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

Irina V. Austokhina[1,*], **Aenis A. Austokhin**[2]

[1]Department of Entrepreneurship and Logistics, Plekhanov Russian University of Economics, Moscow 117997, Russia
[2]Department of Logistics, State University of Management, Moscow 109542, Russia

Emails: Pustohina.IV@rea.ru; da_pustohin@guu.ru

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, and 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 map-ping 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 ($\geq$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 over-arching 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 are advancing faster than the physical infrastructure and institutional capacity required to act on their outputs; and the persistent gap between nationally determined contributions and the technology de-ployment 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 working in this field.

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

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].

DOI: https://doi.org/10.54216/JSDGT.060203

Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

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 the 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 to below USD 139/kWh by late 2023, and offshore wind capacity quadrupled since 2018 [29]. These cost trajectories are characterised empirically as technology improvement curves that follow Moore's Law-like regularities [54].

Despite this momentum, a growing body of evidence documents structural barriers that risk slowing or reversing progress. Critical mineral constraints—lithium, cobalt, nickel, and rare earth elements—emerge repeatedly 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 underresolved [38, 48]. Recent evidence on climate tipping points adds urgency to the timeline [1].

This paper addresses a specific gap: while numerous discipline-specific reviews cover individual technology clusters in depth, comparatively few works integrate technological, economic, environmental, social, and governance dimensions into a unified analytical lens. The paper is structured as follows. 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 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 a probabilistic analysis grounded in 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 long-standing assumption that decarbonisation necessarily entails net economic cost. Victoria et al. [53] documented that solar PV had reached a state of technical readiness sufficient to power a fully sustainable energy system, with manufacturing capacity—rather than technology maturity—as the binding constraint on faster deployment. Haegel et al. [17] subsequently projected that terawatt-scale PV deployment by 2030 was achievable, requiring annual capacity additions of 500–600 GW per year. Perovskite–silicon tandem architectures attracted intense attention: Min et al. [35] reported a certified power conversion efficiency of 25.6 % for such a cell, approaching the Shockley–Queisser limit for single-junction devices and pointing toward a next-generation product line with lower system costs.

Wind energy research shifted emphasis towards offshore systems and climate interactions. Pryor et al. [40] found regionally heterogeneous climate-change impacts on wind power 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 while 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—trajectories implying grid-scale storage below USD 75/kWh by the late 2020s. Kebede et al. [31] reviewed stationary storage technologies and concluded that while lithium-ion dominates current deployment, flow batteries and sodium–sulphur systems offer competitive prospects for long-duration storage above 8 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 TRL gap between materials discovery and manufactured product in academic literature.

Green hydrogen moved from a niche technology to a central pillar of national decarbonisation strategies for more than 40 countries during the review period. 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 the carbon intensity of the electricity grid than to electrolyser efficiency. Nnabuife et al. [36] noted that while alkaline and PEM electrolysers dominate current deployments, solid-oxide electrolysis operating at high temperature could achieve superior efficiency once durability challenges are resolved. Bogdanov et al. [3] confirmed through a global energy system optimisation model that low-cost renewable electricity is the primary driver of decarbonisation across all sectors.

DOI: https://doi.org/10.54216/JSDGT.060203
Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

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 NDCs embed unrealistic assumptions about CDR volumes given current technology 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 sharpening the case for both rapid emissions reduction and active CDR deployment. McQueen et al. [34] found that current direct air capture costs of USD 250–600 per tonne CO_2 must fall to USD 100–150/tCO_2 for economically defensible broad-scale deployment, identifying sorbent innovation, heat integration, and modular manufacturing as priority research areas. Smith et al. [46] quantified that engineered CDR currently removes approximately 0.002 GtCO_2/year globally—orders of magnitude below mid-century requirements. Junginger et al. [30] cautioned that sustainable biomass supply chains at the scale assumed by most integrated assessment models would require fundamental governance reforms in land use and forest management.

The circular economy literature grew substantially, reflecting recognition that material efficiency is integral to rather than separate from the energy transition. Geissdoerfer et al. [15] identified 45 distinct circular business model archetypes but found quantitative evidence of environmental benefits at scale to be limited and methodologically heterogeneous. Tseng et al. [50] demonstrated that transaction cost economics 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 the circular economy directly to clean energy supply chains, documenting that achieving the IEA's 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 at approximately 1 % per year—far below the 3 % required to align the building sector with net-zero pathways—with split-incentive problems 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 a 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 that total global climate finance flows reached USD 632 billion in 2019–2020 but must scale to USD 4.5 trillion per year by 2030. Flammer [10] found statistically significant environmental performance improvements following corporate green bond issuances. Gillan et al. [16] cautioned that causal evidence for ESG investments 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, while Freitag et al. [11] cautioned that ICT sector rebound effects could offset efficiency gains if not proactively managed. Peters et al. [39] confirmed that CO_2 emissions continued growing through 2019 and resumed their upward trajectory after the 2020 pandemic interruption, a finding corroborated by the annual Global Carbon Budget series [12, 13].

