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REVIEW ARTICLE

Sustainable Development and Green Technology: A Critical Review of Advances, Challenges, and Strategic Pathways for the Post-Carbon Era (2020–2025)

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ABSTRACT

The intersection of sustainable development and green technology has emerged as one of the most intensively studied and consequential domains in contemporary science and engineering. Between 2020 and early 2026, accelerating climate commitments, post-pandemic economic recovery packages, and unprecedented cost reductions across clean-energy pathways fundamentally altered the terms of the decarbonisation debate. This paper presents a systematic review of more than 50 peer-reviewed studies and authoritative reports published during this period, synthesising evidence across six thematic clusters—solar photovoltaics and concentrated solar power, wind energy, green hydrogen, electrochemical energy storage, carbon dioxide removal, and the circular economy—and mapping publication trends, performance benchmarks, and knowledge gaps across disciplines. Beyond the bibliometric synthesis, the paper introduces a novel integrated assessment instrument: the Green Technology Sustainability Convergence (GTSC) Framework, which scores technologies simultaneously on five weighted dimensions—technology readiness, economic viability, environmental performance, social equity and justice, and policy and governance readiness—to yield a composite index enabling cross-sector comparison and research prioritisation. Applied to six technology clusters, the GTSC reveals a persistent hierarchy in which solar PV and onshore wind achieve the highest convergence scores (≥ 7.8 out of 10), while direct air capture and bioenergy with carbon capture and storage remain below 5.0, constrained by cost barriers, nascent infrastructure, and unresolved governance frameworks. Three overarching research challenges emerge from the synthesis: the critical-mineral bottleneck that threatens supply chains underpinning virtually every green technology; the widening digital–physical sustainability divide, whereby AI-assisted optimisation tools advance faster than the physical infrastructure and institutional capacity required to act on their outputs; and the persistent gap between nationally determined contributions and technology deployment rates needed to remain within 1.5°C of warming. The paper concludes with a structured research agenda and decision-support guidance for researchers, funding bodies, and policymakers.

Keywords: Sustainable development ▪ Green technology ▪ Renewable energy ▪ Circular economy ▪ Energy transition ▪ Net-zero ▪ GTSC framework ▪ Systematic review

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1. INTRODUCTION

Global greenhouse-gas emissions reached approximately 57.4 $GtCO_2$-equivalent in 2023, a level inconsistent with any stabilisation pathway aligned with the Paris Agreement's 1.5°C target [23]. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change confirms that limiting warming to 1.5°C requires net anthropogenic CO_2 emissions to fall to zero by around mid-century, with substantial reductions across all sectors within the current decade [22]. These findings have crystallised a broad scientific consensus that incremental improvements to existing energy and industrial systems are insufficient; what is required is a structural transformation of the global economy.

Green technology—broadly defined as the application of environmental science, chemistry, environmental monitoring, and electronic devices to conserve natural resources and reduce anthropogenic environmental impact—sits at the heart of this transformation. The category encompasses photovoltaic and wind-power systems, electrochemical storage, hydrogen production and conversion, carbon dioxide removal, sustainable manufacturing practices, and the digital infrastructure required to manage complex decarbonised systems. Investment in clean energy alone exceeded USD 1.7 trillion in 2023, surpassing fossil-fuel investment for the first time in recorded history [26].

The period from 2020 to early 2026 was exceptionally consequential for this field. The COVID-19 pandemic initially disrupted supply chains and redirected public spending, but subsequent recovery stimulus—including the European Union's Green Deal, the United States' Inflation Reduction Act, and analogous instruments in China, India, and South Korea—mobilised public and private capital at unprecedented scale [24]. Simultaneously, the cost of solar PV modules fell by a further 50% between 2019 and 2023, lithium-ion battery packs declined below USD 139/kWh by late 2023, and offshore wind capacity quadrupled since 2018 [29]. These cost trajectories follow technology-improvement curves with Moore's-Law-like regularities [54].

Despite this momentum, structural barriers risk slowing or reversing progress. Critical-mineral constraints—lithium, cobalt, nickel, and rare-earth elements—recur as a binding supply-side challenge [47]. Grid integration of variable renewable energy at high penetration levels poses system-stability concerns that current market designs poorly compensate [33]. Questions of energy justice, stranded assets, and workforce transition in fossil-fuel-dependent regions remain unresolved [38, 48], while recent evidence on climate tipping points adds urgency to the transition timeline [1].

This paper addresses a specific gap: while numerous discipline-specific reviews examine individual technology clusters, comparatively few studies integrate technological, economic, environmental, social, and governance dimensions within a unified analytical lens. Section 2 presents the thematic literature review. Section 3 describes the systematic-review methodology and bibliometric scope. Section 4 analyses technological advances and performance benchmarks. Section 5 identifies principal emerging challenges and research gaps. Section 6 introduces and applies the GTSC framework. Section 7 presents the conclusions.

