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Review

Sustainable Energy Development: History and Recent Advances

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Abstract: 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. This article presents the history of SED and then uses a critical discourse approach to summarize existing review studies in SED. Ten interlinked themes of SED are identified, with two of them considered to be among the least studied in existing SED reviews and in the current global discussion around climate change. This study explores these two themes, which include energy financing and the need for 100% renewable energy (RE), a sub-theme of decarbonization strategy working towards the 1.5–2.0 °C scenario. The study suggests that the current G20 countries' contributions, if maintained continuously per annum, in addition to 80% more funding from private investment compared to the amount in the 1.5 °C scenario financial requirements for clean energy, are sufficient to limit global warming. In addition to the present drive for 100% RE, the article also discusses emerging issues, such as energy storage options with an indication of hydrogen as the most promising, other energy-related development agendas, and the need for regional security stability to prevent energy wars. Selected SED decarbonization strategies are presented across the power, transport, building, and industrial sectors. The study concludes with progress and directions for future research, mainly the need for re-defining nationally determined contribution (NDC) through an emissions budgeting and centralized global or regional emissions stock-taking strategy working towards the 1.5 °C scenario.

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

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1. Introduction

There is an anticipated decline in global oil demand from 2022 to 2028 because of the ongoing energy transition and a peak in fossil fuel combustion at around 81.6 million barrels per day, as shown in Figure 1. The acceleration of this economic slowdown has been facilitated by the invasion of Ukraine by Russia and the post-COVID-19 recovery spending plans implemented by governments. According to numerous projections from international organizations and government agencies, which were compiled and compared by R. Daniel et al. [1] in the current year of this study, oil demand is envisaged to have a substantial decline by the year 2050. This decline is expected to plateau during the 2030s, ultimately resulting in a level that is partly consistent with achieving global climate objectives [2]. According to the evolving policy scenarios, the projection shows a decrease in oil demand within a range of 20–25 million barrels per day by the mid-century [1], given the rise and anticipated massive adoption of renewable energies in the bid to reduce the global carbon footprint from the CO_2 associated with fossils fuels. This move is part of the United Nations (UN)'s drive to achieve sustainable development.

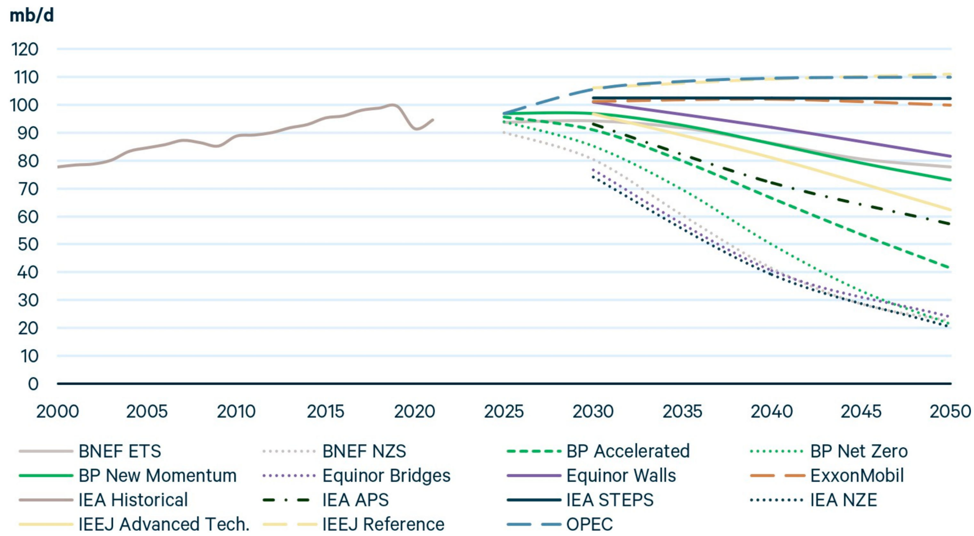
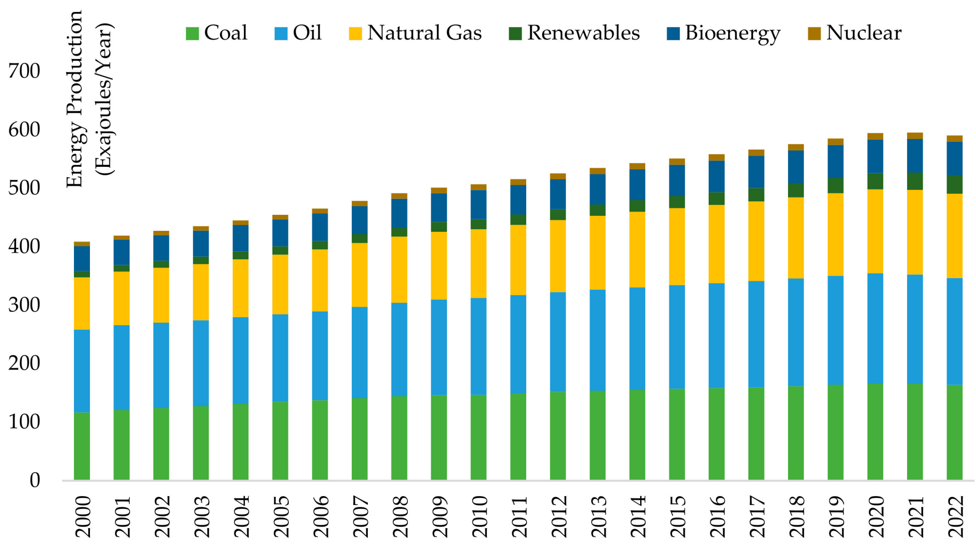


