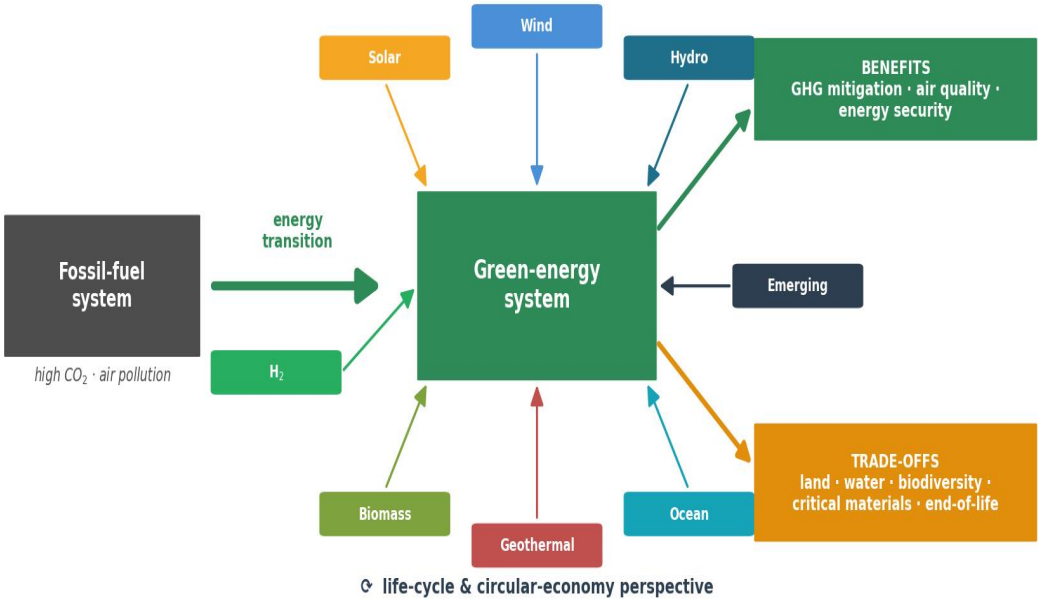

Key message: renewables cut carbon by 1–2 orders of magnitude, but net sustainability depends on the whole life cycle, not operation alone.

1. INTRODUCTION

1.1 The global energy crisis and climate change

Energy underpins every dimension of human development, yet the dominant means of supplying it remains fundamentally incompatible with planetary stability. In 2024, total energy-related carbon dioxide (CO_2) emissions rose by 0.8% to an all-time high of 37.8 Gt, a trajectory that pushed atmospheric CO_2 concentrations to a record 422.5 ppm approximately 50% above pre-industrial levels (IEA, 2025a). When all greenhouse gases (GHGs) are considered, global anthropogenic emissions reached an estimated 53.2 Gt CO_2-equivalent in 2024 (European Commission, JRC, 2025). These figures are not abstract: the Sixth Assessment Report of the Intergovernmental Panel on Climate Change concluded that human influence has unequivocally warmed the climate, that the remaining carbon budget for limiting warming to 1.5 °C is small and rapidly depleting, and that deep, immediate, and sustained emission reductions are required across all sectors (IPCC, 2023).

The scale of the challenge is compounded by the structure of energy demand. Global

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energy demand grew by 2.2% in 2024 well above the 1.3% average of the previous decade and global electricity consumption rose by roughly 1,100 TWh (+4.3%), the largest increase ever recorded outside of post-recession rebounds (IEA, 2025a). This surge was driven by record temperatures and cooling demand, electrification of transport and heat, industrial expansion, and the rapid growth of data centres. Crucially, energy demand is rising fastest in emerging and developing economies, which accounted for more than 80% of the 2024 increase, meaning that the transition must reconcile decarbonisation with legitimate development and energy-access imperatives (IEA, 2025a; UNEP, 2024).

The mismatch between current trajectories and climate goals is stark. Under prevailing policies, long-term warming is now projected at around 3.1 °C, and the latest assessments accept that temporarily exceeding 1.5 °C has become effectively unavoidable, implying some reliance on carbon-dioxide removal to return warming below that threshold later in the century (IEA, 2025b; UNEP, 2024). The energy transition is therefore not merely desirable but existential, and its pace over the next decade will largely determine the magnitude of overshoot.

1.2 Environmental concerns associated with conventional energy

The case against fossil energy extends well beyond climate. Combustion of coal, oil, and natural gas is the principal anthropogenic source of CO_2, but it also releases sulphur and nitrogen oxides, fine particulate matter, mercury, and volatile organic compounds that impose an enormous burden of premature mortality and morbidity, with ambient air pollution implicated in millions of deaths annually [REF]. In the 2024 global power mix, coal alone still generated about 35% of electricity and natural gas more than 20%, so the externalities of fossil generation remain dominant even as clean sources expand (IEA, 2025a). Upstream activities mining, drilling, hydraulic fracturing, transport, and refining additionally drive land degradation, water contamination, fugitive methane emissions, oil spills, and ecosystem fragmentation. These impacts are frequently borne disproportionately by vulnerable communities, giving the transition an irreducible justice dimension.

1.3 The need for a green energy transition

Against this backdrop, the deployment of green energy has accelerated to historically unprecedented rates. The world added 692 GW of renewable power capacity in 2025 a 15.5% annual increase and the largest on record bringing cumulative renewable capacity to 5,149 GW; renewables accounted for 85.6% of all new capacity additions (IRENA, 2026). For the first time, renewables and nuclear together supplied 40% of global electricity generation in 2024, with renewables alone providing roughly one-third hydropower 14%, wind 8%, solar photovoltaics (PV) 7%, and bioenergy and waste 3% (IEA, 2025a). Solar and wind dominate the expansion, jointly representing 96.8% of net renewable additions in 2025 (IRENA, 2026). This momentum is reinforced by economics: in 2024, 91% of newly commissioned utility-scale renewable capacity delivered electricity more cheaply than the least-cost fossil alternative, and renewables are estimated to have avoided around USD 467 billion in fossil-fuel costs (IRENA, 2025b).

Yet record deployment has not yet bent the global emissions curve, which reflects

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three uncomfortable realities. First, renewables are still being added on top of, rather than in place of, fossil capacity in many systems; non-renewable additions nearly doubled in 2025 relative to 2024, driven largely by coal in China (IRENA, 2026). Second, deployment remains geographically concentrated: China, the United States, and the European Union accounted for the large majority of 2025 additions, while Africa — despite its record 15.9% growth — held just 82 GW of capacity, and small island developing states 0.2% of the global total (IRENA, 2026). Third, the world is not on track for the COP28 goal of tripling renewable capacity to more than 11 TW by 2030; on current trends, capacity would reach roughly 8 TW, a shortfall of nearly 28% (IRENA, 2025a). This paradox of record growth alongside record emissions is summarised in Figure 1.

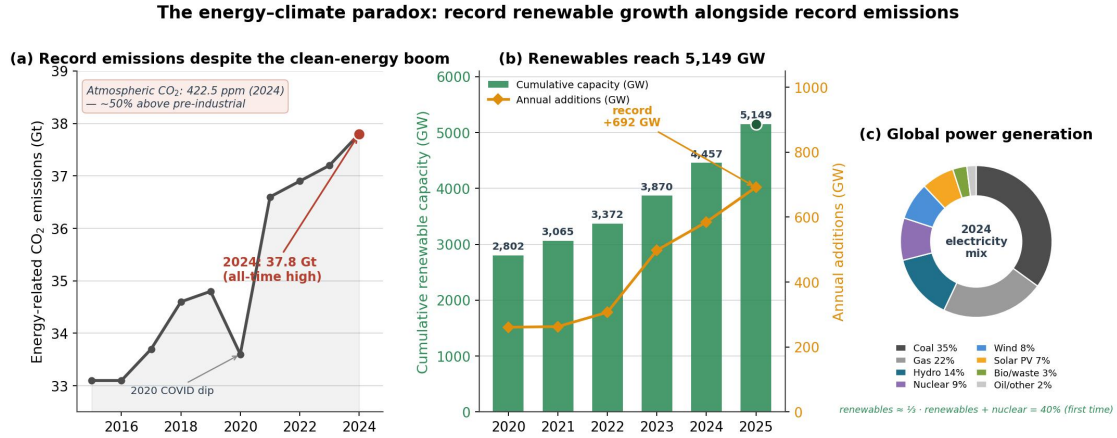

Figure 1. The energy–climate paradox. (a) Energy-related CO_2 emissions reached a record 37.8 Gt in 2024, with atmospheric CO_2 at 422.5 ppm; (b) cumulative renewable capacity reached 5,149 GW after a record 692 GW addition in 2025; (c) the 2024 global electricity mix. Data: IEA (2025a); IRENA (2026).

1.4 The often-overlooked environmental costs of green energy

The central premise of this review is that the environmental evaluation of green energy must move beyond a binary "clean versus dirty" framing. While renewables decisively outperform fossil fuels on climate and air quality, they are not environmentally neutral. Their impacts are simply different in kind and distribution: they are typically front-loaded in the manufacturing and construction phases, embodied in materials and land rather than in operational emissions, and concentrated around mineral extraction, habitat modification, water use, and end-of-life waste. As deployment scales toward the terawatt frontier, these burdens grow in absolute terms and can become locally or regionally significant. A credible sustainability assessment therefore requires a life-cycle perspective, attention to the water–energy–land–materials nexus, and explicit treatment of biodiversity and social equity dimensions that remain unevenly addressed in the literature.

1.5 Novelty, objectives, and scope of this review

A substantial body of recent reviews addresses individual green energy technologies, and several survey renewable energy economics or climate mitigation potential. Comparatively fewer integrate, within a single critical synthesis, (i) the most recent

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(2022–2026) technological and cost developments across all major green sources; (ii) a systematic, comparative treatment of their full environmental footprint, including the negative and contested impacts; and (iii) an explicit identification of controversies, knowledge gaps, and research priorities. This review addresses that gap. Its specific objectives are:

1. To classify and critically characterise the principal green energy sources, including their operating principles, current global status, and most recent technological and efficiency advances (2022–2026).
2. To critically analyse both the beneficial and adverse environmental effects of each source, spanning GHG mitigation, biodiversity, land and water use, soil, noise and visual impacts, resource depletion, and life-cycle burdens.
3. To compare the major sources through life-cycle assessment (LCA) and techno-economic and environmental metrics, including a critical comparison matrix.
4. To synthesise recent innovations — artificial intelligence (AI), smart grids, storage, the hydrogen economy, carbon-capture integration, circular-economy approaches, and hybrid and net-zero systems — and the challenges that constrain them.
5. To articulate the principal research gaps and to offer technological, policy, and environmental-management recommendations and research priorities for the coming decade.

The scope is deliberately cross-cutting and global, with an emphasis on peer-reviewed literature and authoritative agency data published between 2022 and 2026. The review adopts a critical rather than descriptive stance throughout: each section foregrounds tensions, uncertainties, and trade-offs rather than cataloguing established facts.

2. Literature search methodology

2.1 Overall design

This review follows a structured, reproducible search and screening protocol aligned with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement, adapted for a critical narrative review. The protocol combined a systematic database search for peer-reviewed primary and review literature with the targeted incorporation of authoritative grey literature (IEA, IRENA, IPCC, and UNEP reports) for global statistics and policy context. The search was restricted to the period January 2022–2026 to capture the most recent advances, with seminal earlier works admitted only where required for conceptual grounding.

2.2 Databases and search strings

Five bibliographic databases were searched: Scopus, Web of Science Core Collection, ScienceDirect, SpringerLink, and IEEE Xplore. The search combined controlled and free-text terms across three conceptual blocks — energy source, environmental dimension, and assessment approach — using Boolean operators, truncation, and

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field tags (title/abstract/keywords). Representative search strings are summarised in Table 1; the master string had the form:
("renewable energy" OR "green energy" OR "clean energy" OR solar OR photovoltaic OR wind OR hydropower OR biomass OR bioenergy OR geothermal OR "ocean energy" OR "tidal energy" OR "wave energy" OR "green hydrogen") AND ("environmental impact*" OR "life cycle assessment" OR "carbon footprint" OR biodiversity OR "land use" OR "water footprint" OR ecotoxicity OR sustainability) AND (2022:2026[Year])

Table 1. Conceptual search blocks and representative terms combined with the Boolean operators AND/OR and truncation (*).