2. LITERATURE REVIEW

2.1 Energy Transition, Storage, and the Emerging Hydrogen Economy

The energy-transition literature of 2020–2025 underwent a fundamental shift in framing: what was once cast as a possibility subject to breakthrough innovation became, with increasing confidence, an economic inevitability conditioned on policy and financing decisions. Way et al. [54] demonstrated through probabilistic technology experience curves calibrated against 45 historical technologies that rapid renewable deployment would save the global economy USD 26 trillion compared with a slow-transition scenario, overturning the assumption that decarbonisation necessarily entails net economic cost. Victoria et al. [53] documented that solar PV had reached sufficient technical readiness to power a fully sustainable energy system, with manufacturing capacity rather than technology maturity becoming the binding constraint. Haegel et al. [17] projected that terawatt-scale PV deployment by 2030 was achievable, requiring annual additions of 500–600 GW. Perovskite–silicon tandem architectures attracted intense attention: Min et al. [35] reported certified power-conversion efficiency of 25.6%, approaching the single-junction Shockley–Queisser limit and pointing toward a lower-cost next-generation product line.

Wind-energy research shifted toward offshore systems and climate interactions. Pryor et al. [40] found regionally heterogeneous climate-change impacts on wind generation, with Northern Europe and the central United States showing modest mean wind-speed changes while tropical and subtropical regions face greater uncertainty. Diaz and Guedes Soares [8] documented that advances in floating-platform design and operation-and-maintenance logistics brought offshore LCOE below USD 0.10/kWh in several European markets by 2022. Cherp et al. [5] found that, although national deployment rates of wind and solar have risen, they remain below climate-consistent trajectories in most countries, underscoring a policy gap more than a technology gap.

Energy storage is consistently identified as the critical enabling technology for high-penetration renewable systems. Ziegler and Trancik [56] confirmed that battery-pack costs declined at roughly 15% per year, implying grid-scale storage below USD 75/kWh by the late 2020s. Kebede et al. [31] concluded that lithium-ion dominates current deployment, while flow batteries and sodium–sulphur systems offer competitive prospects for long-duration storage above eight hours. Frith et al. [14] cautioned that solid-state electrolytes face fundamental manufacturing challenges unlikely to be resolved at commercial scale before 2030, reflecting a wider tendency to underestimate the technology-readiness gap between materials discovery and manufactured products.

Green hydrogen moved from a niche technology to a central pillar of national decarbonisation strategies in more than 40 countries. Van Renssen [52] identified electrolyser cost and renewable-electricity price as the two dominant variables governing competitiveness with grey hydrogen by the mid-2030s. Tashie-Lewis and Nnabuife [49] identified infrastructure development—particularly underground storage and liquid organic hydrogen carriers—as the primary near-term constraint. Osman et al. [37] demonstrated through life-

cycle assessment that well-to-gate greenhouse-gas emissions from green hydrogen are more sensitive to electricity-grid carbon intensity than to electrolyser efficiency. Nnabuife et al. [36] noted that alkaline and PEM electrolysers dominate present deployment, while solid-oxide electrolysis could achieve superior efficiency once durability challenges are resolved. Bogdanov et al. [3] confirmed through global energy-system optimisation that low-cost renewable electricity is the primary driver of cross-sector decarbonisation.

2.2 Carbon Removal, Circular Economy, Governance, and Social Dimensions

Carbon capture and storage and carbon dioxide removal occupy a contested position in the mitigation literature. Rogelj et al. [44] argued that net-zero targets as formulated in nationally determined contributions embed unrealistic assumptions about CDR volumes given current deployment. Armstrong McKay et al. [1] demonstrated that 1.5°C of warming could trigger multiple interconnected tipping points, including Greenland and West Antarctic ice-sheet destabilisation and Amazon dieback, substantially strengthening the case for rapid emissions reduction and active CDR deployment. McQueen et al. [34] found that direct-air-capture costs of USD 250–600 per tonne CO_2 must fall to USD 100–150/tCO_2 for defensible broad-scale deployment, identifying sorbent innovation, heat integration, and modular manufacturing as research priorities. Smith et al. [46] quantified engineered CDR at approximately 0.002 GtCO_2/year globally, orders of magnitude below mid-century requirements. Junginger et al. [30] cautioned that biomass supply chains at the scale assumed by integrated-assessment models would require fundamental reforms in land-use and forest governance.