The social dimensions of green technology received growing scholarly 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 across thematic domains. 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 over 56,000 by 2025 (an aggregate increase of roughly 124 %), with green hydrogen experiencing the fastest growth rate at approximately 229 %.

DOI: https://doi.org/10.54216/JSDGT.060203
Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

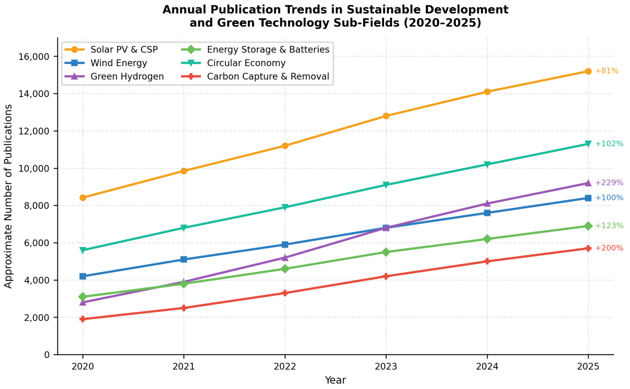

Figure 1. Annual publication trends in sustainable development and green technology sub-fields, 2020–2025. Data compiled from Scopus and Web of Science database queries.

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 26T; 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 ready to power sustainable system; manufacturing, not technology, is the constraint	Limited treatment of storage co-deployment; focuses on developed-market grids
Haegel et al. [17] (2023)	Terawatt-scale PV deployment	Capacity projection; policy analysis	500–600 GW/yr installation required by 2030; achievable under current policy trajectories	Does not quantify grid integration costs; land-use competition not fully modelled
Ziegler and Trancik [56] (2021)	Battery technology improvement	Historical dataset; Wright's Law regression	Li-ion cost declining at 15%/yr; 2030 target of USD 75/kWh plausible	Dataset ends pre-2021; supply-chain cost uncertainty not propagated
Luderer et al. [33] (2022)	Electrification and RE costs	Integrated assessment modelling (REMIND)	Declining RE costs increase optimal electrification by 10–30% in low-emission scenarios	IAM structural assumptions; limited representation of social acceptance barriers
Cherp et al. [5] (2021)	National renewable deployment rates	Cross-national time-series analysis (140+ countries)	Most countries below climate-consistent deployment rates; policy gap dominates	Data quality varies across countries; does not model policy interaction effects
Creutzig et al. [6] (2022)	Demand-side climate solutions	Literature synthesis; scenario analysis	Demand-side measures = 40–70% of 2050 mitigation; high well-being co-benefits	Demand-side scenarios under-represented in national policies; measurement heterogeneity
Sovacool et al. [47] (2020a)	Critical minerals	Multi-criteria sustainability assessment	40× lithium increase needed by 2040; major social and environmental justice risks	Relies on IEA Sustainable Development Scenario which may itself be optimistic
Armstrong McKay et al. [1] (2022)	Climate tipping points	Expert elicitation; review of observational evidence	16 potential tipping points identified; several activated at 1.5 °C	Large uncertainty bounds; cascade dynamics poorly quantified
McQueen et al. [34] (2021)	Direct air capture	Techno-economic review	DAC costs USD 250–600/tCO_2; must fall to USD 100–150 for scale-up	Focus on solid sorbent systems; liquid solvent DAC less covered
Rogelj et al. [44] (2021)	Net-zero targets	Policy analysis; scenario review	Net-zero targets vague; CDR assumptions inconsistent across NDCs	Does not quantify cost of CDR ambiguity; normative rather than quantitative
Geissdoerfer et al. [15] (2020)	Circular business models	Systematic literature review; taxonomy	45 circular business model archetypes identified; limited quantitative evidence of benefits	Grey literature excluded; geographic concentration in Europe
Pryor et al. [40] (2020)	Wind energy and climate change	Climate model ensemble analysis	Regionally heterogeneous wind speed changes; Northern Europe minimally affected	Coarse spatial resolution in some models; does not account for wake effects at scale
Osman et al. [37] (2022)	Green hydrogen life cycle	LCA and techno-economic analysis	GHG emissions highly sensitive to electricity carbon intensity; PEM vs. alkaline efficiency gap closes by 2030	Country-specific electricity mixes not fully resolved; infrastructure costs underweighted
Roelfsema et al. [43] (2021)	NDC implementation gap	Policy database analysis; emissions modelling	Current policies → 2.6 °C; implementation gap largest in buildings and transport	Policy effectiveness assumptions simplified; no explicit modelling of policy spillovers
Rissman et al. [41] (2020)	Industrial decarbonisation	Technology roadmap; emissions accounting	Full industrial decarbonisation technically feasible by 2070 through electrification, H_2, CCS and circularity	Cost estimates have wide uncertainty ranges; policy implementation costs excluded