Conceptual block	Representative controlled and free-text terms
Block 1 — Energy source	"renewable energy" OR "green energy" OR "clean energy" OR solar OR photovoltaic OR "solar PV" OR CSP OR wind OR "offshore wind" OR hydropower OR "run-of-river" OR biomass OR bioenergy OR biofuel OR geothermal OR EGS OR "ocean energy" OR "tidal energy" OR "wave energy" OR OTEC OR "green hydrogen" OR electroly*er
Block 2 — Environmental / sustainability dimension	"environmental impact*" OR "life cycle assessment" OR LCA OR "carbon footprint" OR "greenhouse gas" OR biodiversity OR "land use" OR "land-use change" OR "water footprint" OR "water consumption" OR ecotoxicity OR "soil degradation" OR noise OR "visual impact" OR sustainability OR "circular economy"
Block 3 — Assessment / outcome approach	review OR "systematic review" OR "techno-economic" OR LCOE OR efficiency OR "energy payback" OR EROI OR "critical materials" OR recycling OR "grid integration" OR storage OR "machine learning" OR policy
Combination	(Block 1) AND (Block 2) AND (Block 3 where narrowing was required), restricted to 2022–2026, English, document type = article/review/agency report

2.3 Inclusion and exclusion criteria

Inclusion criteria were: (i) peer-reviewed journal articles, authoritative agency reports, or high-quality conference papers; (ii) publication between 2022 and 2026;

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(iii) English language; (iv) substantive treatment of at least one green energy source and at least one environmental or sustainability dimension. Exclusion criteria were: (i) editorials, opinion pieces, and non-peer-reviewed preprints without verifiable data; (ii) studies addressing only fossil or nuclear energy; (iii) duplicate records; (iv) studies without extractable environmental, technological, or economic outcomes; and (v) predatory or non-indexed sources. Where feasible, priority was given to articles published in Q1 journals (e.g., *Renewable and Sustainable Energy Reviews*, *Renewable Energy*, *Energy Conversion and Management*, *Journal of Cleaner Production*, *Applied Energy*, *Nature Energy*) to maintain evidential quality.

2.4 PRISMA flow

The screening process is depicted in Figure 2 and quantified illustratively in Table 2. Records identified through database searching and grey-literature sources were de-duplicated, screened by title and abstract against the eligibility criteria, and assessed in full text, with the final corpus retained for qualitative synthesis. (The numerical values in Table 2 are presented as a template; authors should replace them with the exact counts returned by their own searches before submission.)

Table 2. PRISMA 2020 record-flow template (illustrative counts; to be replaced with the authors' executed-search values).

PRISMA stage	Action	Records (template)
Identification	Records identified from Scopus	n_1
Identification	Records identified from Web of Science	n_2
Identification	Records identified from ScienceDirect, SpringerLink, IEEE Xplore	n_3
Identification	Additional records from grey literature (IEA, IRENA, IPCC, UNEP)	n_4
Identification	Duplicates removed before screening	$-d$
Screening	Records screened by title/abstract	N_screen
Screening	Records excluded at screening (off-topic, wrong scope)	$-e_1$
Eligibility	Full-text articles assessed for eligibility	N_fulltext
Eligibility	Full-text articles excluded with reasons (no extractable outcome; not	$-e_2$

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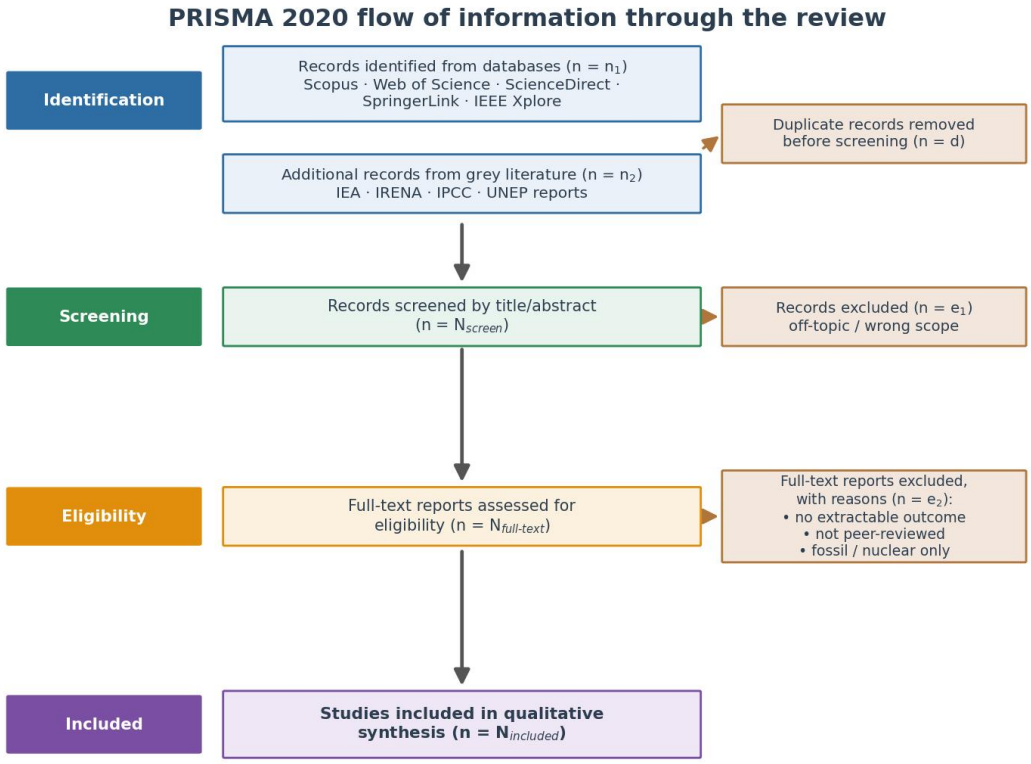
PRISMA stage	Action	Records (template)
	peer-reviewed; fossil/nuclear only)	
Included	Studies included in qualitative synthesis	N_included



Counts shown as a template (n_1, n_2, …); replace with values from the executed search (see Table 2).

Figure 2. PRISMA 2020 flow of the literature identification, screening, eligibility, and inclusion process. Counts are shown as a template (n_1, n_2, …) to be replaced with values from the executed search (Table 2).

2.5 Bibliometric analysis approach

To characterise the structure and dynamics of the field, a bibliometric analysis was conducted on the metadata (titles, abstracts, keywords, authors, affiliations, citations) of the retrieved Scopus and Web of Science records. Annual publication counts were used to quantify growth, and keyword co-occurrence and bibliographic coupling networks were constructed using VOSviewer to identify dominant research clusters and emerging themes. The intended outputs are: (i) a publication-trend curve for 2022–2026; (ii) a keyword co-occurrence map distinguishing technology-, impact-, and policy-oriented clusters; and (iii) an analysis of the most productive countries, institutions, and source journals. Section 7.1 and Figure 3 summarise the qualitative findings; the underlying counts should be generated by the authors from a frozen query executed on a single date to ensure reproducibility.

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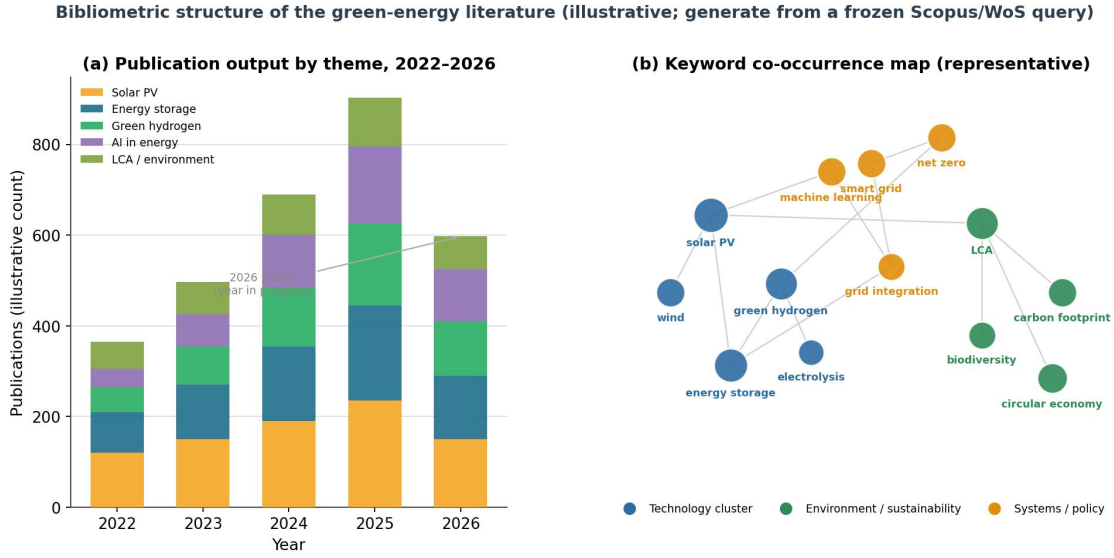

Figure 3. Bibliometric structure of the green-energy literature: (a) publication output by theme, 2022–2026; (b) a representative keyword co-occurrence map showing technology, environment/sustainability, and systems/policy clusters. Values are illustrative and should be regenerated from a frozen Scopus/Web of Science query.

3. Classification of green energy sources

Green energy sources can be classified by primary resource (solar, kinetic, gravitational/hydraulic, geothermal, and chemical/biological) and by maturity, from fully commercial technologies (hydropower, onshore wind, solar PV) to those at demonstration or early-commercial stages (ocean energy, green hydrogen, several emerging concepts). Table 3 summarises the current global capacity and recent additions of the principal renewable sources, and Table 4 maps each source to its operating principle, indicative technology readiness level (TRL), typical capacity factor, and commercial status. Table 5 reports current (2024) levelised cost of electricity (LCOE) and total installed costs, and Figure 5 traces their decline since 2010. The subsections that follow treat each source critically, emphasising recent (2022–2026) advances and the tensions between performance, cost, and environmental footprint; the overall taxonomy is shown in Figure 4.

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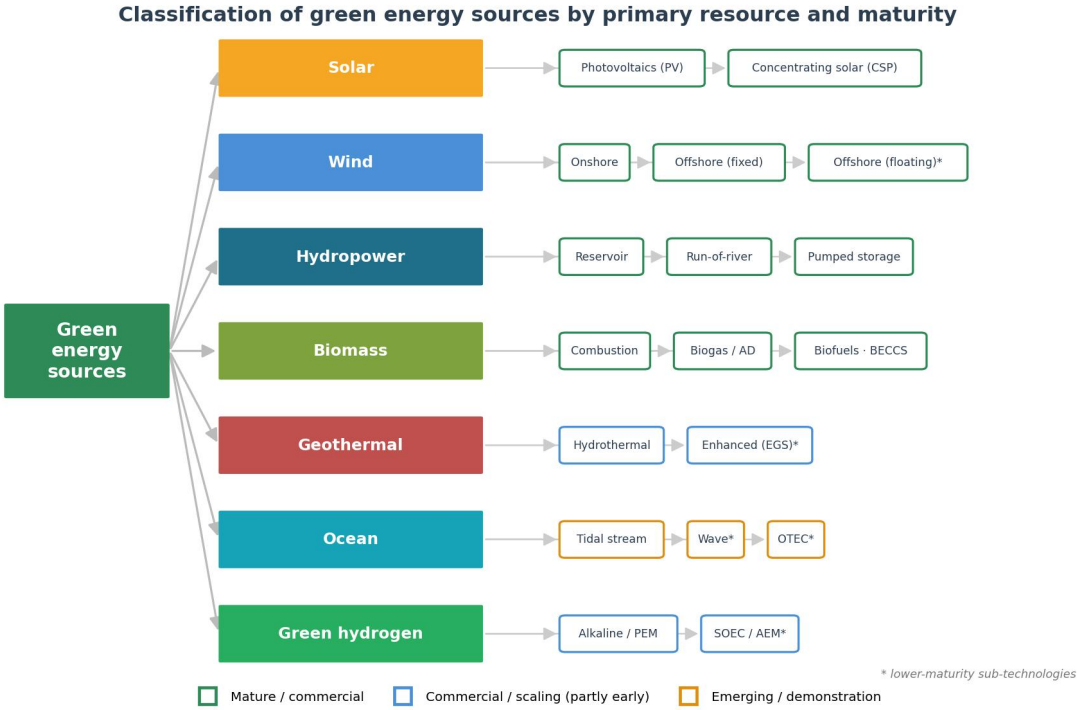

Figure 4. Classification of green energy sources by primary resource and maturity, with representative sub-technologies colour-coded by technology-readiness level.