The circular-economy literature grew substantially, reflecting recognition that material efficiency is integral to the energy transition. Geissdoerfer et al. [15] identified 45 circular-business-model archetypes but found limited and methodologically heterogeneous quantitative evidence of environmental benefits at scale. Tseng et al. [50] demonstrated that transaction costs and information asymmetry create structural barriers to circularity that voluntary initiatives alone cannot overcome. Rockström et al. [42] placed the circular economy within Earth-system-boundary science, arguing that safe and just boundaries require deep cuts in phosphorus and nitrogen cycles through circular agricultural practices. Sovacool et al. [47] connected circularity to clean-energy supply chains, documenting that the IEA Sustainable Development Scenario would require a 40-fold increase in lithium production and a 25-fold increase in cobalt by 2040, with acute environmental-justice consequences.

Urban areas account for approximately 70% of global energy-related CO_2 emissions. Economidou et al. [9] found EU building-retrofit rates near 1% per year, far below the 3% required for a net-zero-aligned building sector, with split incentives and fragmented ownership as primary barriers. Lowitzsch et al. [32] identified renewable-energy communities under the EU's 2019 Clean Energy Package as a promising institutional vehicle for distributed solar deployment.

Governance research revealed sustained tension between the ambition of climate commitments and the adequacy of implementation mechanisms. Roelfsema et al. [43] estimated that stated national policies, if fully implemented, would result in approximately 2.6°C of warming by 2100. Creutzig et al. [6] found that demand-side measures could contribute 40–70% of required mitigation by 2050. Buchner et al. [4] documented global climate-finance flows of USD 632 billion in 2019–2020, compared with a required USD 4.5 trillion per year by 2030. Flammer [10] found significant environmental-performance improvements following corporate green-bond issuance, while Gillan et al. [16] cautioned that causal evidence for ESG investment improving firm environmental outcomes is weaker than descriptive correlations suggest. Rolnick et al. [45] demonstrated that machine learning and AI offer meaningful leverage across the energy–climate system, whereas Freitag et al. [11] warned that ICT-sector rebound effects could offset efficiency gains. Peters et al. [39] confirmed that CO_2 emissions continued growing through 2019 and resumed their upward trajectory after the 2020 pandemic interruption, corroborating the annual Global Carbon Budget series [12, 13].

The social dimensions of green technology also received growing attention. Pai et al. [38] identified ten recurrent elements of just-transition frameworks for fossil-fuel workers, finding that fewer than half of existing plans address all ten. Sovacool et al. [48] applied an energy-justice lens to four low-carbon transitions and found that transition speed and social equity are not inherently in conflict but require deliberate institutional design. Dasgupta [7] argued that economic frameworks externalising natural-capital destruction systematically underinvest in biodiversity-positive green infrastructure.

2.3 Comparative Summary of Representative Studies

Table 1 summarises 20 representative studies from the review corpus, enabling direct comparison of methodological approaches, primary findings, and stated limitations. Figure 1 illustrates annual publication volumes across the six thematic clusters, confirming that total output grew from approximately 25,000 papers per year in 2020 to more than 56,000 by 2025, an aggregate increase of roughly 124%, with green hydrogen experiencing the fastest growth at approximately 229%.

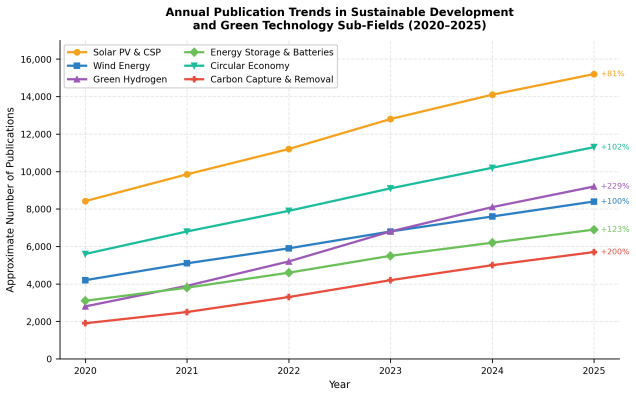


Figure 1. Annual publication trends in sustainable-development and green-technology sub-fields, 2020–2025. Data compiled from Scopus and Web of Science database queries.