Continued on next page

DOI: https://doi.org/10.54216/JSDGT.060203
Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

Study	Focus Area	Methodology	Key Findings	Limitations / Gaps
Bogdanov et al. [3] (2021)	100% RE global system	Energy system optimisation (LUT model)	Low-cost RE enables full decarbonisation in all world regions by 2050 at LCOE $<$ USD 0.05/kWh	Transmission infrastructure costs may be underestimated; technology deployment rates idealised
Economidou et al. [9] (2020)	Building energy efficiency policy	Policy review; retrofit rate analysis	EU retrofit rate 1%/yr vs. 3% required; split incentives, fragmented finance are primary barriers	Focus on EU; non-EU developing country building stock largely unexamined
Pai et al. [38] (2021)	Just transition for workers	Systematic review; content analysis	10 key elements identified; income security and retraining most common; anti-discrimination least	Sample dominated by OECD-country transition plans; qualitative methodology
Rolnick et al. [45] (2022)	AI and machine learning for climate	Domain mapping review	ML applications across full energy-climate system; largest near-term gains in grid optimisation and materials discovery	Rebound effects and data access barriers in developing economies not quantified

3. Research Design and Systematic Search Protocol

3.1. Search Strategy, Eligibility Criteria, and Screening

The review follows an adapted PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol applied to three electronic databases: Scopus, Web of Science (Core Collection), and ScienceDirect. The search was executed in January 2026 using a structured Boolean query combining terms in sustainable development, green technology, clean energy, renewable energy, circular economy, net-zero, and decarbonisation, each intersected with methodological descriptors (review, assessment, analysis, 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 subject categories. 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 a SCImago Journal Rank (SJR) ≥ 0.5 or 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 records were screened by title and abstract, of which 412 were retrieved for full-text review. A final corpus of 273 papers formed the broader reading base. From this corpus, 55 publications—selected for representativeness across themes, geographic coverage, and methodological diversity—are explicitly cited in this manuscript. Data extracted from each retained source included: research domain, geographic scope, methodology, key quantitative findings, identified limitations, and policy implications.

3.2. Bibliometric Scope and Geographic Coverage

The thematic distribution of the broader corpus across the six identified clusters is presented in Figure 2, and the geographic distribution of research output is illustrated in Figure 3. Both figures reveal patterns with direct implications for where research effort should be directed: solar energy and the circular economy dominate publication volumes, and research production remains heavily concentrated in high-income countries, creating a systematic mismatch between where knowledge is generated and where the deployment challenge is most acute.

4. Technological Landscape: Advances and Performance Benchmarks

4.1. Solar Photovoltaics

The dramatic cost reduction in solar photovoltaics continued unabated during the review period. Global weighted-average LCOE for utility-scale solar PV fell from USD 0.057/kWh in 2020 to USD 0.044/kWh in 2023, a 23 % further decline on top of the 90 % reduction achieved over the prior decade [29]. China accounted for approximately 80 % of global module manufacturing capacity by 2023, introducing substantial geographic concentration risk into the supply chain. The commercial efficiency frontier for mono-PERC modules stabilised around 22–23 %, with heterojunction and back-contact architectures reaching 24–25 % in volume production. In the laboratory, 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 of tandem devices requires resolution of perovskite layer stability under field conditions—a problem that is the focus of substantial ongoing research effort.

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

4.2. Wind Energy

Global installed wind capacity reached approximately 906 GW onshore and 64 GW offshore by end-2022, reflecting consistent year-on-year additions of 80–90 GW for onshore and 8–12 GW for offshore systems [28]. Offshore wind crossed several technical thresholds during the period: turbine nameplate capacity of 15 MW became commercially