Table 3. Global installed renewable power capacity and recent annual additions by technology (year-end values).

Technology	Cumulative capacity, end-2024	2025 net additions	2025 growth rate	Share of 2025 renewable additions
Solar PV	~1,865 GW	+510.3 GW	+27.2%	~74%
Wind (on + offshore)	~1,133 GW	+158.7 GW	+14.0%	~23%
Hydropower (excl. pumped storage)	~1,283 GW	+18.4 GW	+1.4%	~2.7%
Bioenergy	~150 GW	+3.4 GW	~+2%	~0.5%
Geothermal	~15 GW	+0.3 GW	+1.7%	~0.04%
Marine / ocean	~0.5 GW	<0.1 GW	low	<0.1%
Total renewables	**~4,457 GW**	**+692 GW**	**+15.5%**	**100%**

Source: compiled from IRENA (2026) and IRENA (2025a). Cumulative values are approximate and subject to annual revision; pure pumped-storage hydropower (~160 GW) is excluded from renewable totals. Per-technology end-2024 splits are indicative.

Table 4. Classification, operating principle, and maturity of the principal green energy sources.

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Source	Primary resource	Core conversion principle	Indicative TRL	Typical capacity factor	Commercial status
Solar PV	Solar radiation	Photovoltaic effect (semiconductor)	9 (c-Si); 7–8 (perovskite/tandem)	10–25%	Mature, fastest-growing
Concentrating solar power (CSP)	Direct solar radiation	Thermal concentration → steam cycle	8–9	25–45% (with storage)	Commercial, niche
Wind (onshore)	Wind kinetic energy	Aerodynamic lift → generator	9	25–45%	Mature
Wind (offshore, fixed)	Wind kinetic energy	Aerodynamic lift → generator	8–9	40–55%	Commercial, scaling
Wind (offshore, floating)	Wind kinetic energy	Aerodynamic lift → generator	6–7	45–60%	Demonstration/early
Hydropower	Hydraulic head/flow	Hydraulic turbine	9	30–60%	Mature
Biomass/bioenergy	Biological carbon	Combustion, gasification, AD, biofuels	8–9	50–80%	Mature, contested
Geothermal	Earth heat	Steam/binary cycle; EGS	9 (hydrothermal); 4–6 (EGS)	70–90%	Mature (site-limited)
Ocean (tidal stream)	Tidal currents	Underwater turbine	7–8	30–40%	Early commercial
Ocean (wave)	Wave energy	Oscillating/overtopping devices	5–7	20–35%	Demonstration
Green hydrogen	Renewable electricity	Water electrolysis	7–9 (alkaline/PEM stacks)	n/a (energy carrier)	Early commercial

AD = anaerobic digestion; EGS = enhanced geothermal systems; TRL = technology readiness level (1–9).

3.1 Solar energy

Principle and technology. Solar energy is harvested either photovoltaically — through the direct conversion of photons to electricity in semiconductors — or thermally, by concentrating direct radiation to drive a heat engine (CSP). Crystalline silicon (c-Si) dominates the PV market (>95% of modules), while thin-film (CdTe,

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CIGS) and, increasingly, perovskite and perovskite/silicon tandem architectures define the research and early-commercial frontier.

Current global status. Solar PV is the most dynamic energy technology in history. A record 510 GW of solar capacity was added in 2025 — about three-quarters of all renewable additions — and solar PV now supplies roughly 7% of global electricity (IEA, 2025a; IRENA, 2026). Deployment is heavily concentrated in China, which accounted for the majority of 2024–2025 additions, raising both supply-chain-resilience and equity concerns.

Recent advances (2022–2026). The defining development of this window is the maturation of tandem photovoltaics. Two-terminal perovskite/silicon tandem cells crossed the single-junction Shockley–Queisser limit of 33.7% and reached a certified 34.85% in 2025, against a theoretical ceiling near 43% for this architecture (NREL, 2025). Single-junction perovskite cells reached ~26–27% certified efficiency, and a certified 33.6%-efficient *flexible* perovskite/silicon tandem with markedly improved mechanical and damp-heat stability was demonstrated, narrowing the historic gap between record efficiency and operational durability (Liu et al., 2025; Pei et al., 2025). Parallel advances include the transition to n-type TOPCon and heterojunction (HJT) cells in mass production, bifacial modules, and improved module-level power electronics. The central remaining barrier for perovskites is long-term operational and environmental stability, together with lead-content and encapsulation concerns [REF].

Efficiency and economic feasibility. Utility-scale solar PV LCOE fell to USD 0.043 kWh^{-1} in 2024 — about 41% below the cheapest fossil alternative and a 90% decline since 2010 — with total installed costs of about USD 691 kW^{-1}, projected to fall below USD 600 kW^{-1} and toward USD 388 kW^{-1} later this decade (IRENA, 2025b). These economics make solar the default least-cost option for new generation in most markets, although permitting, interconnection, and balance-of-system costs sustain higher prices in Europe and North America. The principal environmental tensions — addressed in Section 4 — concern land use, the energy and emissions embodied in manufacturing, water for cleaning in arid regions, and the looming challenge of module end-of-life management.

3.2 Wind energy

Principle and technology. Wind turbines convert the kinetic energy of moving air into electricity via aerodynamic lift on rotor blades coupled to a generator. The dominant architecture is the three-bladed horizontal-axis turbine; offshore deployment uses fixed-bottom foundations in shallow water and, increasingly, floating platforms in deep water.

Current global status. Wind is the second-largest contributor to renewable growth, with 159 GW added in 2025 (+14%) and a global share of about 8% of electricity generation (IEA, 2025a; IRENA, 2026). Offshore wind, although still a small fraction of total capacity (~1.8% of renewables), is the fastest-scaling segment in several markets.

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Recent advances (2022–2026). The defining trend is upscaling. Offshore turbine ratings have advanced toward and beyond 15–16 MW, with larger rotors capturing more energy per unit and reducing per-MWh foundation and installation costs. Floating offshore wind has progressed from single demonstrators to pre-commercial arrays, unlocking deep-water resources off coastlines previously inaccessible to fixed foundations [REF]. Other advances include longer and segmented blades, improved wake-steering and farm-level control (often AI-assisted; Section 7.1), enhanced grid-forming converters, and early commercial efforts on recyclable thermoplastic and bio-based blade resins to address the blade-waste problem.

Efficiency and economic feasibility. Onshore wind remained the cheapest source of new electricity in 2024 at USD 0.034 kWh^{-1} — roughly 53% below the least-cost fossil option — with total installed costs near USD 1,041 kW^{-1} (IRENA, 2025b). Offshore wind is more expensive (LCOE ~USD 0.078–0.080 kWh^{-1}; installed costs ~USD 2,852 kW^{-1}) and has faced recent cost inflation, supply-chain strain, and project cancellations in some markets, illustrating that the offshore transition is technically proven but financially fragile. Principal environmental considerations include avian and bat mortality, marine-mammal and benthic disturbance offshore, noise and visual impacts, and blade end-of-life waste.

3.3 Hydropower

Principle and technology. Hydropower converts the gravitational potential and kinetic energy of water into electricity using turbines. It spans large reservoir (dam) plants, run-of-river schemes, and pumped-storage hydropower (PSH), the last of which is the dominant form of grid-scale energy storage worldwide.

Current global status. Hydropower remains the largest single source of renewable electricity, supplying about 14% of global generation, but its growth is now slow: only 18.4 GW was added in 2025 (+1.4%), with 96% of that increase occurring in China (IEA, 2025a; IRENA, 2026). Suitable sites are increasingly scarce, and social and ecological opposition constrains new large dams.

Recent advances (2022–2026). Innovation centres less on the turbine and more on system roles and mitigation: digital optimisation and "hydropower flexibility" to complement variable renewables, fish-friendly turbine designs, sediment-management techniques, and the repowering and re-equipping of ageing fleets. PSH is experiencing renewed interest as long-duration storage, including closed-loop and underground concepts that reduce river-ecosystem impacts [REF].

Efficiency and economic feasibility. Hydropower has high conversion efficiency (often >85–90%) and the lowest operating costs of any source once built; its 2024 LCOE was USD 0.057 kWh^{-1} (IRENA, 2025b). However, capital costs are highly site-specific, lead times are long, and the climate footprint of reservoirs — particularly methane emissions from flooded vegetation in tropical settings — remains a major and unresolved controversy (Section 4.1 and 5.1). Reservoir

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creation also drives habitat fragmentation, altered flow and sediment regimes, and population displacement.

3.4 Biomass energy

Principle and technology. Bioenergy derives from organic matter — agricultural and forestry residues, energy crops, and organic wastes — converted through combustion, gasification, pyrolysis, anaerobic digestion (biogas), or biochemical/thermochemical routes to liquid biofuels. It is the most versatile renewable, supplying electricity, heat, and transport fuels.

Current global status. Bioenergy and waste supply roughly 3% of global electricity and a larger share of heat and transport energy, but installed power capacity grows slowly (~3 GW added in 2025) (IEA, 2025a; IRENA, 2026). Its role is contested precisely because its sustainability is so dependent on feedstock and land-use choices.

Recent advances (2022–2026). Key developments include advanced (second- and third-generation) biofuels from lignocellulosic and algal feedstocks that avoid food-crop competition, integrated biorefineries, improved anaerobic-digestion and biomethane upgrading, and the coupling of biomass combustion with carbon capture and storage (BECCS) as a candidate negative-emissions technology. Sustainable aviation fuel (SAF) has emerged as a major demand driver [REF].

Efficiency and economic feasibility. Bioenergy is dispatchable and can provide firm capacity and grid services, a significant advantage over variable renewables, but its LCOE rose by about 13% in 2024 and is sensitive to feedstock supply and logistics (IRENA, 2025b). Its environmental profile is the most controversial of any "green" source: carbon neutrality is conditional and time-dependent (the "carbon-debt" problem), and feedstock production can drive deforestation, biodiversity loss, soil degradation, water use, and competition with food production. These tensions are examined critically in Sections 4 and 5.

3.5 Geothermal energy

Principle and technology. Geothermal energy exploits the Earth's internal heat, using hydrothermal resources (naturally occurring steam or hot water) to drive turbines directly or via binary (organic Rankine) cycles, and — at the frontier — enhanced geothermal systems (EGS) that engineer permeability in hot dry rock to access far larger resources.

Current global status. Geothermal remains a small contributor (~15 GW globally; +0.3 GW in 2025), historically constrained to tectonically favourable regions such as the Philippines, Indonesia, the United States, Iceland, Türkiye, and East Africa (IRENA, 2026).

Recent advances (2022–2026). EGS and "next-generation" geothermal — including closed-loop advanced geothermal systems and the transfer of horizontal drilling and stimulation techniques from the oil-and-gas sector — are the most consequential developments, with several pilot projects demonstrating that geothermal could in principle become a globally distributed, dispatchable, firm low-carbon resource

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[REF]. Co-production of lithium from geothermal brines is an emerging value stream of direct relevance to the storage supply chain.