Figure 1. Global oil demand and peak assessment (compilation of scenarios from different bodies and international agencies), according to R. Daniel et al. in [1].

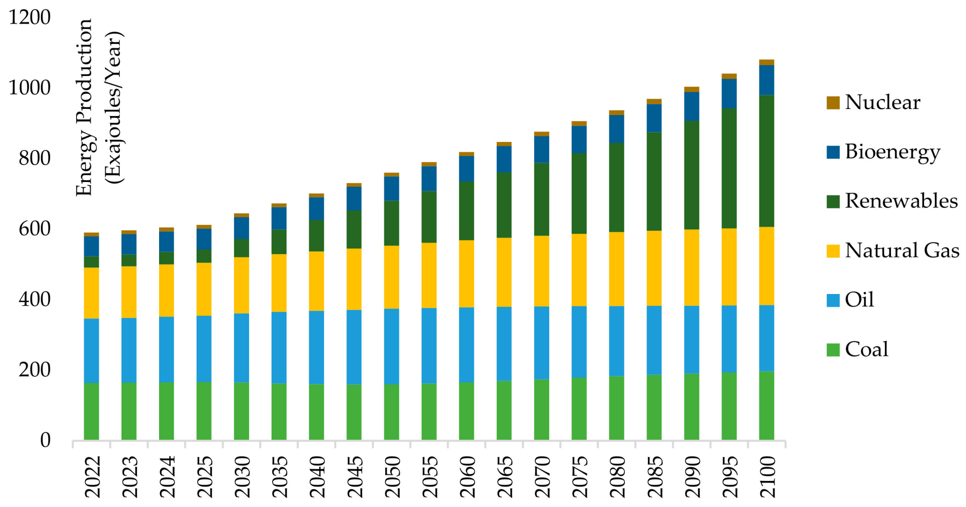
Consequently, an earlier discussion in the "Our common future" report in [3] from the United Nations underlined the importance of energy in attaining sustainable development (a concept described as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"), with the year 2000 seeing the beginning of the concept of sustainable energy.

While global oil prices show a decline in demand in succeeding years, other fossil energy sources have also been predicted to experience a reduction in supply and demand, with a growth in renewable energy for utilization. These predictions are displayed in Figure 2 below.



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. Global primary energy mix. Data from Climate Interactive in [4] based on IEA and bp reports in [5,6], respectively. (**a**) Historical path; (**b**) predicted path.

This article is structured in seven sections, as presented in Figure 3: Section 1 introduces the work. The history of SED and critical discourse on the summary of existing reviews on SED are presented in Sections 2 and 3, respectively. Section 4 reveals the rationale behind this study, while Section 5 synthesizes and discusses the selected SED themes. Section 5 focuses on energy financing under the 1.5 °C scenario and presents updated national energy policies. In addition, Section 5 introduces the rise in the desire to reach 100% renewable energy (RE), with some issues and challenges, particularly for developing countries without 100% electrification. The limitations of reaching 100% RE are numerous, forming most emerging energy issues, including energy war and energy storage. An overview of energy storage technology is presented in the subsequent Section 6. In Section 6, SED progress, including emerging issues and the interconnections between energy security, innovation, climate change, and financing for sustainable development, is discussed. Section 7 explores the intersection between energy, climate change, and innovation. The conclusion, with possible areas of further research areas, is included in Section 8.