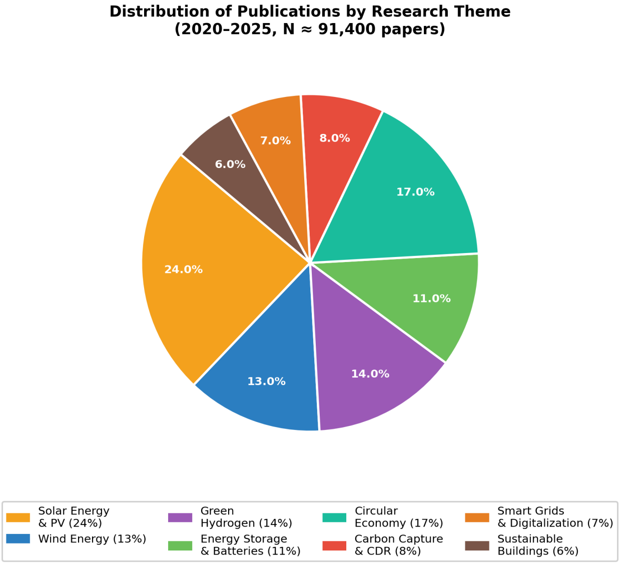

Figure 2. Proportional distribution of publications across thematic research clusters in sustainable development and green technology (2020–2025, N ≈ 91,400 papers). Data compiled from Scopus thematic classification.

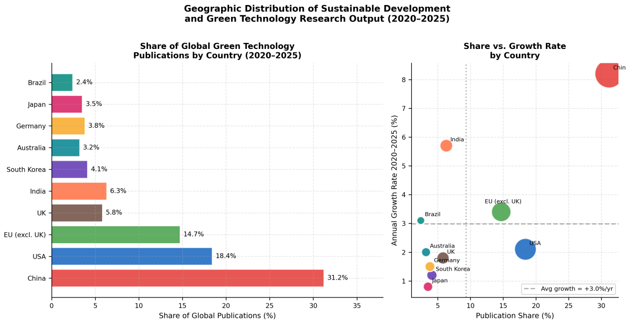

Figure 3. Geographic distribution of research publications on sustainable development and green technology (2020–2025). Left panel: publication shares by country. Right panel: publication share versus annual growth rate. China and India exhibit the highest growth rates; established research powers (USA,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

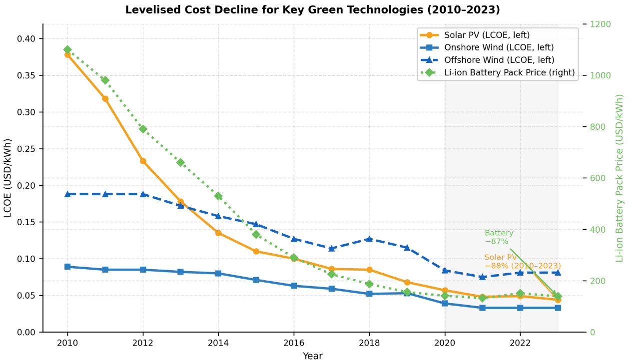

Figure 4. Levelised cost of electricity (LCOE) for solar PV, onshore wind, and offshore wind (left axis, USD/kWh) and lithium-ion battery pack prices (right axis, USD/kWh), 2010–2023. Sources: IRENA Renewable Power Generation Costs series [27, 29]; BloombergNEF battery price surveys.

DOI: https://doi.org/10.54216/JSDGT.060203
Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

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's Net Zero by 2050 scenario requires offshore wind capacity to grow from 35 GW in 2020 to over 2,000 GW by 2050—a rate of addition approximately three times higher than anything 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 both EV applications and short-duration (2–4 hour) grid storage. Pack-level energy density improved from approximately 220 Wh/kg in 2019 to over 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 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.

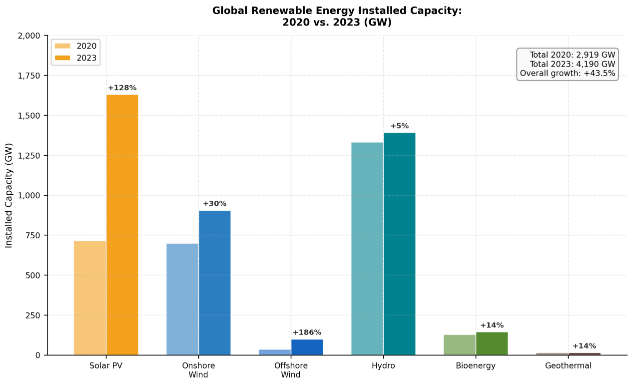

Figure 5. Global installed renewable energy capacity (GW) by technology for 2020 and 2023. Solar PV and offshore wind exhibited the highest relative growth rates (+128 % and +186 % respectively). Data sources: IRENA [28, 29]; IEA World Energy Outlook 2023 [26].

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 cost 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 during the review period. Global capture capacity grew to approximately 45 $MtCO_2$/year by 2022, against a target of 5,600 $MtCO_2$/year in the IEA's Net Zero scenario—a gap that illustrates the scale of the challenge. A comprehensive review of sustainable biomass supply chains [30] found that the land area 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; rare earths in China—creates both geopolitical risk and localised environmental and social impact. The circular economy literature offers partial solutions through battery recycling and design-for-disassembly, but material recovery rates remain below 50 % for most battery chemistries, and secondary material supply will not be sufficient at scale before the mid-2030s at the earliest.