Efficiency and economic feasibility. Geothermal offers very high capacity factors (often 70–90%) and provides firm, baseload-capable, low-carbon power, an increasingly valuable attribute in renewable-heavy grids. Costs fell by about 16% in 2024 but remain site- and resource-dependent, and EGS economics are unproven at scale (IRENA, 2025b). Environmental considerations include induced seismicity (notably for EGS), emissions of dissolved gases (CO_2, H_2S) from some reservoirs, land subsidence, and water and brine management.

3.6 Ocean energy

Principle and technology. Ocean energy encompasses tidal-range (barrage), tidal-stream (current), wave, ocean-thermal-energy-conversion (OTEC), and salinity-gradient technologies. Tidal-stream turbines and wave-energy converters are the most actively developed.

Current global status. Ocean energy remains pre-commercial, with global capacity well below 1 GW concentrated in a few tidal-range and tidal-stream installations (IRENA, 2026). Despite an enormous theoretical resource, high costs and the harsh marine environment have slowed deployment.

Recent advances (2022–2026). Tidal-stream arrays have demonstrated multi-year reliability and improving capacity factors, and wave-energy developers have advanced device survivability and power take-off efficiency, supported by improved resource characterisation and standardised testing at marine-energy centres [REF]. The predictability of tides is a distinctive advantage relative to wind and solar, potentially providing firm, schedulable renewable power.

Efficiency and economic feasibility. Ocean energy currently has the highest LCOE of the renewables considered here, reflecting its early maturity and the costs of marine engineering, installation, and maintenance. Cost reduction depends on learning-by-doing and array-scale deployment. Environmental considerations are still poorly characterised but include effects on marine habitats, benthic communities, sediment transport, marine fauna (collision and noise), and electromagnetic fields from cables.

3.7 Green hydrogen

Principle and technology. Green (renewable) hydrogen is produced by splitting water through electrolysis powered by renewable electricity, using alkaline, proton-exchange-membrane (PEM), or — at earlier maturity — solid-oxide and anion-exchange-membrane electrolysers. As an energy carrier and feedstock, it is central to decarbonising "hard-to-abate" sectors such as steel, ammonia, refining, shipping, and aviation.

Current global status. Global hydrogen demand reached nearly 100 Mt in 2024, but less than 1% was low-emissions; the overwhelming majority is still produced from unabated fossil fuels (IEA, 2025c). Installed electrolyser capacity remains small — about 4.9 GW globally, up from 0.6 GW in 2021 — with China holding roughly 60% of manufacturing capacity (IEA, 2025c).

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Recent advances (2022–2026). This window has seen rapid manufacturing scale-up alongside a sobering re-evaluation of near-term feasibility. Chinese electrolysers are offered at roughly USD 300–500 kW^{-1} versus USD 750–1,300 kW^{-1} for Western systems, and large projects (hundreds of MW) have been commissioned (IEA, 2025c). Technical progress includes higher current densities, improved catalyst loadings, and PEM gains for variable-renewable coupling. However, the IEA's 2030 projection for low-emissions hydrogen production fell from 49 to 37 Mt yr^{-1} between its 2024 and 2025 reviews, reflecting cost increases, slow final-investment-decision conversion, and weak offtake (IEA, 2025c). The aspirational USD 1 kg^{-1} cost target by 2030 remains contingent on continued electrolyser and electricity-cost declines.

Efficiency and economic feasibility. Electrolysis entails round-trip energy penalties (system efficiency typically 60–75% on a higher-heating-value basis), and the full power-to-hydrogen-to-end-use chain incurs substantial losses, which is why hydrogen is best reserved for applications without direct-electrification alternatives. Green hydrogen is currently more expensive than fossil-based hydrogen, and the cost gap widened recently as natural-gas prices fell (IEA, 2025c). Environmental considerations include the very large renewable-electricity and freshwater requirements of large-scale production (with implications for water-stressed regions), and hydrogen's own indirect global-warming effect through atmospheric chemistry if leakage is not controlled.

3.8 Emerging renewable technologies

Beyond the established sources, several emerging technologies could reshape the green energy landscape within the review horizon. These include: **agrivoltaics and floating PV (floatovoltaics)**, which co-locate generation with agriculture or water bodies to reduce land competition and, in the case of floating PV, evaporation; **building-integrated and tandem/transparent PV**; **airborne wind energy** using tethered kites or drones to access higher-altitude winds; **next-generation and small modular geothermal**; **osmotic (salinity-gradient) power**; **space-based solar power**, still highly speculative; and **green ammonia and other hydrogen derivatives** as transportable energy vectors. Most remain at low-to-medium TRL, and their environmental footprints are correspondingly under-characterised. Recent technological milestones across all sources are summarised in Table 6.

Table 5. Levelised cost of electricity and total installed costs of major renewable technologies, 2024 (global weighted averages).

Technology	LCOE 2024 (USD kWh^{-1})	Change vs 2023	Total installed cost 2024 (USD kW^{-1})	Benchmark
Onshore wind	0.034	+3%	1,041	53% below least-cost fossil
Solar PV	0.043	+0.6%	691	41% below

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Technology	LCOE 2024 (USD kWh^{-1})	Change vs 2023	Total installed cost 2024 (USD kW^{-1})	Benchmark
(utility)				least-cost fossil
Hydropower	0.057	−2%	site-specific	—
Geothermal	resource-specific	−16%	site-specific	firm/baseload
Bioenergy	feedstock-specific	+13%	feedstock-specific	dispatchable
Offshore wind	0.078–0.080	+4%	2,852	scaling
Battery storage (utility)	—	—	192 (USD kWh^{-1})	−93% since 2010
Coal (reference)	0.073	—	—	fossil benchmark
Combined-cycle gas (reference)	0.085	—	—	fossil benchmark

Source: IRENA (2025b). LCOE values are global weighted averages for newly commissioned utility-scale projects; regional values vary substantially (e.g., onshore wind LCOE was USD 0.029 kWh^{-1} in China).

Table 6. Representative recent technological advances by green energy source (2022–2026).

Source	Headline advance	Significance
Solar PV	Certified 34.85% perovskite/Si tandem; flexible 33.6% tandem; n-type TOPCon/HJT mass production	Efficiency beyond single-junction limit; durability gains; lower USD kW^{-1}
Wind	15–16+ MW offshore turbines; pre-commercial floating arrays; recyclable blades	Deeper-water resource access; lower per-MWh cost; waste reduction
Hydropower	Closed-loop/underground PSH; fish-friendly turbines; digital flexibility	Long-duration storage; reduced ecological impact
Biomass	Advanced biofuels, SAF, biomethane upgrading, BECCS pilots	Defossilising hard-to-abate sectors; candidate negative emissions
Geothermal	EGS and closed-loop "next-gen" geothermal; brine lithium co-production	Geographically distributed firm power; critical-mineral synergy
Ocean	Multi-year tidal-stream array reliability; improved	Path toward firm, predictable marine power

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Source	Headline advance	Significance
	wave-device survivability	
Green hydrogen	Manufacturing scale-up; sub-USD 500 kW^{-1} electrolysers; large projects	Industrial decarbonisation pathway; cost trajectory still uncertain
Cross-cutting	Agrivoltaics, floating PV, AI-based forecasting and control, advanced storage	Reduced land/water competition; improved system integration

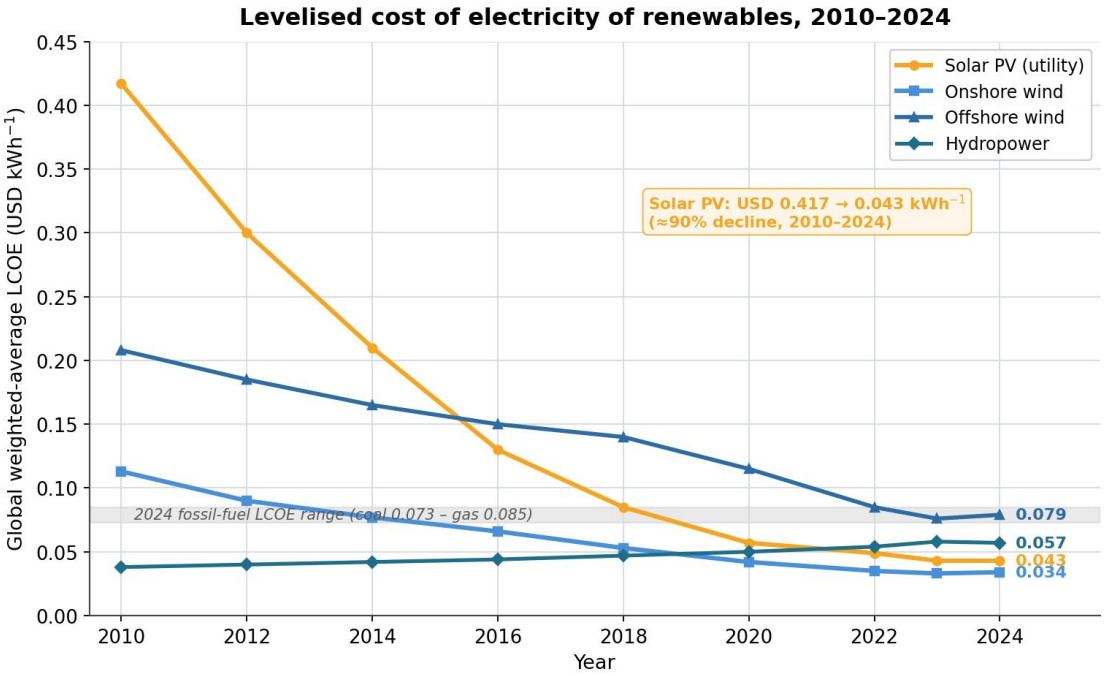

Figure 5. Evolution of the global weighted-average levelised cost of electricity (LCOE) of renewables, 2010–2024, against the 2024 fossil-fuel cost range. Solar PV fell ≈90% to USD 0.043 kWh⁻¹ and onshore wind ≈70% to USD 0.034 kWh⁻¹. Data: IRENA (2025b).

4. Environmental effects of green energy sources

A defining contribution of this review is to treat the environmental performance of green energy with the same critical scrutiny conventionally applied to fossil fuels. The dominant narrative — that renewables are "clean" — is correct in the climate and air-quality dimensions but incomplete. This section analyses both the beneficial and adverse effects, organised by impact category. Table 9 consolidates a qualitative positive-versus-negative impact matrix across sources.

4.1 Greenhouse-gas mitigation and carbon-footprint reduction

The central environmental benefit of green energy is the displacement of fossil combustion. In 2024, the avoided fossil-fuel cost attributable to renewables reached

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an estimated USD 467 billion, and the first-ever achievement of 40% low-carbon electricity (renewables plus nuclear) demonstrably restrained emissions growth in advanced economies, where renewables and nuclear now supply over half of generation (IEA, 2025a; IRENA, 2025b). On a life-cycle basis, wind and solar emit roughly 11–50 $gCO_2eq\ kWh^{-1}$ against approximately 490 $gCO_2eq\ kWh^{-1}$ for gas and 820 $gCO_2eq\ kWh^{-1}$ for coal — a reduction of one to nearly two orders of magnitude [REF].

Yet the mitigation accounting is more contested for two sources. First, hydropower reservoirs can emit substantial methane from the anaerobic decomposition of flooded organic matter; in tropical reservoirs, life-cycle emissions can, in extreme cases, approach or exceed those of fossil plants per unit of electricity, although boreal and temperate reservoirs are typically far lower [REF]. Second, the carbon neutrality of biomass is conditional: combustion releases CO_2 immediately, while regrowth sequesters it only over years to decades, creating a "carbon debt" whose repayment period depends on feedstock, prior land use, and counterfactual. Treating all biomass as carbon-neutral by convention can therefore overstate near-term climate benefit (Section 5.1). These controversies underscore that GHG mitigation is source- and context-specific rather than uniform across "renewables".