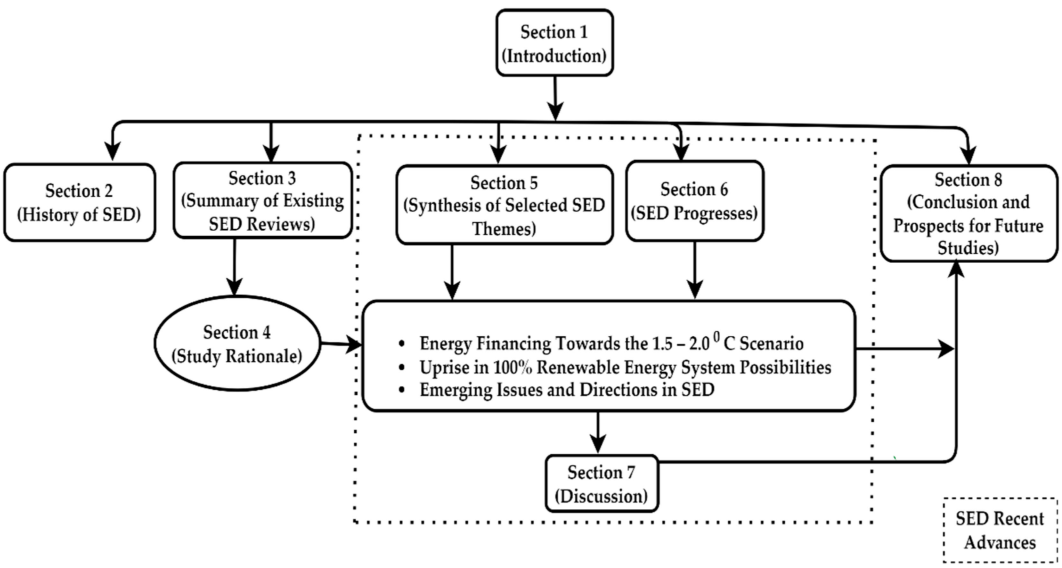


Figure 3. Organization of the study.

2. 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 [7]. 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 [8]. 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 [8]; 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 [9].

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.	[10]
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. • 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).	[11–13]
1987	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.	[3]

Table 1. *Cont.*

Year	Protocol and Description	Ref.
1988	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; • 2023 AR6 Synthesis Report—Climate Change.	[14]
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.	[7]
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.	[15]
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.	[16]
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.	[17]
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.	[18]
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.	[19]
2000	UNDP World Energy Assessment Report The first proposal for sustainable energy development was introduced in this assessment report.	[7]

Table 1. *Cont.*

Year	Protocol and Description	Ref.
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.	[20]
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.	[21]
2003	UN World Summit on Sustainable Development report A report on the UN World Summit on Sustainable Development discussion was released.	[21]
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.	[21]
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.	[22]
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); • 2021 to 2023—Tracking SDG 7, the energy progress report.	[23]
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.	[19,24]
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	[25]
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.	[26]
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.	[27,28]
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.	[29,30]

Table 1. *Cont.*

Year	Protocol and Description	Ref.
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.	[31]
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.	

3. Summary of Existing SED Reviews

In 2020, Gunnarsdottir et al. [8] studied the evolution of SED. They concluded from the several studies reviewed that the primary objective of SED is linked to achieving global sustainable development. This link involves the connection between several themes, such as energy security, sustainable energy use, affordable access to modern energy services, and sustainable energy supply, as depicted in Figure 2. Z. Guzović et al. [32] summarized a compilation of papers published in a leading journal dedicated to selected papers from the series of SDEWES conferences to summarize recent advances in the development of sustainable energy systems. Five key domain areas were identified: energy policy analysis, energy conservation, cogeneration or polygeneration, alternative energy resource use (biomass in this case), and energy and environmental sustainability. Kabeyi M. and O. Olanrewaju, in their study in [33], combined the characteristics included in the Johannesburg definition in [21] with those listed in the International Atomic Energy Agency (IAEA) definition in [34] to present four primary themes for the promotion of sustainable energy development. These themes include energy efficiency improvement, energy security improvement, environmental impact reduction, and increasing energy accessibility, availability, and affordability.

Accordingly, in 2022, a systematic literature review on SED was carried out by Łukasiewicz et al. [35], highlighting three activities key to achieving SED, which were identified and discussed. These include the switch to more renewable energy sources in the global energy mix, lessening its negative effects on the environment and human health, and sustainable energy use through increasing energy efficiency measures.

