Sustainable Energy Development: History and Progress

Subjects: Energy & Fuels
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Sustainable energy development (SED) is a crucial component of the Sustainable Development Goals (SDG), aiming to maintain economic and social progress while protecting the environment and mitigating climate change's effects. SED serves as a transition paradigm for sustainable development, providing a blueprint for energy peace and prosperity for people and all uses.

sustainable energy development | SED themes | SED emerging issues | 1.5 °C scenario | energy financing | 100% renewable energy uprise | decarbonization strategies

1. History

Sustainable energy development (SED) is a concept introduced by the United Nations World Energy Assessment (WEA) report that considers energy development's economic, social, and environmental aspects. The United Nations' WEA report highlighted the significance of not "exceeding the carrying capacity of ecosystems" regarding energy production and use. It also stressed how critical it is to have a reliable, low-cost source of electricity [1]. Since then, SED has been a global policy priority to address the issues plaguing the modern energy sector, such as the depletion of fossil fuels, increasing energy consumption, and global warming [2]. Notably, over the years, there has been a growing interest in and increasing strategies aimed at achieving sustainable development from the energy sector. The historical development of energy and sustainable development was first highlighted by I. Gunnarsdottir et al. in [2]; hence, an updated and more detailed history is presented in **Table 1**, extracted from an original supplementary part of the work by J. Akpan and O. Oludolapo in [3].

Table 1. Historical path of energy versus sustainable development with key selected reports.

Year	Protocol and Description	Ref.
1972	Stockholm Meeting The first international meeting devoted to global environmental issues, which led to the formation of the Brundtland Commission.	[4]
1974	International Energy Agency (IEA) A year after the Stockholm meeting, a global oil crisis occurred in 1973. In response to the global physical disruption in oil supplies, IEA, under the framework of the Organization for Economic Co-operation and Development (OECD), was formed to compile data on the international oil market with the aim of promoting energy efficiency and conservation and fostering international technological cooperation for research and development. Subsequently, there have been relevant energy reports and world energy outlooks from the IEA. • The 1998 editions used a "business-as-usual" approach, focusing on energy trends without new policies. • The 2001 edition extended its projection horizon to 2030. • The 2003 edition quantified global energy investment needs. • The 2004 edition questioned the sustainability of the current energy systems. • The 2005 edition assessed energy prospects in the Middle East and North Africa, focusing on China and India. • The 2009 edition analyzed the financing of energy investment under a post-2012 climate framework, global natural gas markets, and energy trends in Southeast Asia. • The 2010 edition presented a scenario that considered recent commitments to tackle climate change and worsening energy insecurity, focusing on renewable energy technologies, unconventional oil, climate policies, Caspian energy prospects, energy poverty, and energy subsidies.	[5][6][7]