4.2 Effects on biodiversity

Biodiversity impacts are among the most significant and least quantified environmental costs of green energy, and they differ sharply by technology. Wind turbines cause direct mortality of birds and, especially, bats through collision and barotrauma, with raptors and migratory species of particular concern; offshore, the issues shift to seabird displacement, underwater construction noise affecting marine mammals, and electromagnetic effects on benthic and pelagic fauna [REF]. Solar installations can fragment and transform habitat, particularly large utility-scale plants in desert and grassland ecosystems, and can create "lake effect" attraction hazards for aquatic birds. Hydropower is perhaps the most ecologically disruptive at the ecosystem scale, blocking fish migration, fragmenting river connectivity, and altering the flow, temperature, and sediment regimes on which aquatic biodiversity depends. Bioenergy's biodiversity footprint is dominated by land-use change: the conversion of forests, grasslands, or peatlands to energy-crop monocultures is a leading driver of habitat and species loss. Critically, biodiversity impacts are difficult to aggregate, are rarely captured in standard LCA, and are highly site-dependent, which is a major reason they are systematically under-weighted in technology comparisons.

4.3 Land-use change and land occupation

Green energy is generally more land-intensive per unit of energy than fossil generation, although the nature of that land use varies. Wind farms have a large geographic footprint but a small physical land-occupation footprint — typically a few percent of the array area is actually occupied by turbines and access roads, leaving the remainder available for agriculture or grazing. Solar PV requires more

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contiguous land per MWh but can be sited on rooftops, degraded land, or co-located with agriculture (agrivoltaics) or water (floating PV) to reduce competition. Biomass is by far the most land-intensive, since photosynthetic energy capture is inefficient (typically <1%), so energy crops require vast areas relative to their output — the principal reason large-scale BECCS raises severe land-and-food concerns. Hydropower reservoirs can flood extensive areas, with associated displacement and habitat loss. As deployment scales toward terawatts, cumulative land requirements and land-use conflicts (with food production, conservation, and communities) become a first-order sustainability constraint rather than a marginal concern.

4.4 Water consumption and water footprint

The water dimension reverses several intuitions. Solar PV and wind consume essentially no water during operation (aside from periodic PV cleaning), giving them a dramatic advantage over thermoelectric generation — including coal, gas, and nuclear — which withdraws and consumes large volumes for cooling. However, CSP and geothermal can be water-intensive, hydropower drives substantial evaporative losses from reservoir surfaces (often counted as a large "blue" water footprint), and bioenergy has by far the largest water footprint of any source when feedstock irrigation is included. Green hydrogen introduces a new and under-appreciated water demand: producing one kilogram of hydrogen requires roughly nine kilograms of water stoichiometrically and more in practice, so gigatonne-scale hydrogen ambitions imply significant freshwater needs, frequently in arid regions with excellent solar resources but acute water stress. The water–energy nexus is thus a critical and uneven axis of comparison (Section 5.3).

4.5 Soil degradation

Soil impacts are most pronounced for bioenergy, where intensive energy-crop cultivation can deplete soil organic carbon and nutrients, increase erosion, and degrade soil structure, particularly where residues are removed wholesale. Conversely, well-managed perennial energy crops and the application of biochar can, in some contexts, improve soil carbon and quality, illustrating the strong management-dependence of bioenergy outcomes. Construction of solar, wind, hydropower, and geothermal facilities causes localised soil disturbance, compaction, and erosion during the build phase, generally reversible and minor relative to bioenergy's systemic soil pressures.

4.6 Noise pollution

Noise is a localised but socially salient impact. Wind turbines generate aerodynamic and mechanical noise and low-frequency/infrasound that contributes to community opposition and siting setbacks, although evidence on direct health effects beyond annoyance and sleep disturbance remains contested [REF]. Offshore, underwater construction noise (notably pile-driving) is a serious concern for marine mammals and fish, motivating noise-abatement requirements. Geothermal and biomass plants produce industrial noise comparable to conventional facilities. Solar PV is essentially silent in operation.

4.7 Visual pollution and landscape impact

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Aesthetic and landscape impacts, while not "pollution" in the chemical sense, materially affect public acceptance and project viability. Large wind farms — especially on ridgelines and coastlines — and utility-scale solar arrays alter valued landscapes and seascapes, and transmission infrastructure compounds the effect. These impacts are subjective and culturally mediated but are a leading cause of permitting delays and local opposition, making them a genuine constraint on deployment that technical analyses often neglect.

4.8 Ecological disturbance and other effects

Beyond the categories above, green energy can cause ecological disturbance through habitat fragmentation by access roads and transmission corridors, microclimatic effects (e.g., localised warming downwind of large wind farms, and altered surface energy balance under solar arrays), barrier effects on wildlife movement, and disruption of marine sediment transport by tidal and offshore installations. Many of these effects are second-order and reversible, but their cumulative and synergistic significance at landscape and seascape scales is poorly understood.

4.9 Resource and critical-material depletion

A defining and rapidly growing concern is the material intensity of the clean-energy transition. Solar PV, wind, batteries, and electrolysers depend on a range of metals and minerals — including copper, silicon, silver, aluminium, rare-earth elements (neodymium, dysprosium for permanent magnets), lithium, nickel, cobalt, graphite, and platinum-group metals — whose extraction carries its own environmental and social burdens (habitat loss, water use, tailings, toxic releases, and frequently problematic labour and governance conditions in producer regions). Supply is geographically concentrated, raising resilience and geopolitical risks analogous to those long associated with oil. The transition thus shifts the locus of environmental pressure from combustion emissions to mining and materials, and the sustainability of green energy increasingly hinges on material efficiency, substitution, and circularity (Section 7.6) rather than on operational performance alone.

4.10 Life-cycle and end-of-life impacts

Because the environmental burdens of renewables are concentrated in manufacturing, construction, and disposal rather than operation, life-cycle and end-of-life considerations are decisive. The first large cohorts of solar panels and wind turbines installed in the 2000s and 2010s are now reaching retirement, generating rapidly growing waste streams: photovoltaic module waste and composite wind-blade waste are projected to reach tens of millions of tonnes cumulatively within two decades [REF]. Current recycling rates are low, recovery of high-value materials (silicon, silver, rare earths) is technically and economically challenging, and blade composites are notoriously difficult to recycle. Battery end-of-life presents both a hazard (if mismanaged) and an opportunity (urban mining of lithium, nickel, and cobalt). Without deliberate design-for-recycling and policy mandates, end-of-life waste could undercut the sustainability case for renewables precisely as deployment peaks — a risk examined further in Sections 5 and 7.6.

5. Comparative life-cycle assessment

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Life-cycle assessment (LCA) — the cradle-to-grave quantification of environmental burdens — is the most rigorous framework for comparing energy technologies, because it captures the upstream and downstream impacts that operational metrics miss. This section synthesises comparative LCA evidence across the principal sources and is necessarily critical: the literature is heterogeneous in scope, boundaries, functional units, allocation methods, and regional assumptions, which limits direct comparability and is itself a key research gap (Section 9). The indicative ranges reported below are drawn from the harmonised LCA literature and should be treated as order-of-magnitude comparisons rather than precise values; authors should anchor each value to specific harmonised studies in the final manuscript.

5.1 Life-cycle CO_2 intensity

Across harmonised assessments, the life-cycle carbon intensity of green sources is far below that of fossil generation, but with important spread and overlap (Table 7). Wind (onshore and offshore) and nuclear typically cluster at the low end (~10–13 $gCO_2eq\ kWh^{-1}$), solar PV somewhat higher and falling as manufacturing decarbonises and efficiencies rise (~25–45 $gCO_2eq\ kWh^{-1}$), geothermal intermediate (~35–40 $gCO_2eq\ kWh^{-1}$) but variable with reservoir gas content, and hydropower highly variable (~10 to >100 $gCO_2eq\ kWh^{-1}$) depending on reservoir type and climate. Biomass is the most uncertain, with reported values spanning a very wide range depending on feedstock, land-use change, and the carbon-debt treatment — the single largest source of inter-study divergence in energy LCA. The policy implication is that "low-carbon" status cannot be assumed uniformly across renewables and must be established per technology and context (Figure 6).

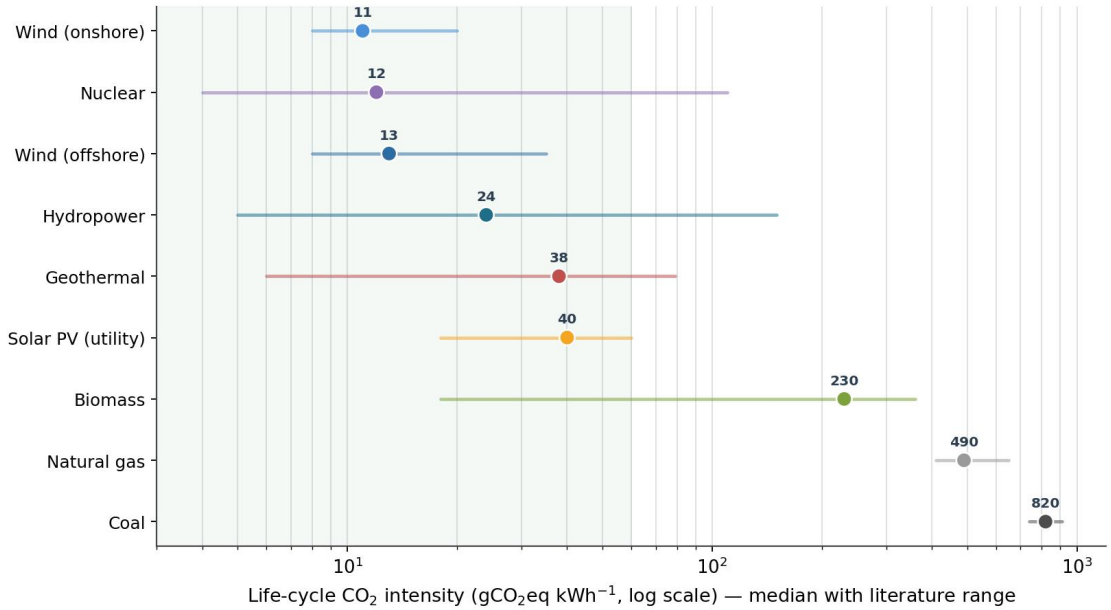

Figure 6. Life-cycle carbon intensity (median and literature range, log scale) of green and fossil electricity sources. Wind, nuclear, and solar PV are one to two orders of magnitude below coal and gas, whereas biomass and tropical-reservoir

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hydropower show wide ranges. Ranges follow harmonised IPCC-based LCA literature.

5.2 Energy payback time and energy return on investment

Energy payback time (EPBT) — the time for a system to generate the energy used to make it — and energy return on investment (EROI) are central to net-energy sustainability. Modern solar PV has an EPBT of roughly one to two years against operational lifetimes of 25–35 years, and wind often under one year, implying that both deliver large net-energy surpluses over their lifetimes [REF]. EROI estimates place hydropower very high, wind high, solar PV moderate-but-rising, geothermal moderate, and conventional biomass low (often single digits), reflecting the energy intensity of feedstock production. Declining EPBT for solar and wind is one of the clearest sustainability success stories of the past decade, even as the absolute material and manufacturing footprint grows with scale.

5.3 Water footprint

As noted in Section 4.4, the water footprint ranking diverges from the carbon ranking. Wind and solar PV have negligible operational water footprints; CSP, geothermal, and especially hydropower (evaporative) and irrigated bioenergy have large ones. Green hydrogen adds a stoichiometric and process water demand that is modest per unit of hydrogen but potentially significant at national scales and acute in water-stressed regions. Integrating water into technology comparisons frequently reorders the apparent "best" options and is essential for siting decisions in arid and semi-arid regions (Figure 7).