DOI: https://doi.org/10.54216/JSDGT.060203

Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

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

Variable renewable energy 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 that recurs across multiple disciplinary domains—here termed 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 are the binding constraints in most developing economy contexts. Freitag et al. [11] further documented that the ICT sector's own 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 the 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, particularly in the Global South, where identical technologies carry higher financing costs due to perceived political and currency risk. Social acceptance of large-scale infrastructure deployment—wind farms, transmission lines, hydrogen pipelines, 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 (GTSC) Framework

6.1. Framework Architecture and Rationale

Existing technology assessment tools—most notably the Technology Readiness Level scale and Levelised Cost of Energy analysis—each capture a single dimension of technology suitability and are insufficient when used in isolation. A technology can reach TRL 9 while remaining economically non-viable (as CCS did for much of the 2010s), or can be 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 (1–11), normalised to 0–10. Weighting: 0.20.
2. **Economic Viability (EV):** Composite of current LCOE or total cost of ownership relative to the cost target for a net-zero scenario, and projected cost trajectory. Weighting: 0.25.
3. **Environmental Performance (EP):** Life-cycle greenhouse gas emissions per unit of energy or service delivered, land-use intensity, water consumption, and biodiversity impact, scored relative to technology-class benchmarks. Weighting: 0.25.
4. **Social Equity and Justice (SEJ):** Scores access equity, local employment creation, community engagement quality, and supply chain social risk. Weighting: 0.15.
5. **Policy and Governance Readiness (PGR):** Assesses regulatory framework completeness, international standard alignment, carbon pricing coverage, and institutional enforcement capacity. Weighting: 0.15.

The composite GTSC score is computed as:

$$\text{GTSC} = 0.20 \cdot TR + 0.25 \cdot EV + 0.25 \cdot EP + 0.15 \cdot SEJ + 0.15 \cdot PGR \tag{1}$$

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

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 ($\geq$7.8), reflecting full commercial maturity, competitive economics, and well-established policy frameworks. Offshore wind is in the scale-up phase, constrained primarily by current economics and policy frameworks that have not yet accommodated floating platforms at scale. Green hydrogen scores 5.4, reflecting emerging economic viability in favourable locations but

DOI: https://doi.org/10.54216/JSDGT.060203

Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

persistent infrastructure and governance gaps. Both BECCS and DAC score below 5.0—not because of technical immaturity per se, but because economic viability, social equity considerations, and governance frameworks remain nascent.

Table 2: Illustrative GTSC Convergence Scores by Technology (based on evidence from this review)

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 offers three practical applications. For *researchers*, it provides a gap-identification protocol: a technology with a high TR score but low SEJ or PGR score signals that future research should shift from technical optimisation toward governance and social science. For *funding bodies*, the framework supports portfolio balancing, distinguishing between development-phase technologies that warrant patient capital and public guarantees from deployment-phase technologies that require 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 from a 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 GTSC framework architecture and the resulting convergence scores for the six technology clusters.

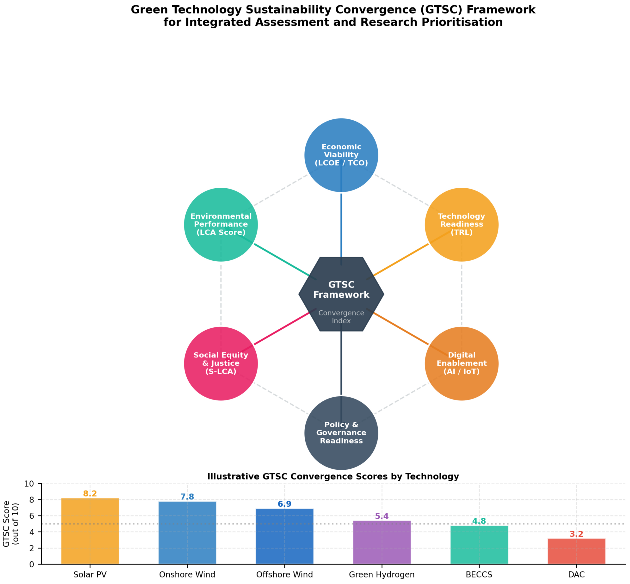

Figure 6. The Green Technology Sustainability Convergence (GTSC) Framework. The central node represents the composite convergence index; the surrounding pillars represent the five assessment dimensions and the digital enablement cross-cutting theme. The bar inset shows illustrative GTSC scores for the six main 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; the binding constraints have shifted from the laboratory to the grid, to supply chains, to governance institutions, and to financing markets, particularly in the Global South where the same technologies carry higher financing costs due to perceived political and currency risk. The parallel development of green hydrogen, carbon dioxide removal, and industrial decarbonisation pathways cannot be deferred: these technologies serve segments of the energy system that

DOI: https://doi.org/10.54216/JSDGT.060203
Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

electrification alone cannot address at acceptable cost, yet their GTSC scores signal the need for a qualitatively different policy environment—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 the period 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 the regulatory frameworks required to establish a circular battery economy at scale. The GTSC framework introduced in this paper provides a practical instrument for tracking multi-dimensional progress across all 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.