<table>
<tr><th>Year</th><th>Protocol and Description</th><th>Ref.</th></tr>
<tr><td></td><td>The 2011 report noted that emerging economies’ oil demand for transport grew by almost 50%.
The 2012 edition featured new projections extended to 2040.
The 2017 edition introduced the Sustainable Development Scenario, a major new scenario aimed at achieving internationally agreed objectives on climate change, air quality, and universal access to modern energy.
The 2018 edition focused on producer economies and the impacts of the COVID-19 pandemic on the energy sector.
The 2020 edition worked through energy financing and funding.
The 2022 edition focused on the implications of the ongoing energy crisis triggered by Russia’s invasion of Ukraine.
The 2023 edition focused on oil analysis and forecasting to 2028.
The 2023 edition looked at world energy investment (yet to be concluded).</td><td></td></tr>
<tr><td>1987</td><td>Our Common Future—Brundtland Report
At the Brundtland Commission meeting, sustainable development was introduced, with energy being an integral part of the concept, because of concerns about the global oil crisis.</td><td>[8]</td></tr>
<tr><td>1988</td><td>International Climate Negotiations—Intergovernmental Panel on Climate Change (IPCC)
The United Nations Environmental Protection (UNEP) Agency sought an international convention to provide direction for restricting greenhouse gas emissions while improving energy and industrial processes and driving sustainable development. Then, the IPCC was formed, which has, since its establishment, made public findings from the scientific community and summarized them in the following reports, which were more specific to energy and sustainable development. These include the following:
IPCC Report of 1994 (Guidelines for National Greenhouse Gas Inventories);
IPCC Report of 1994 (Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios);
Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories
IPCC 2000 (Emission Scenarios);
IPCC 2001 (TAR Climate Change 2001—Mitigation);
IPCC 2005 (CO_2 Capture and Storage);
IPCC Report of 2006 (Guidelines for National Greenhouse Gas Inventories);
IPCC 2007 (IPCC Report of 1994 (Guidelines for National Greenhouse Gas Inventories);
2007 AR4 Synthesis Report—Climate Change;
2007 AR4 Mitigation of Climate Change;
2011 Renewable Energy Sources and Climate Change Mitigation;
2014 AR6 Synthesis Report—Climate Change;
2022 AR6 Climate Change—Mitigation of Climate Change;
IPCC 2018 (Global Warming of 1.5 degree Celsius);
IPCC Report of 2019 (Refinement to 2006 IPCC Guidelines for National Greenhouse Gas Inventories);
2022 AR6 Climate Change;</td><td>[9]</td></tr>
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Year	Protocol and Description	Ref.
	• 2023 AR6 Synthesis Report—Climate Change.	
1992	UN Agenda 21 Following the Brundtland report Our Common Future, the IPCC's formation, and the identification of the importance of energy, an action plan was developed that was discussed in more detail in the UN Kyoto Protocol of 1997.	[1]
1992	UN Framework Convention on Climate Change (UNFCCC) As a result of the action plan developed by the UN Agenda 21, countries made a global commitment to work together to develop solutions to limit rising global average temperatures, and the UNFCC was founded.	[10]
1995	Conference of Parties (COP) The Conference of the Parties (COP) is the highest decision-making body for the UNFCC, which first held its meetings in Berlin every year (with this year's known as COP28, to be held in Dubai, UAE), involving delegates from all parties' countries, meeting to assess the convention's effectiveness through evaluating national communications and emission inventories of countries working towards sustainable societies.	[11]
1997	UN General Assembly The 1997 UN General Assembly emphasized sustainable energy production, distribution, and use for improved sustainable development. The UN Commission on Sustainable Development focused on atmosphere, energy, and transport in 2001.	[12]
1997	UNDP Kyoto Protocol A protocol was developed to ensure financial assistance for clean energy projects under the Clean Development Mechanism (CDM), which emphasizes that organizations must engage in sustainability practices to be able to receive funding for energy programs and projects.	[13]
2000	UN Millennium Declaration In September of 2000, world leaders signed the United Nations Millennium Declaration, committing to work together to end extreme poverty, hunger, disease, illiteracy, environmental degradation, and gender discrimination. However, sustainable energy targets were not included in the declaration.	[14]
2000	UNDP World Energy Assessment Report The first proposal for sustainable energy development was introduced in this assessment report.	[1]
2001	UN Commission on Sustainable Development (CSD-9) The UN Commission on Sustainable Development was birthed from the UN 1997 General Assembly, which proposed CSD-9 to focus on atmosphere, energy, and transport.	[15]
2002	UN World Summit on Sustainable Development Following the establishment of UN CSD-9, the world's first summit on sustainable development was held in Johannesburg, where the concept of a sustainable energy development initiative was discussed and adopted, alongside another set of activities that considered respect for the environment, with ten-year regional and national sustainable production and consumption programs being proposed.	[16]
2003	UN World Summit on Sustainable Development report A report on the UN World Summit on Sustainable Development discussion was released.	[16]
2004	UN-Energy Following the UN World Summit on Sustainable Development, the UN Energy inter-agency mechanism was established to aid countries in transitioning to sustainable energy by accelerating roadmap implementation, especially through the activities listed in the resolution of the UN World Summit on Sustainable Development report. Consequently, this initiative called for existing and newly created energy organizations at the national, regional, and international levels to come together to work towards sustainable development.	[16]
2005	Energy Indicators for Sustainable Development Five international agencies and organizations (United Nations Department of Economic and Social Affairs (UNDESA), International Energy Agency (IEA), International Atomic Energy Agency (IAEA), European Environment Agency (EEA), and Eurostat), recognized worldwide as leaders in energy and environmental statistics and analysis, presented a set of indicators for sustainable energy development.	[17]
2009	International Renewable Energy Agency (IRENA) IRENA, an international organization promoting renewable energy adoption and sustainable use, was formed to ensure that both industrialized and developing countries' needs are addressed. • 2023 Edition—World's Energy Transition Outlook (1.5 °C pathway);	[18]