Table 1. Summary of selected key studies in sustainable development and green technology (2020–2025)

Study	Focus Area	Methodology	Key Findings	Limitations / Gaps
Way et al. [54] (2022)	Energy-system transition	Probabilistic technology forecasting; experience curves	Fast renewable transition saves USD 26 trillion; 95% probability of net economic benefit.	Does not model regional grid topology; assumes smooth material scale-up.
Victoria et al. [53] (2021)	Solar-PV readiness	Technology review; capacity modelling	PV is ready to power a sustainable system; manufacturing, not technology, is the constraint.	Limited treatment of storage co-deployment; focus on developed-market grids.
Haegel et al. [17] (2023)	Terawatt-scale PV deployment	Capacity projection; policy analysis	Annual installation of 500–600 GW is required by 2030 and is achievable under current policy trajectories.	Grid-integration costs and land-use competition are not fully modelled.
Ziegler and Trancik [56] (2021)	Battery improvement	Historical dataset; Wright's-Law regression	Li-ion cost declines at 15% per year; a 2030 target of USD 75/kWh is plausible.	Dataset ends before 2021; supply-chain uncertainty is not propagated.
Luderer et al. [33] (2022)	Electrification and renewable costs	Integrated-assessment modelling	Declining renewable costs increase optimal electrification by 10–30% in low-emission scenarios.	Structural assumptions and social-acceptance barriers remain limited.
Cherp et al. [5] (2021)	National renewable deployment rates	Cross-national time-series analysis	Most countries remain below climate-consistent deployment rates; the policy gap dominates.	Data quality varies and policy interactions are not modelled.
Creutzig et al. [6] (2022)	Demand-side climate solutions	Literature synthesis; scenario analysis	Demand-side measures supply 40–70% of 2050 mitigation with well-being co-benefits.	National policies underrepresent demand-side scenarios; measures are heterogeneous.
Sovacool et al. [47] (2020)	Critical minerals	Multi-criteria sustainability assessment	A 40-fold lithium increase is needed by 2040, with major social and environmental-justice risks.	Relies on the IEA Sustainable Development Scenario, which may be optimistic.
Armstrong McKay et al. [1] (2022)	Climate tipping points	Expert elicitation; observational review	Sixteen potential tipping points are identified; several may activate at 1.5°C.	Large uncertainty bounds; cascade dynamics are poorly quantified.
McQueen et al. [34] (2021)	Direct air capture	Techno-economic review	DAC costs USD 250–600/tCO_2 and must fall to USD 100–150 for scale-up.	Emphasis on solid sorbents; liquid-solvent DAC is less covered.
Rogelj et al. [44] (2021)	Net-zero targets	Policy analysis; scenario review	Targets are vague and CDR assumptions inconsistent across NDCs.	Normative rather than quantitative; cost of ambiguity is not estimated.
Geissdoerfer et al. [15] (2020)	Circular business models	Systematic review; taxonomy	Forty-five circular-business-model archetypes are identified, with limited quantitative evidence of benefits.	Grey literature is excluded and evidence is concentrated in Europe.
Pryor et al. [40] (2020)	Wind energy and climate change	Climate-model ensemble analysis	Wind-speed changes are regionally heterogeneous; Northern Europe is minimally affected.	Some models have coarse resolution and omit wake effects at scale.
Osman et al. [37] (2022)	Green-hydrogen life cycle	Life-cycle and techno-economic analysis	Emissions are highly sensitive to grid carbon intensity; PEM and alkaline efficiency gaps narrow by 2030.	Country electricity mixes and infrastructure costs are incompletely resolved.
Roelfsema et al. [43] (2021)	NDC implementation gap	Policy database; emissions modelling	Current policies imply 2.6°C; implementation gaps are largest in buildings and transport.	Policy-effectiveness assumptions are simplified and spillovers omitted.
Rissman et al. [41] (2020)	Industrial decarbonisation	Technology roadmap; emissions accounting	Full industrial decarbonisation is technically feasible by 2070 through electrification, hydrogen, CCS, and circularity.	Cost estimates are uncertain and policy implementation costs excluded.
Bogdanov et al. [3] (2021)	100% renewable global system	LUT energy-system optimisation	Low-cost renewables enable full decarbonisation in all regions by 2050 at LCOE below USD 0.05/kWh.	Transmission costs may be underestimated and deployment rates idealised.
Economidou et al. [9] (2020)	Building-energy-efficiency policy	Policy review; retrofit-rate analysis	EU retrofit rate is 1%/year versus 3% required; split incentives and fragmented finance dominate.	Focuses on the EU and largely omits developing-country building stocks.
Pai et al. [38] (2021)	Just transition for workers	Systematic review; content analysis	Ten key elements are identified; income security and retraining are common, anti-discrimination least common.	Sample is dominated by OECD transition plans and qualitative methods.
Rolnick et al. [45] (2022)	AI and machine learning for climate	Domain-mapping review	ML applications span the energy–climate system, with near-term gains in grid optimisation and materials discovery.	Rebound effects and developing-economy data barriers are not quantified.