References

[1] Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950

[2] Bieker, G. (2021). *A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars*. International Council on Clean Transportation. https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars-2021/

[3] Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., De Souza Noel Simas Barbosa, L., Fasihi, M., Khalili, S., Traber, T., & Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy, 227*, 120467. https://doi.org/10.1016/j.energy.2021.120467

[4] Buchner, B., Clark, A., Falconer, A., Macquarie, R., Meattle, C., Tolentino, R., & Wetherbee, C. (2021). *Global landscape of climate finance 2021*. Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2021/

[5] Cherp, A., Vinichenko, V., Tosun, J., Gordon, J. A., & Jewell, J. (2021). National growth dynamics of wind and solar power compared to the requirements for global climate targets. *Nature Energy, 6*(7), 742–754. https://doi.org/10.1038/s41560-021-00863-0

[6] Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., Figueroa, M., Grubler, A., Lamb, W. F., Leip, A., Masanet, E., Mata, É., Mattauch, L., Minx, J. C., Mirasgedis, S., Mulugetta, Y., Nugroho, S. B., Oberle, B., Rao, N., & Wiedenhofer, D. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nature Climate Change, 12*(1), 36–46. https://doi.org/10.1038/s41558-021-01219-y

[7] Dasgupta, P. (2021). *The economics of biodiversity: The Dasgupta review*. HM Treasury. https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review

[8] Diaz, H., & Guedes Soares, C. (2020). Review of the current status, technology and future trends of offshore wind farms. *Ocean Engineering, 209*, 107381. https://doi.org/10.1016/j.oceaneng.2020.107381

[9] Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., & Castellazzi, L. (2020). Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings, 225*, 110322. https://doi.org/10.1016/j.enbuild.2020.110322

[10] Flammer, C. (2021). Corporate green bonds. *Journal of Financial Economics, 142*(2), 499–516. https://doi.org/10.1016/j.jfineco.2021.01.010

[11] Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G. S., & Friday, A. (2021). The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. *Patterns, 2*(9), 100340. https://doi.org/10.1016/j.patter.2021.100340

DOI: https://doi.org/10.54216/JSDGT.060203
Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

[12] Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Bates, N. R., Becker, M., Bellouin, N., & Zeng, J. (2022). Global carbon budget 2022. *Earth System Science Data, 14*(11), 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

[13] Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneth, A., Arora, V., Bates, N. R., & Zeng, J. (2020). Global carbon budget 2020. *Earth System Science Data, 12*(4), 3269–3340. https://doi.org/10.5194/essd-12-3269-2020

[14] Frith, J. T., Lacey, M. J., & Ulissi, U. (2023). A non-academic perspective on the future of lithium-based batteries. *Nature Communications*, *14*(1), 420. https://doi.org/10.1038/s41467-023-35851-7

[15] Geissdoerfer, M., Pieroni, M. P. T., Pigosso, D. C. A., & Soufani, K. (2020). Circular business models: A review. *Journal of Cleaner Production, 277*, 123741. https://doi.org/10.1016/j.jclepro.2020.123741

[16] Gillan, S. L., Koch, A., & Starks, L. T. (2021). Firms and social responsibility: A review of ESG and CSR research in corporate finance. *Journal of Corporate Finance, 66*, 101889. https://doi.org/10.1016/j.jcorpfin.2021.101889

[17] Haegel, N. M., Verlinden, P., Victoria, M., Altermatt, P., Atwater, H., Barnes, T., Breyer, C., Case, C., De Wolf, S., Deline, C., Feldman, D., Glunz, S., Goldschmidt, J. C., Habas, H., Hahn, G., Hallam, B., Heben, M., Hertwich, E., Holman, Z., & Margolis, R. (2023). Terawatt-scale photovoltaics: Transform global energy. *Science*, *380*(6640), 39–42. https://doi.org/10.1126/science.adf6957

[18] Hydrogen Council, & McKinsey & Company. (2021). *Hydrogen insights 2021*. https://hydrogencouncil.com/en/hydrogen-insights-2021/

[19] IEA, IRENA, UNSD, World Bank, & WHO. (2023). *Tracking SDG 7: The energy progress report 2023*. World Bank. https://trackingsdg7.esmap.org/downloads