Year	Protocol and Description	Ref.
	• 2021 to 2023—Tracking SDG 7, the energy progress report.	
2010	UN Millennium Development Goals follow-up resolution As a follow-up to the outcome of the Millennium summit and the declaration of 2000, energy was recognized and stressed as necessary to achieving the MDGs and sustainable development.	[14][19]
2011	UN Sustainable Energy for All (SE4ALL) UN initiative focused on advancing sustainable energy development. Presently, the SE4ALL has become an international organization that works with the UN and leaders in government, the private sector, financial institutions, civil society, and philanthropies to accelerate Sustainable Development Goal 7 (SDG7)—access to affordable, reliable, sustainable, and modern energy for all by 2030—in line with the Paris Agreement on climate change	[20]
2015	UN 2030 Agenda for Sustainable Development The SDGs were first introduced, with energy and climate change established as an integral part of sustainable development, with SDG 7 for energy and SDG 13 for climate change actions.	[21]
2015–present	Development of SDG Trackers As a result of the responsibilities for stocktaking and progress measurement of implementation towards sustainable development achievements, different organizations have used the targets and indicators from the UN 2030 Agenda for Sustainable Development to build platforms to assess the progress levels of countries. 2015 and later years to present—Research on SDG indicators' assessment and composition. 2019—SDG tracker systems and platforms.	[22][23]
2016	National Determined Contribution (NDC) The Lima COP agreed to cut emissions using collective and collaborative efforts under the concepts of NDC referenced in Article 4(2) of the Paris Agreement.	[24][25]
2018–present	Stocktaking for National Determined Contribution (NDC) Following the Paris Agreement's framework, mandates were created for countries to submit revised and enhanced nationally determined contributions (NDCs) in 2020 and every five years after that. In addition, beginning in 2023, signatories to the agreement are enjoined in a global stocktaking of progress towards reducing global CO_2 emissions every five years.	[26]
2019–present	Emerging New Global Energy System Many discussions revolve around emerging global energy systems because of the several issues governing energy, such as the following: i. Energy finance and justice/equity in relation to climate goals; ii. Aligning climate change and sustainable development finance through the lens of the SDGs; iii. The proximity in time to 2030 and sustaining of the 1.5–2.0 °C threshold for global warming; iv. Inflation and energy war (as of September 2022, a third of the wealthy world's inflation rate of 9% is attributable to energy due to Russia's invasion of Ukraine); v. Upsurge in 100% renewable energy investigations; vi. Emerging fuels and technologies (energy storage and hydrogen technologies).	Authors' elaboration
2023	IEA World Energy Investment Alongside the issues mentioned regarding the need for a new emerging energy system, IEA's support of the Paris Agreement's first global stocktake has resulted in a need for a world energy investment path. The upcoming UN Climate Change Conference, COP28 UAE, is expected to be held at Dubai Expo City from 30 November to 12 December 2023. The conference represents the culmination of the first global stocktake of the Paris Agreement.	
2023	1st African Climate Summit The first-ever Africa Climate Summit on 4–6 September 2023, in Kenya, focused on clean energy and industrial financing and Africa's negotiating their stance in the global discourse ahead of COP 28 for mitigating climate change consequences, being the most affected continent.	