During the current year of this study, D. Morea et al. [36], in a short editorial, reviewed selected papers promoting SED and presented possible future research directions for SED, which included the development of energy management protocols to address the behavioural barriers of energy-vulnerable households, optimal and even allocation of risks and penalties to energy stakeholders, and critical assessment of expenditures for global climate change actions. Other areas highlighted were energy diversification into capture and utilization technologies through the development of pricing, cost, and clear emission reduction estimation mechanisms for the utilization and promotion of CO_2 capture technologies and the evolution of development and energy security in fossil-fuel-dominant energy communities.

Finally, the analysis by X. Pan et al. in [37] made use of bibliometrics to gather the existing literature on the topic of energy and sustainable development and draw connections between the various pieces of information. In this work, climate change, energy's relationship with other SDGs, planetary boundaries, nexus informatics, economic growth, and energy consumption were the interconnected categories found.

Therefore, expanding upon the existing themes of SED to capture these newly identified areas needed to facilitate SED, Table 2 presents themes of SED and categorizes them into new SED themes in Table 3.

Table 2. Themes of SED (based on selected existing review studies of SED).

Year of Study	Review Method	Sub-Themes	Main Themes Nomenclature	Ref.
2021	Citation analysis of most cited energy development studies	• Energy security [1] • Sustainable energy use [2] • Affordable access to modern energy services [3] • Sustainable energy supply [4]	1, 2, 3, 4	[8]
2022	Two-decade overview of studies from SED conferences and special issues	• Energy policy analysis [5] • Energy use and conservation [2] • Co/poly generation and energy efficiency [6] • Alternative energy resource [7] • Energy and environmental sustainability [8]	5, 2, 6, 7, 8	[32]
2022	Critical review of sustainable energy transition strategies	• Energy efficiency improvement [6] • Energy security improvement [1] • Environmental impact reduction [8] • Increasing energy accessibility, availability, and affordability [3]	6, 1, 8, 3	[33]
2022	Analysis of studies from selected energy journals	• Rise in renewable energy penetration in the global/national mix [7] • Energy and environmental sustainability [8] • Energy efficiency [6]	7, 8, 6	[35]
2023	Bibliometric	• Climate change [8] • Energy with other SDGs [9] • Planetary boundaries [8] • Nexus informatics (energy-water-land-food) [9] • Economic growth [9] • Energy consumption [2]	8, 9, 2	[37]
2023	Editorial	• Energy use management [2] • Energy stakeholders' accountability [3] • Energy innovation and carbon capture/sequestration technologies development [7] • Energy-related development contribution [9] • Energy financing for climate change mitigation [10]	2, 3, 7, 9, 10	[36]

The numbers 1 to 10 are nomenclatures used to show the commonality and similarities with each sub-theme from different studies reviewed in Table 2, which are rearranged and placed in the applicable category in Table 3.

Table 3. Categorization of SED themes. Source: authors' elaboration.

Theme No.	Sub-Themes	Main Themes
1	• Energy security • Energy security improvement	Energy security
2	• Sustainable energy use • Energy use and conservation • Energy consumption • Energy use management	Energy use
3	• Affordable access to modern energy services • Increasing energy accessibility, availability, and affordability • Accountability to energy stakeholders	Accessibility, affordability, and availability
4	• Sustainable energy supply	Energy supply
5	• Energy policy analysis	Energy policy
6	• Energy efficiency • Energy efficiency improvement • Co/poly generation and energy efficiency	Energy efficiency
7	• Alternative energy resources • Rise in renewable energy penetration in the global/national mix • Energy innovation and carbon capture/sequestration technologies development	Decarbonization
8	• Energy and environmental sustainability • Environmental impact reduction • Climate change • Planetary boundaries	Environmental protection
9	• Economic growth • Energy with other SDGs • Nexus informatics (energy-water-land-food) • Energy-related development contribution	Energy-X nexus
10	• Energy financing for climate change mitigation	Energy finance

For the energy-X nexus, X can be other infrastructural areas such as land, water, food, information, and communication technology.

4. Study Rationale

All ten themes from Table 3 are related to the environmental, social, and economic dimensions of industries linked with energy, forming the basis of SED, as shown in Figure 4. Recent reviews, such as the one discussed in Section 3, have focused more on sustainable energy use, affordable access to modern energy services, sustainable energy supply, energy policy analysis, co/poly generation and energy efficiency, alternative energy resources, energy and environmental sustainability, energy stakeholders' accountability, energy innovation and carbon capture/sequestration technologies development, and energy-related development contribution.