[20] Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte et al., Eds.). https://doi.org/10.1017/9781009157896

[21] Intergovernmental Panel on Climate Change. (2022a). *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report* (H.-O. Pörtner et al., Eds.). https://doi.org/10.1017/9781009325844

[22] Intergovernmental Panel on Climate Change. (2022b). *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report* (P.R. Shukla et al., Eds.). https://doi.org/10.1017/9781009157926

[23] Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report* (Core Writing Team, H. Lee & J. Romero, Eds.). https://doi.org/10.59327/IPCC/AR6-9789291691647

[24] International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector*. https://www.iea.org/reports/net-zero-by-2050

[25] International Energy Agency. (2022). *World energy outlook 2022*. https://www.iea.org/reports/world-energy-outlook-2022

[26] International Energy Agency. (2023). *World energy outlook 2023*. https://www.iea.org/reports/world-energy-outlook-2023

[27] International Renewable Energy Agency. (2021). *Renewable power generation costs in 2020*. https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

[28] International Renewable Energy Agency. (2022). *World energy transitions outlook 2022: 1.5°C pathway*. https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022

[29] International Renewable Energy Agency. (2023). *Renewable power generation costs in 2022*. https://www.irena.org/publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022

Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

[30] Junginger, H. M., Mai-Moulin, T., Daioglou, V., Fritsche, U., Guisson, R., Hennig, C., Thrän, D., & van Dam, J. (2020). The future of biomass and bioenergy deployment and trade: A synthesis of 15 years IEA Bioenergy Task 40 on sustainable international bioenergy trade. *Biofuels, Bioproducts and Biorefining, 14*(2), 228–250. https://doi.org/10.1002/bbb.2076

[31] Kebede, A. A., Kalogiannis, T., Van Mierlo, J., & Berecibar, M. (2022). A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. *Renewable and Sustainable Energy Reviews, 159*, 112213. https://doi.org/10.1016/j.rser.2022.112213

[32] Lowitzsch, J., Hoicka, C. E., & van Tulder, F. J. (2020). Renewable energy communities under the 2019 European Clean Energy Package—Governance model for the energy clusters of the future? *Renewable and Sustainable Energy Reviews, 122*, 109489. https://doi.org/10.1016/j.rser.2019.109489

[33] Luderer, G., Madeddu, S., Merfort, L., Ueckerdt, F., Pehl, M., Pietzcker, R., Rottoli, M., Schreyer, F., Bauer, N., Baumstark, L., Bertram, C., Dirnaichner, A., Humpenöder, F., Levesque, A., Popp, A., Rodrigues, R., Strefler, J., & Kriegler, E. (2022). Impact of declining renewable energy costs on electrification in low-emission scenarios. *Nature Energy, 7*(1), 32–42. https://doi.org/10.1038/s41560-021-00937-z

[34] McQueen, N., Gomes, K. V., McCormick, C., Blumberg, K., Pisciotta, M., & Wilcox, J. (2021). A review of direct air capture (DAC): Scaling up commercial technologies and innovating for the future. *Progress in Energy, 3*(3), 032001. https://doi.org/10.1088/2516-1083/abf1ce

[35] Min, H., Lee, D. Y., Kim, J., Kim, G., Lee, K. S., Kim, J., Paik, M. J., Kim, Y. K., Kim, K. S., Kim, M. G., Shin, T. J., & Seok, S. I. (2021). Perovskite solar cells with atomically coherent interlayers on SnO_2 electrodes. *Nature, 598*(7881), 444–450. https://doi.org/10.1038/s41586-021-03964-8

[36] Nnabuife, S. G., Ugbeh-Johnson, J., Okeke, N. E., & Ogbonnaya, C. (2022). Present and projected developments in hydrogen production: A technological review. *Carbon Capture Science & Technology, 3*, 100042. https://doi.org/10.1016/j.ccst.2022.100042

[37] Osman, A. I., Mehta, N., Elgarahy, A. M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2022). Hydrogen production, storage, utilisation and environmental impacts: A review. *Environmental Chemistry Letters, 20*(1), 153–188. https://doi.org/10.1007/s10311-021-01322-8

[38] Pai, S., Harrison, K., & Zerriffi, H. (2021). A systematic review of the key elements of a just transition for fossil fuel workers. *One Earth*, *4*(11), 1657–1669. https://doi.org/10.1016/j.oneear.2021.10.015

[39] Peters, G. P., Andrew, R. M., Canadell, J. G., Friedlingstein, P., Jackson, R. B., Korsbakken, J. I., Le Quéré, C., & Peregon, A. (2020). Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nature Climate Change, 10*(1), 3–6. https://doi.org/10.1038/s41558-019-0659-6