2. SED Progress

2.1. Emerging Issues and Directions in SED

2.1.1. Energy War

The ongoing geopolitical tensions between Russia and Ukraine have significantly affected the European energy sector. Meanwhile, other similar but diverse issues of war that have impeded energy development progress have been prevalent in other parts of the world, for instance, in African countries, particularly in the Sahel and sub-Saharan region of the continent. These tensions have had implications for climate change dynamics and global efforts to limit global warming to 1.5 °C. The ongoing conflict has significantly disrupted supply chains and heightened uncertainty within the energy industry. As a result, the transportation of natural gas and energy prices, for instance, in Europe, have been notably impacted. The ongoing conflict has resulted in a notable transition towards carbon-intensive energy sources, with a particular emphasis on coal. This shift poses a significant challenge to limiting global warming to the critical threshold of 1.5 °C. The global community faces intricate challenges posed by climate change and its geopolitical ramifications, underscoring the significance of international collaboration in mitigating the adverse impacts of conflict on energy security and climate change objectives.

The global imperative for energy security and the imperative to transition towards sustainable energy sources have emerged as crucial priorities on a global scale. In the face of global climate change and the imperative for a transition to clean energy, it is evident that international cooperation in clean energy financing plays a crucial role in averting potential conflicts over energy resources. The Russia–Ukraine via Europe energy conflict exemplifies the crucial need for collaborative endeavours to safeguard energy security, promote energy source diversification, and mitigate reliance on fossil fuels. In addition to the need for international collaboration, the energy security issue has also necessitated the massive adoption of storage technologies that can serve as an alternative measure in fostering energy independence. Presently, the need cannot be overemphasized as the technology must gain maturity.

The next section presents the different energy storage pathways and concludes with a discussion of the progress in hydrogen policy planning in the selected top GHG emitters by energy.

2.1.2. Energy Storage

Using energy storage technologies is becoming more prevalent to decouple the timing of energy output from its consumption, whether in the form of electricity or heat. Chemical methodologies such as lead-acid and lithium-ion batteries are widely employed, whereas pumped hydro storage represents a mechanical approach. Molten salts are a highly efficient means of storing thermal energy in concentrating on solar power systems, allowing for a more compact storage solution. The declining costs associated with renewable energy sources such as solar and wind are expected to contribute to an increased proportion of these sources within the broader energy mix. The growing prevalence of intermittent renewable energy sources necessitates the development of power grid facilities capable of accommodating and responding to fluctuating conditions. The advancement of electricity storage systems, with a specific focus on battery and hydrogen technology, has a pivotal impact on the adaptability of the electrical grid. A comparison of energy storage technologies' performance based on different metrics is presented in **Table 2**, and the rating is summarized in **Figure 1**. These prominent energy storage technologies are five, namely chemical energy storage, thermal energy storage, electromagnetic energy storage, mechanical energy storage, and peak cutting and trough filling technology.

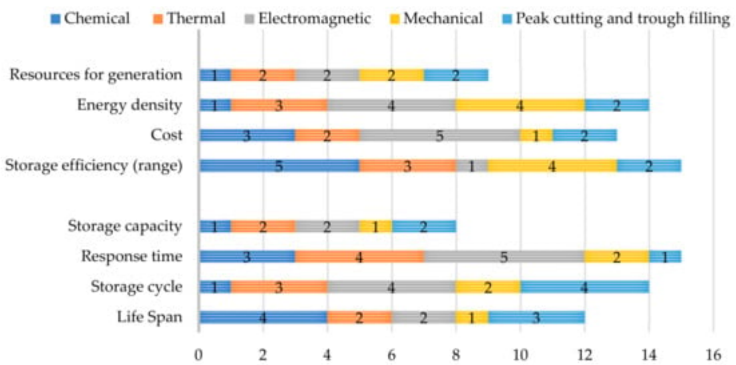

Figure 1. Performance rating of energy storage pathways.

Table 2. Performances of energy storage pathways.