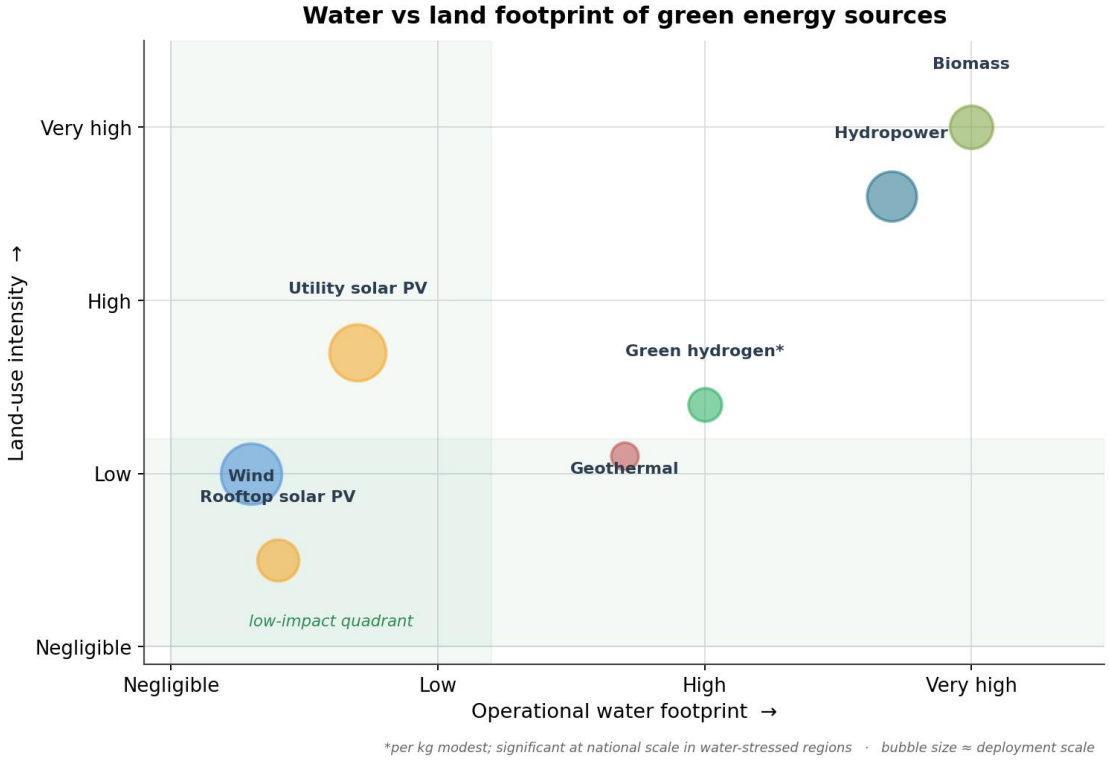

Figure 7. Operational water footprint versus land-use intensity of green energy sources (qualitative positioning; bubble size ≈ deployment scale). Wind and rooftop

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solar occupy the low-impact quadrant, whereas biomass and reservoir hydropower are the most resource-intensive.

5.4 Land requirement

Land-use intensity (m^2 per MWh or per MW) follows the order, from lowest to highest: rooftop solar and wind (low physical occupation) < utility solar < hydropower (reservoir) < bioenergy (very high). Power density — power output per unit land area — is correspondingly high for wind turbines (per occupied area) and solar, and very low for biomass. Land-use efficiency and multifunctional land use (agrivoltaics, floating PV, dual-use wind-agriculture) are increasingly important LCA and planning metrics as deployment scales.

5.5 Ecotoxicity and other impact categories

Beyond carbon, energy, water, and land, LCA captures ecotoxicity, human toxicity, eutrophication, acidification, particulate formation, and metal and mineral depletion. Here the picture is more nuanced: solar PV and batteries can score relatively high on metal-depletion, toxicity, and mineral-resource categories owing to their material intensity and the mining and processing of metals (including, for some thin-film and perovskite chemistries, cadmium and lead). Bioenergy tends to score poorly on eutrophication and acidification because of fertiliser use. These categories are precisely where renewables do *not* uniformly dominate fossil fuels, and their systematic inclusion is necessary for an honest, multi-criteria comparison.

5.6 Toward an integrated sustainability index

No single impact category captures overall sustainability, and technologies that excel on one axis (e.g., wind on carbon) may underperform on another (e.g., material criticality or land). Multi-criteria decision-analysis and composite sustainability indices attempt to integrate environmental, economic, technical, and social dimensions, but results are sensitive to the weighting scheme, which embeds value judgements. A transparent, multi-criteria, and uncertainty-aware sustainability index — rather than a single headline metric — is the most defensible basis for comparison and is operationalised qualitatively in Tables 9 and 10 and Figure 8.

Table 7. Indicative life-cycle CO_2 intensity, energy payback time, and energy return on investment by source (literature ranges; to be anchored to specific harmonised studies).

Source	Life-cycle CO_2 intensity ($gCO_2eq\ kWh^{-1}$)	Energy payback time	EROI (indicative)	Key uncertainty
Wind (onshore)	~11–12	<1 year	high (~15–25)	end-of-life blade treatment
Wind (offshore)	~12–15	~1 year	high	foundation/installation

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Source	Life-cycle CO_2 intensity ($gCO_2eq\ kWh^{-1}$)	Energy payback time	EROI (indicative)	Key uncertainty
Solar PV (utility)	~25–45	~1–2 years	moderate–rising (~10–15)	energy manufacturing electricity mix
Hydropower	~10 to >100	very short (operational)	very high (~40–80)	reservoir methane (tropical)
Geothermal	~35–40	short	moderate (~10)	reservoir gas content
Biomass	very wide (≈ −ve to >300)	feedstock-dependent	low (~3–8)	land-use change, carbon debt
Nuclear (reference)	~12	~few years	high	—
Natural gas (reference)	~490	n/a	—	methane leakage
Coal (reference)	~820	n/a	—	—

Values are order-of-magnitude literature ranges intended for comparison; they are highly sensitive to system boundaries, allocation, and regional context.

Table 8. Indicative operational water footprint and land-use intensity by source.

Source	Operational water footprint	Land-use intensity	Notes
Solar PV (rooftop)	negligible	very low (existing structures)	dual-use
Solar PV (utility)	low (cleaning only)	moderate	agrivoltaics/floating reduce conflict
Wind	negligible	low physical occupation; large array footprint	co-use with agriculture
Hydropower	high (reservoir evaporation)	high (reservoir flooding)	highly site-specific
Geothermal	moderate–high	low–moderate	brine/water reinjection
Biomass	very high (irrigation)	very high	strong food/land competition
Green hydrogen	moderate per kg; large at scale	depends on renewable source	acute in water-stressed regions
Coal/gas/nuclear (reference)	high (thermoelectric cooling)	low–moderate	withdrawal vs consumption distinction

6. Techno-economic and environmental comparison

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This section integrates the technical, economic, and environmental evidence into comparative matrices to support a multi-criteria assessment. Table 10 is the review's critical comparison matrix, scoring each major source across efficiency, cost, scalability, environmental risk, and an integrated sustainability rating. Such scoring is inherently semi-quantitative and weighting-dependent; the ratings below synthesise the evidence in Sections 3–5 and the cited agency data, and are intended to structure judgement rather than to substitute for context-specific analysis.

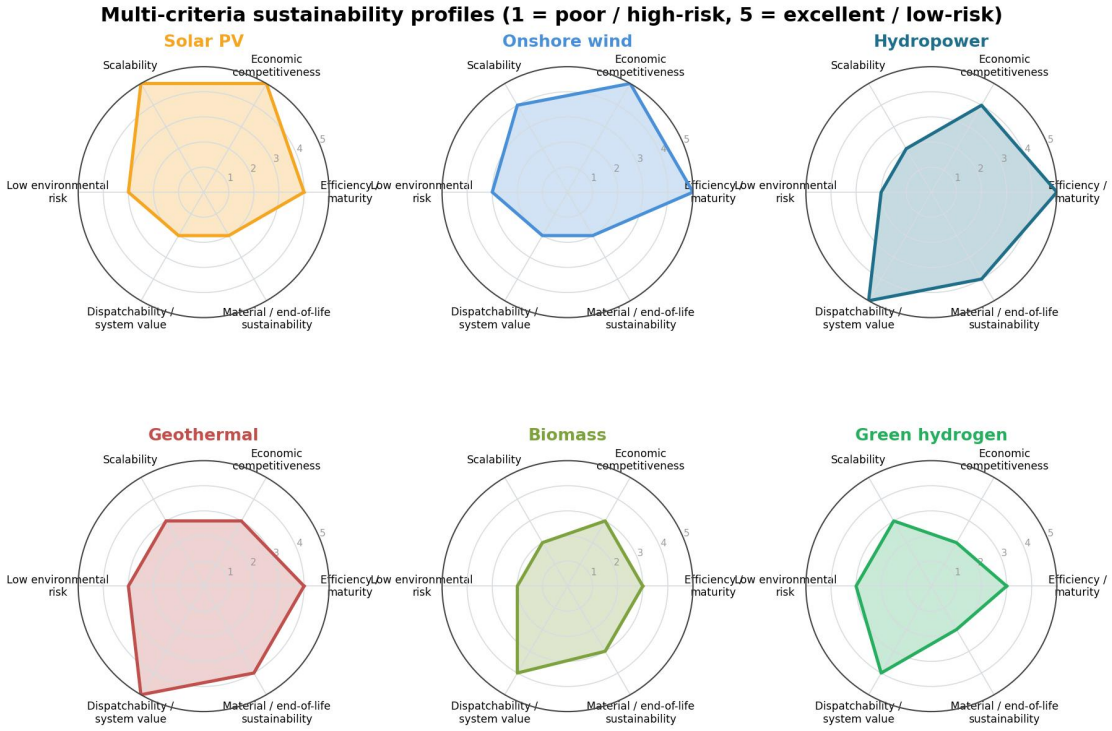

Figure 8. Multi-criteria sustainability profiles of the major green energy sources across six dimensions (1 = poor/high-risk, 5 = excellent/low-risk), visualising the trade-offs summarised in Table 10.

Several cross-cutting conclusions emerge. First, on the combined criteria of cost, carbon, and scalability, onshore wind and solar PV are the strongest performers and the justified backbone of near-term decarbonisation, reflecting both their record-low LCOEs and their enormous and rapidly realised deployment potential (IRENA, 2025b, 2026). Second, their principal weaknesses — variability, land and material intensity, and end-of-life waste — are precisely the areas where complementary technologies (storage, firm renewables, and circular-economy systems) and system integration are essential. Third, firm and dispatchable low-carbon sources — geothermal, hydropower, sustainable bioenergy, and potentially ocean energy — have higher costs or more constrained potential but provide system value (reliability, flexibility, inertia) that is undervalued by LCOE alone. Fourth, green hydrogen scores well on its decarbonisation potential for hard-to-abate sectors but poorly on near-term cost and efficiency, and its environmental merit is entirely contingent on genuinely additional renewable electricity and responsible water sourcing. A balanced portfolio, rather than a single "winner", is therefore the rational system-

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level conclusion.

Table 9. Qualitative matrix of principal positive and negative environmental impacts by source.

Source	GHG mitigation	Biodiversity	Land	Water	Materials /EoL	Other salient impacts
Solar PV	✓✓✓	◐ (habitat)	◐	✓✓ (low)	✗ (module waste, metals)	silent; manufacturing energy
Wind	✓✓✓	✗ (birds/bats, marine)	✓ (low occupation)	✓✓✓	✗ (blade waste, rare earths)	noise, visual
Hydropower	✓✓ (variable)	✗✗ (rivers, fish)	✗ (flooding)	✗ (evaporation)	✓ (long-lived)	displacement, sediment
Biomass	◐ (conditional)	✗✗ (land-use change)	✗✗ (very high)	✗✗ (irrigation)	✓	air emissions, soil, food competition
Geothermal	✓✓✓	◐	✓	◐	✓	induced seismicity, H_2S
Ocean	✓✓✓	◐ (under-characterised)	✓	✓✓✓	◐	marine habitat, sediment
Green hydrogen	✓✓ (if additional RE)	◐	◐	✗ (at scale)	✗ (catalysts, stacks)	H_2 leakage warming, energy losses

✓✓✓ strong benefit / low impact; ✓✓ moderate; ✓ modest; ◐ mixed or context-dependent; ✗ notable adverse impact; ✗✗ severe or highly contested impact. EoL = end of life.