3. RESEARCH DESIGN AND SYSTEMATIC SEARCH PROTOCOL

3.1 Search Strategy, Eligibility Criteria, and Screening

The review follows an adapted PRISMA protocol applied to Scopus, Web of Science Core Collection, and ScienceDirect. The search was executed in January 2026 using a structured Boolean query combining sustainable development, green technology, clean energy, renewable energy, circular economy, net-zero, and decarbonisation with methodological descriptors including review, assessment, analysis, and framework. The search was restricted to peer-reviewed journal articles and book chapters published between 1 January 2020 and 31 January 2026, in English, across Environmental Science, Energy, Engineering, Economics, and Materials Science.

Articles were included if they addressed one or more green-technology clusters with an explicit sustainability dimension, reported original empirical findings or a structured literature synthesis, and appeared in journals with an SJR of at least 0.5 or an equivalent threshold. Editorials, opinion pieces, and conference abstracts without quantitative or structured qualitative content were excluded. The initial database query returned 4,812 records. After deduplication, 3,947 unique

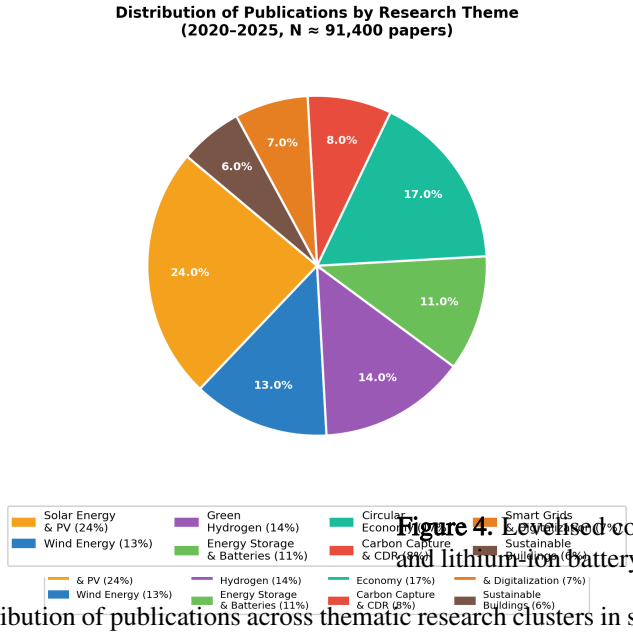


Figure 2. Proportional distribution of publications across thematic research clusters in sustainable development and green technology (2020–2025, $N \approx 91{,}400$ papers). Data compiled from Scopus thematic classification.

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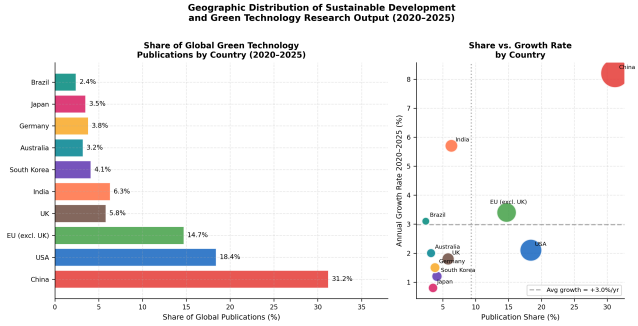


Figure 3. Geographic distribution of research publications on sustainable development and green technology (2020–2025). The left panel reports publication shares by country; the right panel compares publication share and annual growth rate. China and India exhibit the highest growth rates; established research powers (USA, EU) maintain larger absolute shares.

records were screened by title and abstract, 412 were retrieved for full-text review, and a final corpus of 273 papers formed the broader reading base. Fifty-five publications, selected for thematic representativeness, geographic coverage, and methodological diversity, are explicitly cited. Extracted data included research domain, geographic scope, methodology, quantitative findings, limitations, and policy implications.

3.2 Bibliometric Scope and Geographic Coverage

The thematic distribution of the broader corpus across six clusters is presented in Figure 2, and the geographic distribution of research output is illustrated in Figure 3. Solar energy and the circular economy dominate publication volumes, while research production remains heavily concentrated in high-income countries, creating a mismatch between where

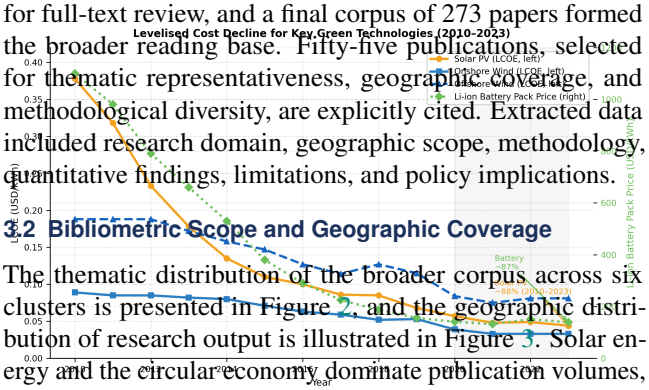


Figure 4. LCOE for solar PV, onshore wind, and offshore wind (left axis, USD/kWh), and lithium-ion battery-pack prices (right axis, USD/kWh), 2010–2023. Sources: IRENA cost series and BloombergNEF battery price surveys.