Performance Indices	Chemical	Thermal	Electromagnetic	Mechanical	Peak Cutting and Trough Filling
Life span	1.14 years [4]	30 years [2]	30 years [2]	30–60 years [1]	2 years [3]
Storage cycle	365 days [1]	7–28 days [3]	1–6 days [4]	7–30 days [2]	1–6 days [4]
Response time	Minutes [3]	Weeks to hours [4]	Days long [5]	Seconds to minutes [2]	Hundred milliseconds[1]
Storage capacity	MW–GW [1]	MW [2]	kW–MW [2]	GW [1]	kW–MW [2]

Performance Indices	Chemical	Thermal	Electromagnetic	Mechanical	Peak Cutting and Trough Filling
Storage efficiency (range)	0.3–0.8 [5]	0.5–0.9 [3]	0.8–0.98 [1]	0.7–0.85 [4]	0.6–0.95 [2]
Cost	USD (2801–7002)/kW [3]	USD (280–420)/kW [2]	- [4 or 5]	USD (140–840)/kW [1]	USD (281–420)/kW [2]
Energy density	Very high [1]	Moderate [3]	Low [4]	Low [4]	High [2]
Environmental Impact					
Resources for generation	Existing energy resources (both fossil and RE), depending on the production method [1]	Heat [2]	Electromagnetic field [2]	Mechanical work [2]	Cutting and trough filling [2]

Data extracted from [27]. Note—1, 2, 3, 4, and 5 are rankings used to show the best performer per indices, with 1 being the best, followed by 2, and so on, with 5 being the worst. These rankings are compared in **Figure 1**.

From **Figure 1**, chemical energy storage (CES) offers the most promising energy storage pathway as it is the only storage pathway coming first in four out of the eight performance ratings. The storage cycle could last for a calendar year in the event of a national energy crisis, which appears to be one of the reasons it is commonly the major energy storage that has gained most countries' national policy attraction. However, the major drawbacks of CES are the cost of producing a kg worth of hydrogen, which requires between 33 and 55 kWh of electricity (with a high cost of USD 2801–7002/kW), and its low storage efficiency. It makes other energy storage options viable even though growing innovative approaches are working toward reducing the hydrogen production cost per kg. Also worth noting is that the hydrogen cost per kWh depends on the production technology and the type of resources used as the feedstock in hydrogen production.

Hydrogen, being a form of CES, has emerged as the most viable energy delivery mechanism for the future as a well-known carbon-free or less gaseous fuel as it is a desired fuel for several power sources, including internal combustion engines, gas turbines, and fuel cells, due to its good mass-basis calorific value, absence of carbon atoms [28], and derivability from existing energy systems and processes. Hydrogen production is divided into three technological groups: thermochemical, electrochemical, and biological. Most hydrogen energy production systems employ cradle/gate-to-gate borders, while most hydrogen transportation systems use cradle/gate-to-grave barriers [29]. The article by N. H. Afgan et al. in [30] discussed the potential for multi-criteria evaluation of hydrogen systems based on performance, environment, market, and social aspects. H. Zhao et al. [31] analyzed and proposed a resilience assessment strategy and improvement-tracking mechanism to integrate hydrogen energy efficiently and in times of emergency. Case studies have been conducted to demonstrate the viability of the proposed approach [31]. Multi-criteria evaluation of hydrogen infrastructure considers performance, environmental factors, and market variables, and the Sustainability General Index (SGI) ranking is more helpful for decision-making than relying on a single indicator [32].

In IRENA's report in [33], using a five-step process, a more detailed methodology for assessing the best energy storage options (of which hydrogen and other forms of energy storage are included) is presented. The first step is determining which energy storage services make variable RE integration easier, and the second is matching the appropriate storage technology with those services. Third, the value of electricity storage systems is compared to other flexibility mechanisms. The fourth stage is to perform revenue modelling by simulating stacking and storing operations, while the last is to assess the feasibility of the storage project, valuing a system based on its expected return on investment. Overall, the merits and demerits of all energy storage technologies, alongside other criteria, are presented in **Table 3**.

Table 3. Comparison of energy storage pathways/technologies.