Table 10. Critical comparison matrix of green energy technologies (semi-quantitative; 1 = poor/high-risk, 5 = excellent/low-risk).

Source	Technical efficiency /maturity	Economic competitiveness	Scalability	Environmental risk (5 = low risk)	Dispatchability/system value	Integrated sustainability rating
Solar PV	4	5	5	3	2	**High**
Onshore	5	5	4	3	2	**High**

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Source	Technical efficiency /maturity	Economic competitiveness	Scalability	Environmental risk (5 = low risk)	Dispatchability/system value	Integrated sustainability rating
wind						
Offshore wind	4	3	4	3	3	**Medium–High**
Hydropower	5	4	2	2	5	**Medium**
Geothermal	4	3	3	3	5	**Medium–High**
Biomass/bioenergy	3	3	2	2	4	**Low–Medium**
Ocean energy	2	1	2	3	4	**Emerging**
Green hydrogen	3	2	3	3	4 (as carrier/storage)	**Medium (contingent)**

Ratings synthesise Sections 3–5 and agency data (IEA, 2025a–c; IRENA, 2025b, 2026); the integrated rating reflects the balance of criteria and is sensitive to weighting and regional context.

7. Recent innovations and emerging trends (2022–2026)

The green energy transition is increasingly a systems challenge rather than a generation-technology challenge. The innovations below are reshaping how renewables are integrated, stored, and coupled to end uses, and several carry their own environmental implications.

7.1 Bibliometric trends, 2022–2026

The research literature on green energy and its environmental effects has expanded rapidly over the review window, consistent with the parallel acceleration in deployment. Publication output has grown year on year across 2022–2026, with the steepest increases in solar PV, energy storage, green hydrogen, and the application of artificial intelligence to energy systems; environmental-impact and LCA studies have grown more slowly than technology-focused work, a thematic imbalance that mirrors the gaps identified in this review. Keyword co-occurrence analysis would be expected to reveal three dominant clusters — a technology cluster (solar, wind, hydrogen, storage), an environmental/sustainability cluster (LCA, carbon footprint, biodiversity, circular economy), and a systems/policy cluster (smart grid, integration, net zero, energy policy) — with "green hydrogen", "energy storage", "machine learning", and "circular economy" emerging as fast-rising terms. China, the United States, the European Union, and India are the most productive regions, and *Renewable and Sustainable Energy Reviews*, *Renewable Energy*, *Journal of Cleaner Production*, *Applied Energy*, and *Energy Conversion and Management* are among the leading source journals. Figure 3 presents the intended visual summary; the

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underlying counts and network maps should be generated by the authors from a frozen Scopus/Web of Science query and VOSviewer analysis.

7.2 Artificial intelligence and machine learning in renewable energy

AI and machine learning have become pervasive enablers across the renewable value chain. Applications include high-resolution solar and wind forecasting (reducing the cost of variability and curtailment), predictive maintenance and digital twins for turbines and PV plants, wake-steering and farm-level control to increase wind-farm yield, accelerated materials discovery for photovoltaics, catalysts, and batteries, optimal dispatch and bidding in electricity markets, and grid state estimation and stability management [REF]. The benefits are real and growing, but AI is not environmentally free: the energy and water demands of large-scale computation — now a material driver of electricity-demand growth (IEA, 2025a) — create a feedback in which the tools of the transition themselves add load. Responsible deployment requires that AI's efficiency gains exceed its direct resource costs.

7.3 Smart grids and system integration

High shares of variable renewables require a fundamental reconfiguration of the grid. Smart grids — characterised by advanced sensing, two-way communication, demand response, distributed-energy-resource management, and grid-forming inverters — are essential to accommodate solar and wind without compromising reliability. Interconnection, market reform, and grid-forming converter technology are increasingly the binding constraints on renewable integration, with grid bottlenecks now delaying projects in many regions. Digitalisation and demand flexibility (smart meters, dynamic pricing, IoT-enabled appliances, electric-vehicle smart charging) are central to managing the system at lowest cost (IRENA, 2025b).

7.4 Energy storage technologies

Storage is the linchpin of a renewable-dominated system, and its economics have transformed: utility-scale battery storage costs fell by 93% between 2010 and 2024 to about USD 192 kWh^{-1} (IRENA, 2025b). Lithium-ion dominates short-duration storage, but the central unsolved problem is cost-effective long-duration and seasonal storage. The portfolio (Table 11) spans electrochemical (lithium-ion, sodium-ion, flow, and emerging solid-state and metal-air batteries), mechanical (pumped hydro — still the dominant grid storage — compressed-air, and gravity), thermal, and chemical (hydrogen and derivatives) options. Sodium-ion has advanced toward commercialisation as a lower-cost, critical-mineral-light alternative for stationary applications, and pumped hydro and emerging long-duration chemistries are central to seasonal balancing. Storage also carries material and end-of-life implications that must be managed through recycling and second-life use (Section 7.6).

7.5 The green-hydrogen economy and carbon-capture integration

Green hydrogen and its derivatives (ammonia, methanol, synthetic fuels) are positioned to decarbonise sectors that resist direct electrification, and to provide long-duration storage and flexibility. As Section 3.7 detailed, the near-term reality is

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more constrained than earlier projections, with rising costs and slow project maturation prompting downward revisions (IEA, 2025c). Carbon capture, utilisation, and storage (CCUS) is a distinct but related lever: relevant to industrial decarbonisation, to "blue" hydrogen, and — coupled with bioenergy (BECCS) or direct air capture — to carbon-dioxide removal, which the latest assessments now treat as unavoidable given the inevitability of temporarily exceeding 1.5 °C (IEA, 2025b; IPCC, 2022). Both remain expensive and unproven at the scale implied by net-zero scenarios, and their environmental and energy penalties require critical scrutiny rather than assumed benignity.

7.6 Circular-economy approaches

Given the material intensity and looming end-of-life waste of renewables (Sections 4.9–4.10), circular-economy strategies — design-for-recycling, material substitution and dematerialisation, reuse and remanufacturing, second-life battery applications, and high-recovery recycling of PV modules, wind blades, and batteries — are increasingly recognised as essential to the sustainability of the transition rather than as an afterthought. Recovery of silicon, silver, rare earths, lithium, nickel, and cobalt through "urban mining" can reduce both primary-extraction impacts and supply risk. The bottleneck is that recycling infrastructure, standards, and economics lag far behind deployment, and most current renewable hardware was not designed for end-of-life recovery — a gap that policy and design standards must close within this decade.

7.7 Hybrid renewable systems and net-zero energy systems

Hybrid systems that combine complementary resources — solar-plus-wind, solar-plus-storage, wind-plus-storage, and renewable-plus-hydrogen — improve capacity factors, smooth output, and lower integrated LCOE; hybrid solar-wind-battery projects have reported weighted-average LCOEs around USD 0.05 kWh^{-1}, competitive with firm fossil generation (IRENA, 2025b). At the building and community scale, net-zero and positive-energy buildings, microgrids, and integrated multi-energy systems (coupling electricity, heat, mobility, and hydrogen) represent the architecture of a decarbonised system. Sector coupling and electrification — of transport, heating, and industry — are the mechanism by which clean electricity displaces fossil fuels across the whole economy, and they are advancing fastest where renewables are cheapest (Figure 9).

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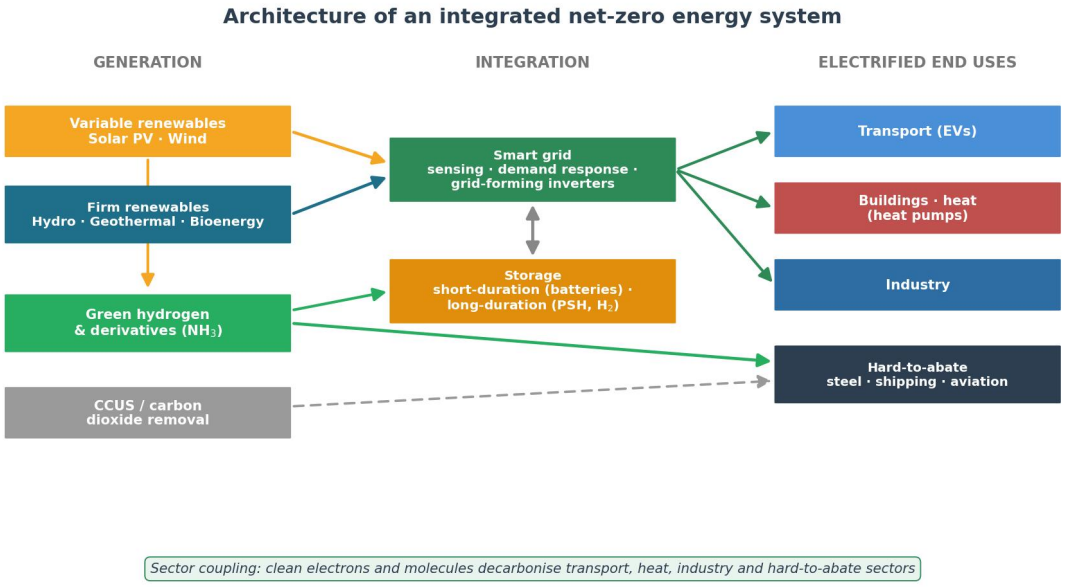

Figure 9. Architecture of an integrated net-zero energy system, coupling variable and firm renewables, smart grids, short- and long-duration storage, green hydrogen, and CCUS/carbon-dioxide removal with electrified end uses and hard-to-abate sectors.

Table 11. Comparison of principal energy-storage technologies for renewable integration.

Technology	Type	Typical duration	Maturity	Key strengths	Key limitations
Lithium-ion battery	Electrochemical	minutes–hours	Mature (cost −93% since 2010)	high efficiency, falling cost, scalable	critical minerals, fire/EoL, short duration
Sodium-ion battery	Electrochemical	minutes–hours	Early commercial	low-cost, mineral-light	lower energy density
Flow battery	Electrochemical	hours	Commercial (niche)	long cycle life, decoupled power/energy	low energy density, cost
Pumped hydro storage	Mechanical	hours–days	Mature (dominant)	large scale, long life	geographic/ecological constraints
Compressed-air / gravity	Mechanical	hours	Demonstration–commercial	long duration, durable	siting, round-trip efficiency

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Technology	Type	Typical duration	Maturity	Key strengths	Key limitations
Thermal storage	Thermal	hours–days	Commercial (with CSP)	cheap, integrates heat	application-specific
Hydrogen / derivatives	Chemical	days–seasonal	Early commercial	seasonal/long-duration, sector coupling	round-trip efficiency, cost

Source: synthesised from IRENA (2025b) and the storage literature.

8. Major challenges and limitations

Despite record deployment and favourable economics, the green energy transition faces structural challenges that this review treats as binding constraints rather than transient obstacles (Table 12).

Intermittency and variability. Solar and wind are weather- and time-dependent, creating supply variability across timescales from seconds to seasons. This is the defining technical challenge of a renewable-dominated system and the root cause of curtailment, the need for firm capacity, and the value of storage and flexibility.

Storage limitations. While short-duration battery storage has become cheap, cost-effective long-duration and seasonal storage remains unsolved at scale (Section 7.4). Without it, very high renewable penetrations require either large overbuild and curtailment or continued reliance on firm (often fossil) backup.