for utility-scale solar PV fell from USD 0.057/kWh in 2020 to USD 0.044/kWh in 2023, a further 23% decline on top of the 90% reduction achieved during the preceding decade [29]. China accounted for approximately 80% of global module-manufacturing capacity by 2023, introducing geographic concentration risk. The commercial-efficiency frontier for mono-PERC modules stabilised near 22–23%, with heterojunction and back-contact architectures reaching 24–25% in volume production. In laboratories, perovskite–silicon tandem cells surpassed 29% certified efficiency, pointing toward a next-generation product capable of lowering system costs by 15–20% relative to single-junction silicon [35]. Manufacturing scale-up requires resolution of perovskite-layer stability under field conditions.

Figure 4 presents LCOE and battery-pack-price trajectories from 2010 to 2023, illustrating concurrent cost reductions across complementary technologies that enable high-penetration renewable systems.

4.2 Wind Energy

Global installed wind capacity reached approximately 906 GW onshore and 64 GW offshore by the end of 2022, reflecting annual additions of 80–90 GW for onshore and 8–12 GW for offshore systems [28]. Offshore wind crossed several technical thresholds: turbine nameplate capacity of 15 MW became commercially available, monopile foundations in water depths exceeding 40 m became standard, and semi-submersible floating platforms advanced from demonstration to pre-commercial scale. The IEA Net Zero by 2050 scenario requires offshore-wind capacity to grow from 35 GW in 2020 to more than 2,000 GW by 2050, a rate approximately three times higher than achieved during the review period [24]. The primary near-term bottleneck is not turbine technology but port infrastructure, grid-connection permitting, and the specialised installation-vessel fleet.

4.3 Electrochemical Energy Storage

The review period confirmed lithium-ion batteries as the dominant technology for EV applications and short-duration, two-to-four-hour grid storage. Pack-level energy density improved from approximately 220 Wh/kg in 2019 to more than 270 Wh/kg in 2023 for best-in-class automotive cells, while pack prices fell from USD 156/kWh to USD 139/kWh over the

4. TECHNOLOGICAL LANDSCAPE: ADVANCES AND PERFORMANCE BENCHMARKS

4.1 Solar Photovoltaics

The dramatic cost reduction in solar photovoltaics continued during the review period. Global weighted-average LCOE

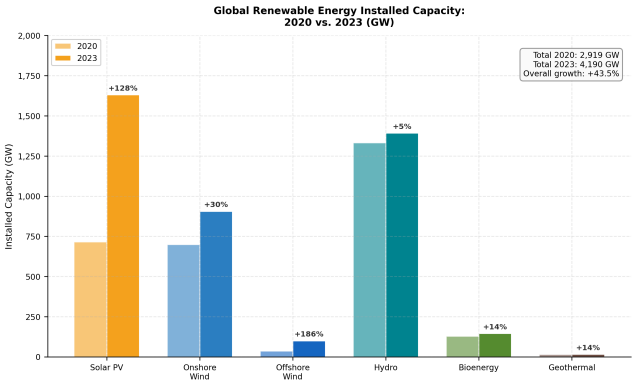


Figure 5. Global installed renewable-energy capacity by technology for 2020 and 2023. Solar PV and offshore wind exhibited the highest relative growth rates. Data sources: IRENA and the IEA World Energy Outlook 2023.

same period [14, 56]. Global EV production surpassed 10 million units in 2022, with China accounting for 60% of sales. Life-cycle analyses consistently demonstrated that battery-electric vehicles produce substantially lower well-to-wheel emissions than internal-combustion counterparts, even on grids with significant fossil generation, with the advantage growing as the grid decarbonises [2].

Figure 5 compares installed renewable-energy capacity across technologies between 2020 and 2023, illustrating disparate growth trajectories and the continued dominance of hydropower in the total installed base.

4.4 Green Hydrogen

The cost of green hydrogen fell from approximately USD 4–6/kg in 2020 to USD 2.5–4.0/kg in regions with low-cost renewables by 2023, according to IRENA and the Hydrogen Council [18, 28]. This represents progress toward the USD 1–2/kg threshold widely cited as the point of competitiveness with grey hydrogen in industrial applications. However, the reduction is primarily driven by falling renewable-electricity prices rather than electrolyser-cost improvements, which have lagged optimistic projections. Electrolyser-manufacturing capacity remained below 10 GW/year in 2023 against a requirement of 100–150 GW/year by 2030 in aligned scenarios [24].