Technology/ Pathway	Storage Application	Applicable Scenarios	Merits	Demerits	Maturity of Technology
Chemical	Hydrogen Natural gas	Large-scale, long-cycle energy storage	Long storage cycle High storage energy volume	High infrastructure requirements Sluggish response Low efficiency but high cost	Low
Thermal	Molten salt	7–28 days	High thermal storage volume	Limited applicable scenarios	Moderate
Electromagnetic	Supercapacitor Superconducting	Peak load regulation,	Long life span Fast response	Seconds to minutes	Low

Technology/ Pathway	Storage Application	Applicable Scenarios	Merits	Demerits	Maturity of Technology
		direct use of thermal energy			
Mechanical	Flywheel Compressed air Hydro-pump	Large-scale energy storage by peak cutting and trough filling	Very high technological maturity Longer life span Low cost of operation Large energy and power capacity	High infrastructure requirements Sluggish response	Very high
Peak cutting and trough filling	Battery	Peak load and frequency regulation	High technological maturity High flexibility in construction/installation Fast response	Intermittent problem of heating High infrastructure cost requirements	High

Information and data extracted from [27].

...vation and diffusion are continuously on the rise, as in the case of Hydrogen. P. Sana et al. [34] investigated the different production processes and examined the economic and environmental effects of three different hydrogen categories based on the resources used as feedstock (fossil fuel—grey, blue—and fully renewable energy—green). In the current paradigm, the emphasis is more on green hydrogen generation technology at the least possible cost because of the net-zero friendliness of green hydrogen compared with the blue and grey types, which are fossil-based. In an editorial by F. Calise et al. in [35], recent advances in green hydrogen technology were reviewed. Such advances include the hydrogenation of captured CO_2 in [36], green hydrogen from multi-renewable energy systems, as seen, for instance, with hydrogen from wind + geothermal in [37], wind + solar + electrolyzers + fuel cells in [38], and solar + electrolyzer + absorption chiller + electric + thermal energy storage in [39].

In addition to the advances towards the least-cost path for green hydrogen generation, legal reforms and political will are paramount to supporting the infrastructural expansion of green hydrogen in the global energy mix. In addition, recent years have seen a boom in the industry's hydrogen production, which has attracted much attention. While established companies drove much of the sector's rapid expansion in the past, the commercial landscape today is more open and welcoming to new entrants in the hydrogen industry.

2.1.3. Decarbonization Strategies for SED in Power and Other Sectors

Many obstacles must be overcome to reach a sustainable, energy-developed society globally. Alongside moving clean energy financing towards 100% and the emerging issues of energy war and storage discussed previously, other key constraints include less political will, regulatory opposition, and high initial costs [40][41][42], among a host of others. Advocacy for a forward-thinking strategy, strong policies, widespread education, and the participation of both the public and private sectors is pertinent. Due to differences in energy resources capacity, geographical challenges, and other challenges, addressing the issues/constraints highlighted in **Table 4** may require a global and integrated perspective and international/regional collaboration for the sustainable development of the energy system that powers a sustainable future.

Table 4. Issues and constraints surrounding SED decarbonization strategies.

Category	Issues and Constraints
Institution and Politics	• Challenging support policies for increasing penetration of RE. • Less government financing and subsidy. • Energy wars. • Rise in the disintegration of international treaties (uprise of the BRICS group versus G7, G20).
Technology Systems	• Challenges in maintaining grid stability because of varying RE in the existing conventional national grid. • The initial cost of decentralized energy generation and storage. • Challenging energy storage trade-offs (less storage cycle, high levelized storage cost). • Challenges with high energy requirements for existing direct carbon capture and sequestration technologies.

Category	Issues and Constraints
Climate Change Concerns	• Deforestation issues in the event of sudden utilization of forest resources for the energy transition. • Material and resource requirements for the energy transition (for instance, there may be a possible overshoot of natural earth resources for renewable and storage applications system development in the event of immediate transition into full 100% RE). • Heat waves—intermittent cooling and heating needs of the population.
Public Opinion	• Energy markets (dwindling public trust for complete transition into 100% RE, less affordability, regional energy trade competitions). • Adaptation issues with changing job and skill requirements for the new energy paradigm. • Rising demand for energy accessibility in developing countries.