Grid integration. Transmission and interconnection bottlenecks, the need for grid-forming inverters and system-strength services, and slow permitting now constrain renewable deployment as much as generation cost does. Grid expansion and modernisation are lagging generation growth in many regions.

High up-front capital cost and financing. Renewables are capital-intensive with low operating costs, so their economics are highly sensitive to the cost of capital. Financing costs are a key determinant of viability, and high capital costs disadvantage developing economies despite their excellent resources, contributing to the deployment inequity evident in the data (IRENA, 2025b, 2026).

Policy, market, and regulatory barriers. Inconsistent policy, fossil-fuel subsidies, permitting delays, market designs that undervalue flexibility and firmness, and trade measures (including tariffs on renewable components) all impede deployment. The 2030 tripling target is currently out of reach largely for policy and deployment-pace reasons rather than technical ones (IRENA, 2025a).

Environmental trade-offs. As Sections 4–5 established, renewables carry real environmental costs in land, water, biodiversity, materials, and waste. Ignoring these risks both ecological harm and social opposition that delays deployment;

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managing them adds cost and complexity.

Material scarcity and supply concentration. Dependence on geographically concentrated critical minerals creates supply, price, and geopolitical risks, and the environmental and social burdens of mining can offset some clean-energy benefits if poorly governed (Section 4.9).

Geographic and social inequity. Deployment, investment, and benefits remain highly concentrated; Africa and small island developing states hold a tiny fraction of global capacity despite acute energy-access needs and high vulnerability (IRENA, 2026). A transition that does not address this inequity is neither just nor globally effective.

Table 12. Major challenges and corresponding mitigation and research directions.

Challenge	Underlying cause	Mitigation / research direction
Intermittency	Resource variability	Storage, hybrids, firm renewables, demand flexibility, interconnection
Long-duration storage	Technology/cost gap	Flow, sodium-ion, PSH, CAES/gravity, hydrogen; long-duration R&D
Grid bottlenecks	Slow grid build-out	Transmission expansion, grid-forming inverters, permitting reform
High capital cost	Capital intensity	Concessional finance, risk reduction, blended finance for EMDEs
Policy barriers	Inconsistent frameworks	Stable policy, subsidy reform, market design for flexibility/firmness
Environmental trade-offs	Land/water/biodiversity/ materials	Spatial planning, agrivoltaics, LCA-informed siting, biodiversity metrics
Material scarcity	Supply concentration	Circular economy, substitution, recycling, diversified supply
Inequity	Concentrated investment	Finance and technology transfer; energy-access focus

9. Research gaps

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Synthesising the preceding analysis, this review identifies a set of unresolved scientific questions that should structure the research agenda:

1. **Harmonised, regionally disaggregated LCA.** The LCA literature is fragmented in boundaries, functional units, allocation, and regional assumptions, undermining comparability. Harmonised, transparent, and geographically specific assessments — especially for fast-changing technologies whose manufacturing footprints decline yearly — are needed.
2. **Biodiversity-explicit impact metrics.** Biodiversity impacts are severe for some sources yet rarely captured in standard LCA or technology comparisons. Robust, comparable, and spatially explicit biodiversity metrics for energy systems are largely absent.
3. **Integrated water–energy–land–materials nexus modelling.** Most assessments treat impact categories in isolation. Integrated nexus models that capture trade-offs and synergies across carbon, water, land, and materials — and their regional heterogeneity — are needed to avoid solving one problem by worsening another.
4. **Reservoir and biomass carbon accounting.** The climate footprint of hydropower reservoirs (especially tropical methane) and the carbon-debt dynamics of biomass remain genuinely contested and require improved measurement, modelling, and standardised accounting conventions.
5. **Long-duration and seasonal storage.** Cost-effective long-duration storage is the central technical gap for very-high-renewable systems and lacks a proven, scalable solution.
6. **End-of-life and circularity.** Recycling technologies, economics, and infrastructure for PV modules, wind blades, and batteries lag deployment; closed-loop material flows and design-for-recycling standards are underdeveloped.
7. **Critical-material sustainability.** The environmental, social, and governance dimensions of the mineral supply chains underpinning the transition are under-quantified, as are substitution and dematerialisation pathways.
8. **Green-hydrogen system value and footprint.** The true life-cycle environmental footprint (including water and indirect warming from leakage), the conditions for genuine additionality, and the realistic role and cost trajectory of green hydrogen remain uncertain.
9. **Cumulative and synergistic ecological effects.** The landscape- and seascape-scale cumulative impacts of large-scale renewable deployment, and their synergies, are poorly understood relative to project-level effects.
10. **Just-transition and equity research.** The distribution of costs, benefits, and impacts — across regions, communities, and generations — and the policy and finance mechanisms to make the transition equitable are critically under-researched relative to the techno-economic literature.

10. Future perspectives and recommendations

10.1 Technological recommendations

Priorities include accelerating long-duration and seasonal storage; advancing tandem and next-generation photovoltaics to commercial durability while resolving lead and stability concerns; scaling floating offshore wind and next-generation geothermal to broaden firm renewable options; maturing recyclable wind blades and

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high-recovery PV and battery recycling; and developing AI and grid-forming technologies for system integration with attention to their own resource footprints. Material efficiency, substitution, and circularity should be treated as core design objectives, not afterthoughts.

10.2 Policy recommendations

Policy should provide stable, long-horizon frameworks; reform and phase out fossil-fuel subsidies while internalising the full life-cycle externalities of all energy sources (including those of renewables); redesign electricity markets to value flexibility, firmness, and system services rather than energy alone; accelerate permitting and grid build-out; mandate circular-economy and end-of-life standards for renewable hardware; and embed biodiversity, water, and land safeguards in siting. Crucially, international finance and technology transfer must address the stark deployment inequity, channelling concessional and blended finance to emerging and developing economies where capital costs, not resources, are the binding constraint (IRENA, 2025b, 2026; UNEP, 2024).

10.3 Environmental-management strategies

Deployment should be guided by spatial planning that steers projects away from high-biodiversity and high-conflict areas; by multifunctional land use (agrivoltaics, floating PV, dual-use wind-agriculture) to reduce land competition; by water-aware siting in arid regions; by mitigation hierarchies (avoid, minimise, restore, offset) for unavoidable ecological impacts; and by mandatory, standardised LCA and environmental monitoring across the asset life cycle, including end-of-life. The goal is to co-optimise decarbonisation with biodiversity, water, soil, and material sustainability rather than to trade them off implicitly.

10.4 Research priorities for the next decade

The research agenda should prioritise the ten gaps in Section 9, with particular emphasis on (i) harmonised, nexus-integrated, biodiversity-explicit sustainability assessment; (ii) long-duration storage and firm renewables; (iii) circular-economy systems for end-of-life infrastructure; and (iv) just-transition science. Methodologically, the field needs greater standardisation, transparency, open data, and uncertainty quantification, and a rebalancing of effort from generation technology toward system integration and environmental impact, where the literature currently lags deployment.

11. Conclusion

The evidence assembled in this review supports a nuanced rather than triumphalist conclusion. Green energy is being deployed at a historically unprecedented pace — a record 692 GW of renewable capacity was added in 2025, renewables supplied 85.6% of new capacity, and clean sources have become the cheapest form of new electricity in most of the world (IEA, 2025a; IRENA, 2025b, 2026). On the decisive metrics of climate and air quality, renewables — and especially wind and solar photovoltaics — outperform fossil fuels by one to two orders of magnitude, and their life-cycle energy and carbon performance continues to improve. The transition is therefore both necessary and, increasingly, economically inevitable.

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Yet three sobering conclusions temper this optimism. First, deployment alone has not yet bent the global emissions curve, which reached a record 37.8 Gt of energy-related CO_2 in 2024, because renewables are still too often added alongside rather than instead of fossil capacity, and because the world remains off track for the 2030 tripling goal and for 1.5 °C (IEA, 2025a, 2025b; IRENA, 2025a). Second, green energy is not environmentally free: its burdens — in land, water, biodiversity, critical materials, and end-of-life waste — are real, unevenly distributed, and growing in absolute terms as deployment scales, and they are systematically under-weighted in a literature still dominated by carbon and cost. Third, persistent controversies (reservoir methane, biomass carbon accounting, hydrogen's contingent benefits, and material and recycling bottlenecks) mean that "renewable" cannot be equated with "sustainable" without qualification.

The path forward is not to slow the transition but to make it genuinely sustainable (Figure 10): to co-optimise decarbonisation with biodiversity, water security, material circularity, and social equity; to invest in storage, system integration, and circular-economy infrastructure at the pace of generation growth; and to build a harmonised, nexus-integrated, and equity-aware evidence base. The next decade will determine not only how fast the world decarbonises, but whether it does so in a way that is ecologically and socially sustainable. Meeting both tests simultaneously is the central challenge — and opportunity — of green energy in the twenty-first century.

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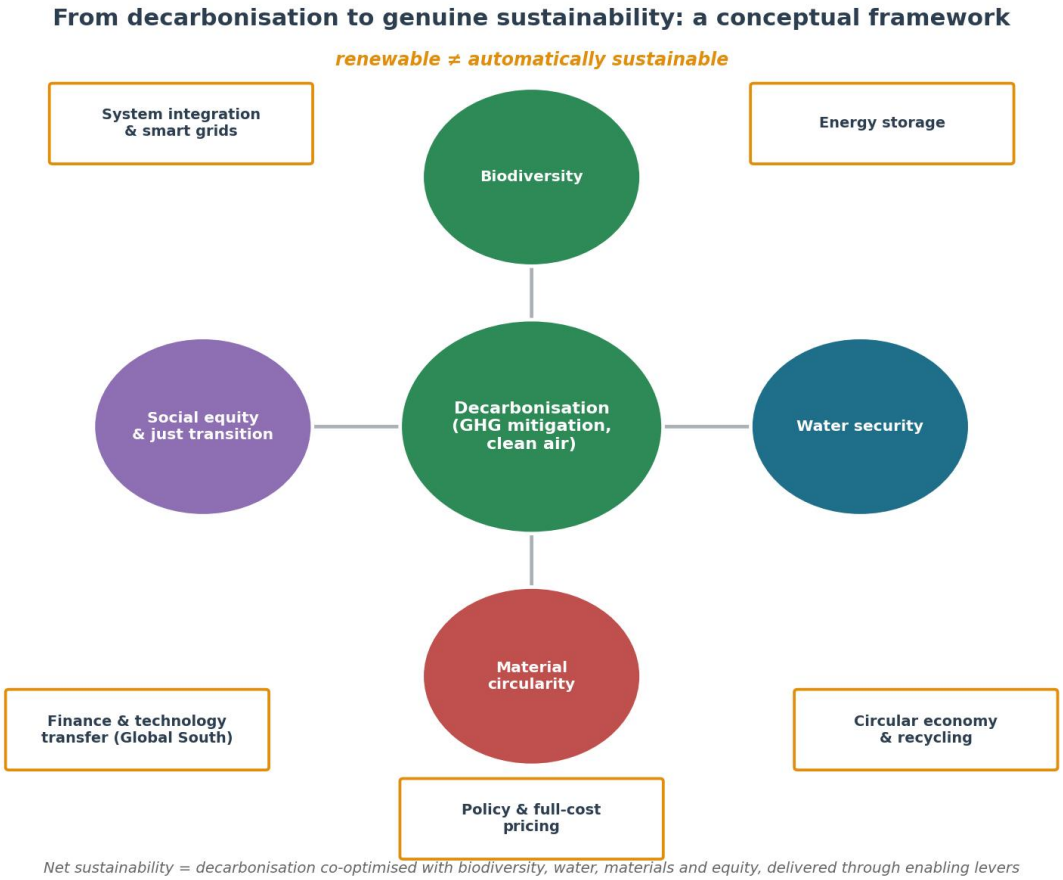

Figure 10. Conceptual framework for a genuinely sustainable energy transition, in which decarbonisation is co-optimised with biodiversity, water security, material circularity, and social equity, delivered through enabling levers (system integration, storage, circular economy, policy, and finance).

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