[40] Pryor, S. C., Barthelmie, R. J., Bukovsky, M. S., Leung, L. R., & Sakaguchi, K. (2020). Climate change impacts on wind power generation. *Nature Reviews Earth & Environment, 1*(12), 627–643. https://doi.org/10.1038/s43017-020-0101-7

[41] Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Fisher, S. A., Rogers, S., Haley, B., Crabtree, J., Ramberg, M., & Williams, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy, 266*, 114848. https://doi.org/10.1016/j.apenergy.2020.114848

[42] Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S., Armstrong McKay, D. I., Bai, X., Bala, G., Bunn, S. E., Ciobanu, D., DeClerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T. M., Loriani, S., & Zhang, X. (2023). Safe and just Earth system boundaries. *Nature, 619*(7968), 102–111. https://doi.org/10.1038/s41586-023-06083-8

[43] Roelfsema, M., van Soest, H. L., Harmsen, M., van Vuuren, D. P., Bertram, C., den Elzen, M., Höhne, N., Iacobuta, G., Krey, V., Kriegler, E., Luderer, G., Riahi, K., Ueckerdt, F., Després, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Gidden, M., & Fujimori, S. (2021). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications, 12*(1), 2096. https://doi.org/10.1038/s41467-021-22294-x

[44] Rogelj, J., Geden, O., Cowie, A., & Reisinger, A. (2021). Three ways to improve net-zero emissions targets. *Nature, 591*(7850), 365–368. https://doi.org/10.1038/d41586-021-00662-3

DOI: https://doi.org/10.54216/JSDGT.060203

Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026

[45] Rolnick, D., Donti, P. L., Kaack, L. H., Kochanski, K., Lacoste, A., Sankaran, K., Ross, A. S., Milojevic-Dupont, N., Jaques, N., Waldman-Brown, A., Luccioni, A., Maharaj, T., Sherwin, E. D., Mukkerjee, S., Körfer, G., Beery, S., Nachmany, M., Pyfer, L. S., Banerjee, A., & Bengio, Y. (2022). Tackling climate change with machine learning. *ACM Computing Surveys, 55*(2), 1–96. https://doi.org/10.1145/3485128

[46] Smith, S. M., Geden, O., Nemet, G., Gidden, M., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratlong, L., & Minx, J. C. (2023). *The state of carbon dioxide removal—1st edition*. The State of Carbon Dioxide Removal. https://doi.org/10.17605/OSF.IO/W3B4Z

[47] Sovacool, B. K., Ali, S. H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., & Mulvaney, D. (2020a). Sustainable minerals and metals for a low-carbon future. *Science, 367*(6473), 30–33. https://doi.org/10.1126/science.aaz6003

[48] Sovacool, B. K., Martiskainen, M., Hook, A., & Baker, L. (2020b). Decarbonization and its discontents: A critical energy justice perspective on four low-carbon transitions. *Climatic Change, 155*(4), 581–619. https://doi.org/10.1007/s10584-019-02521-7

[49] Tashie-Lewis, B. C., & Nnabuife, S. G. (2021). Hydrogen production, distribution, storage and power conversion in a renewable energy economy—A technology review. *Chemical Engineering Journal Advances, 8*, 100172. https://doi.org/10.1016/j.ceja.2021.100172

[50] Tseng, M. L., Chiu, A. S. F., Liu, G., & Jantaralolica, T. (2020). Circular economy enables sustainable consumption and production in multi-level supply chain system. *Resources, Conservation and Recycling, 154*, 104601. https://doi.org/10.1016/j.resconrec.2019.104601

[51] United Nations. (2023). *The sustainable development goals report 2023: Special edition*. https://unstats.un.org/sdgs/report/2023/

[52] van Renssen, S. (2020). The hydrogen solution? *Nature Climate Change, 10*(9), 799–801. https://doi.org/10.1038/s41558-020-0891-0

[53] Victoria, M., Zhu, K., Brown, T., Andresen, G. B., & Greiner, M. (2021). Solar photovoltaics is ready to power a sustainable future. *Joule, 5*(5), 1041–1056. https://doi.org/10.1016/j.joule.2021.03.005

[54] Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. *Joule, 6*(9), 2057–2082. https://doi.org/10.1016/j.joule.2022.08.009

[55] World Bank. (2022). *State and trends of carbon pricing 2022*. https://doi.org/10.1596/978-1-4648-1895-0

[56] Ziegler, M. S., & Trancik, J. E. (2021). Re-examining rates of lithium-ion battery technology improvement and cost decline. *Energy & Environmental Science, 14*(4), 1635–1651. https://doi.org/10.1039/D0EE02681F

DOI: https://doi.org/10.54216/JSDGT.060203
Received: February 08, 2026 Revised: March 12, 2026 Accepted: April 11, 2026