The numbers 1 to 10 are nomenclatures used to show the commonality and similarities with each sub-theme.

The constraints listed in **Table 4** can all be categorized under the 10 themes of SED that were earlier identified. Aligning these interrelated constraints with each of the themes of SED and inclusion in responsive policy regulatory development of countries could help significantly in tackling these issues and the challenges of climate change and SED. Apart from the utilization of promising energy storage solutions, energy efficiency measures, high carbon pricing, introduction of clean electricity standards, fossil fuel taxing, renewables energy subsidy, accelerated retirement of non-renewable energy plants, limiting sales of fossil-fuel-driven transport system, and other circular economy concepts to address the SED decarbonization constraints, the power sector and other sectors are exploring several potential strategies. These decarbonization strategies are depicted in **Table 5**.

Table 5. Selected emerging decarbonization strategies for power and other sectors.

Sector	Emerging Energy-Related Decarbonization Strategies	Merits	Demerits	Technology Maturity Level	Ref.
Power	• Bioenergy with the capture of resulting CO_2 emissions. • Capture of CO_2 from fossil fuel emissions. • CO_2 methanation-energy resource (methane) recovery using the captured CO_2 as a feedstock. • Green hydrogen production and storage • Composites and materials hybridization for solar cell efficiency optimization.	• Reduced CO_2 deposition in the atmosphere. • Alternative energy generation. • Improved generation efficiency.	• High operational cost. • High energy requirement. • CO_2 storage constraint and durability of the reservoir. • Many hybridizations of materials as a composite are still at trial/experimental stages of development.	low	[35] [43] [44] [45] [46]
Industrial processes	• Net-zero carbon and energy-intensive cement production using basalt and other	• Possibility of replacing 98% of cement production from limestones with	• Uncertain solutions (i.e., limestone replacement not yet tested at industrial scale).	low	[47] [48]

Sector	Emerging Energy-Related Decarbonization Strategies	Merits	Demerits	Technology Maturity Level	Ref.
	calcium oxides (replacing limestone). • Industrial symbiosis (the waste in one industry becomes a resource for another). • Composite materials and intelligent manufacturing techniques.	CO_2 emission avoidance. • Waste reduction with energy savings and CO_2 emission avoidance.	• Many hybridizations of materials as composites are still in the trial/experimental stages of development.		
Transport	• Use of vehicle-to-grid (V2G/G2V) for electric vehicle (EV) charging and energy trade. • Smart mobilities such as vehicle-to-vehicle (V2V) and autonomous vehicles. • Battery management system and solid-state batteries for EVs. • Sustainable aviation fuels (SAF) for commercial purposes are made from CO_2 via RE plus water synthesis. • Conversion of petrol/diesel to compressed natural gas (CNG) engines.	• EVs are eco-friendly during their operational phase. • Reduced CO_2 deposition in the atmosphere with CNG use. • Reduced carbon intensity requirement and performance optimization mid-term trade-off for V2G, V2V, EV, SAF, and CNG.	• High initial purchase cost. • The use of EVs requires grid stability and the right charging mechanisms. • EV battery materials resources' availability is not location-specific. • High conversion cost. • High safety handling requirements for CNG vehicles.	low	[49] [50]
Building	*Innovative Active Cooling/Heating* • Use of heat pump, solar, and geothermal heating. • Alternative cooling technologies, such as vortex tubes. • Decentralized district heating and cooling using microgrids. • Intelligent and user-responsive cooling/heating using ML/AI techniques. *Passive Cooling*	• Reduced CO_2 deposition in the atmosphere. • Alternative cooling and heating during intermittent seasonal demands.	• High operational energy requirement for some alternative cooling/heating techniques. • High initial cost of installation and commissioning.	low	[51] [52]

Sector	Emerging Energy-Related Decarbonization Strategies	Merits	Demerits	Technology Maturity Level	Ref.
	5. Efficient building envelope designs and retrofitting. 6. Phase-change materials for cooling and heat storage.				

ML/AI—machine learning/artificial intelligence.

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