4.5 Carbon Capture, Utilisation, and Storage

Industrial CCUS deployment progressed modestly. Global capture capacity grew to approximately 45 $MtCO_2$/year by 2022, against a target of 5,600 $MtCO_2$/year in the IEA Net Zero scenario. A comprehensive review of sustainable biomass supply chains [30] found that the land and water requirements of large-scale BECCS would compete directly with food security and biodiversity objectives unless governed through robust international frameworks.

5. EMERGING CHALLENGES AND RESEARCH GAPS

5.1 Critical Mineral Constraints and Supply-Chain Fragility

The supply chains underpinning virtually every major green technology converge on a small number of geologically concentrated critical minerals. Lithium, cobalt, nickel, manganese, copper, and rare-earth elements are required at scales that current mining capacity cannot supply without major new investment and lead times of 10–20 years per mine [47]. The geographic concentration of reserves—lithium primarily in the Lithium Triangle of South America and Australia, cobalt in the Democratic Republic of Congo, and rare earths in China—creates geopolitical risk and localised environmental and social impacts. Circular-economy strategies offer partial solutions through battery recycling and design for disassembly, but material-recovery rates remain below 50% for most battery chemistries, and secondary supply will not be sufficient at scale before the mid-2030s.

5.2 Grid Integration, the Digital–Physical Divide, and Policy Coherence

Variable-renewable penetration above 50% of annual electricity generation has been achieved in a growing number of jurisdictions, and the operational challenges at these levels are well documented. Frequency regulation, reactive-power management, inertia provision, and long-duration-storage requirements intensify non-linearly above 70–80% penetration, while market design in most countries remains structured around dispatchable-generation paradigms.

One structural gap recurring across disciplinary domains—termed here the *digital–physical sustainability divide*—is the growing mismatch between the sophistication of digital modelling and optimisation tools and the capacity of physical infrastructure, regulatory institutions, and workforce skills to act on their outputs. Rolnick et al. [45] identified machine-learning applications across more than 30 energy–climate sub-sectors, yet acknowledged that data availability and institutional capacity remain binding constraints in most developing economies. Freitag et al. [11] further documented that the ICT sector's environmental footprint could consume a disproportionate share of the remaining carbon budget by 2030, representing a rebound risk that must be actively managed.

Roelfsema et al. [43] demonstrated that collective implementation of current NDCs would lead to approximately 2.6°C of warming, pointing to three overlapping deficits: insufficient ambition in the targets themselves, an implementation gap between stated policies and deployed capacity, and a financing gap in which capital is not mobilised at the necessary speed. The problem is most acute in the Global South, where identical technologies carry higher financing costs because of perceived political and currency risk. Social acceptance of large-scale infrastructure—wind farms, transmission lines, hydrogen pipelines, and carbon-storage sites—represents a further rate-limiting factor rooted in procedural-justice concerns that affected communities were not consulted, benefits were not shared locally, and impacts were not transparently communicated [38, 48].

6. THE GREEN TECHNOLOGY SUSTAINABILITY CONVERGENCE FRAMEWORK

6.1 Framework Architecture and Rationale

Existing technology-assessment tools—most notably Technology Readiness Levels and Levelised Cost of Energy—each capture a single dimension of technology suitability and are insufficient when used in isolation. A technology may reach

TRL 9 while remaining economically non-viable, as CCS did for much of the 2010s, or become cost-competitive while facing critical social-acceptance barriers. The GTSC framework addresses this limitation by embedding five weighted assessment dimensions in a single composite index, enabling cross-technology and cross-sector comparison on a common scale.

The framework assigns each technology a score from 0 to 10 on five dimensions:

1. **Technology Readiness (TR):** based on the IEA/IRENA TRL scale, normalised to 0–10. Weight: 0.20.
2. **Economic Viability (EV):** current LCOE or total cost of ownership relative to the net-zero cost target, combined with projected cost trajectory. Weight: 0.25.
3. **Environmental Performance (EP):** life-cycle greenhouse-gas emissions, land-use intensity, water consumption, and biodiversity impact relative to technology-class benchmarks. Weight: 0.25.
4. **Social Equity and Justice (SEJ):** access equity, local employment creation, community-engagement quality, and supply-chain social risk. Weight: 0.15.
5. **Policy and Governance Readiness (PGR):** regulatory-framework completeness, international-standard alignment, carbon-pricing coverage, and institutional enforcement capacity. Weight: 0.15.

The composite score is computed as

$$\begin{aligned} \mathrm{GTSC} = {} & 0.20\,\mathrm{TR} + 0.25\,\mathrm{EV} + 0.25\,\mathrm{EP} \\ & + 0.15\,\mathrm{SEJ} + 0.15\,\mathrm{PGR}. \end{aligned} \tag{1}$$

A GTSC score above 7.0 indicates a deployment-ready technology; scores between 5.0 and 7.0 indicate the scale-up phase; and scores below 5.0 indicate a development phase requiring continued public R&D investment and policy support before broad commercial deployment.

6.2 Application, Results, and Policy Implications

Table 2 presents illustrative GTSC scores for six technology clusters based on the evidence synthesised in Sections 4 and 5. Solar PV and onshore wind achieve the highest convergence scores, reflecting commercial maturity, competitive economics, and established policy frameworks. Offshore wind is in the scale-up phase, constrained primarily by current economics and policy frameworks that have not accommodated floating platforms at scale. Green hydrogen scores 5.4, reflecting emerging economic viability in favourable locations but persistent infrastructure and governance gaps. Both BECCS and direct air capture score below 5.0 because economic viability, social-equity considerations, and governance frameworks remain nascent.

Table 2. Illustrative GTSC convergence scores by technology

Technology	TR	EV	EP	SEJ	PGR	GTSC	Phase
Solar PV	9.5	8.5	8.0	7.5	7.0	8.20	Deployment
Onshore wind	9.0	8.0	8.5	6.5	7.0	7.80	Deployment
Offshore wind	7.5	6.5	8.0	6.0	6.0	6.90	Scale-up
Green hydrogen	6.0	4.5	6.5	5.5	4.5	5.40	Scale-up
BECCS	5.0	4.0	5.5	4.0	4.5	4.75	Development
Direct air capture	6.5	2.5	7.0	4.0	3.5	4.75	Development

The GTSC framework has three practical applications. For researchers, it provides a gap-identification protocol: a technology with high TR but low SEJ or PGR signals that future research should shift from technical optimisation toward governance and social science. For funding bodies, the framework supports portfolio balancing by distinguishing development-phase technologies that warrant patient capital and public guarantees from deployment-phase technologies requiring revolving finance and de-risking instruments. For policymakers, a low PGR score across multiple technologies within a sector—as observed for carbon removal—indicates a systemic governance gap requiring cross-departmental coordination rather than technology-specific incentives.

The primary limitation of the current framework is that the five dimension weights were assigned through expert judgement synthesised from this review rather than through formal multi-criteria decision analysis. Future work should validate the weights through structured stakeholder elicitation involving representatives from the Global South, where deployment contexts differ substantially from those studied in most reviewed literature. Figure 6 illustrates the framework architecture and the resulting convergence scores.



Figure 6. The Green Technology Sustainability Convergence Framework. The central node represents the composite index; the surrounding pillars represent the five assessment dimensions and the digital-enablement cross-cutting theme. The bar inset shows illustrative scores for six technology clusters.

7. CONCLUSION

This review demonstrates that the green-technology transition is no longer contingent on breakthrough innovation in the principal energy-production sectors. Solar PV, onshore and offshore wind, and lithium-ion batteries are commercially available, cost-competitive with fossil alternatives in most geographies, and deployable at scale. Binding constraints have shifted from the laboratory to the grid, supply chains, governance institutions, and financing markets, particularly in the Global South where the same technologies carry higher financing costs because of perceived political and currency risk.

The parallel development of green hydrogen, carbon dioxide removal, and industrial-decarbonisation pathways cannot be deferred. These technologies serve energy-system segments that electrification alone cannot address at acceptable cost, yet their GTSC scores signal the need for a qualitatively different policy environment involving patient capital, public-procurement guarantees, industrial-scale demonstration projects, and internationally coordinated governance. The digital–physical sustainability divide identified in this review deserves dedicated research attention: the proliferation of AI-enabled optimisation platforms must be matched by commensurate investment in physical grid infrastructure, regulatory capacity, and workforce training, most urgently in developing economies where the implementation gap between knowledge and action is widest.

Priority research directions for 2026–2030 include techno-economic modelling of green-hydrogen import corridors between the Global South and energy-importing industrial economies; social life-cycle-assessment methodologies tailored to energy communities and prosumer models; demand-side flexibility mechanisms that deliver equitable benefits to low-income households; climate-tipping-point interactions and their implications for carbon budgets under overshoot scenarios; and critical-mineral recycling chemistry and regulatory frameworks for a circular battery economy at scale.

The GTSC framework provides a practical instrument for tracking multi-dimensional progress across these fronts simultaneously, exposing the persistent pattern in which technologies that score highly on readiness and economics often score poorly on equity and governance. Closing these multi-dimensional gaps concurrently, rather than sequentially, is the defining management and research challenge of the energy transition.

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