This article discusses the current updates regarding themes not discussed extensively in existing SED reviews, mainly energy financing for climate change mitigation and the rise in renewable energy penetration in the global/national mix, which are key decarbonization strategies, as well as the more recent advances or emerging global issues in SED, such as energy war and energy storage options. To foster economic and social growth with environmental benefits in all countries, SED requires considering all these themes in energy resource and system planning, implementation, and management.

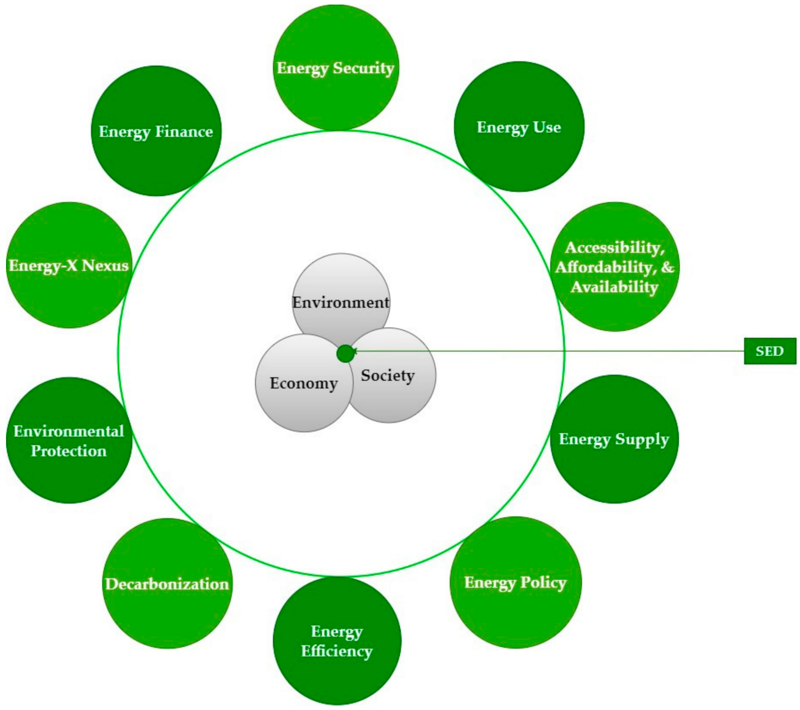


Figure 4. Themes of SED. Source: authors' elaboration.

5. SED Theme Synthesis

5.1. Energy Financing towards the 1.5–2.0 °C Scenario

The energy sector is a key driver for global sustainability, economic growth, and climate change mitigation. Sustainable energy transition has been hastened by government support for renewable energy projects, which has encouraged private sector investment and diversified foreign investment portfolios. This section presents governmental financial pledges for energy development regarding global investment portfolios. Investment portfolios worldwide have become more diversified because of changes in the energy balance of countries and their growing preference for renewable energy. The extracted energy types are organized into five categories, as shown in Table 4 below.

Table 4. Highlights of energy types' categorization and public funding commitments by the G20 (2020–2021).

S/N	Energy Type	Description	Public Funds Commitment (USD Billion)
1	Fossil conditional (FC)	• Policies that encourage the development and consumption of fossil fuels, such as oil, gas, coal, "blue" hydrogen, or fossil-fuel-based power. • Policies that also incorporate climate targets or additional pollution reduction obligations.	113.19
2	Fossil unconditional (FU)	• Policies that encourage the development and consumption of fossil fuels, such as oil, gas, coal, "grey" hydrogen, or fossil-fuel-based power. • Policies that do not incorporate any climate targets or extra actions for pollution mitigation.	357.78
3	Clean conditional (CC)	• Potentially clean policies that declare willingness to assist in the transition away from fossil fuels but lack specificity about adopting necessary environmental protections during their implementation.	326.13

Table 4. *Cont.*

S/N	Energy Type	Description	Public Funds Commitment (USD Billion)
4	Clean unconditional (CU)	• Policies that consider only an unconstrained and unrestrained state of cleanliness, including renewable energy and "grey" hydrogen. • Policies that support the production or consumption of energy are distinguished by being low-carbon and having little environmental impact.	98.46
5	Other energy type (OT)	• Policies that cross over between the two categories of "fossil" and "clean" energy. • Policies that encourage the use of incineration, hydrogen from ambiguous sources, and a combination of both fossil and clean energy sources. • Policies that encourage the use of nuclear energy, including uranium mining and "first generation" biofuels, biomass, and biogas, despite their well-known detrimental impacts on the environment.	204.11

Data extracted from the energy policy tracker in [38].

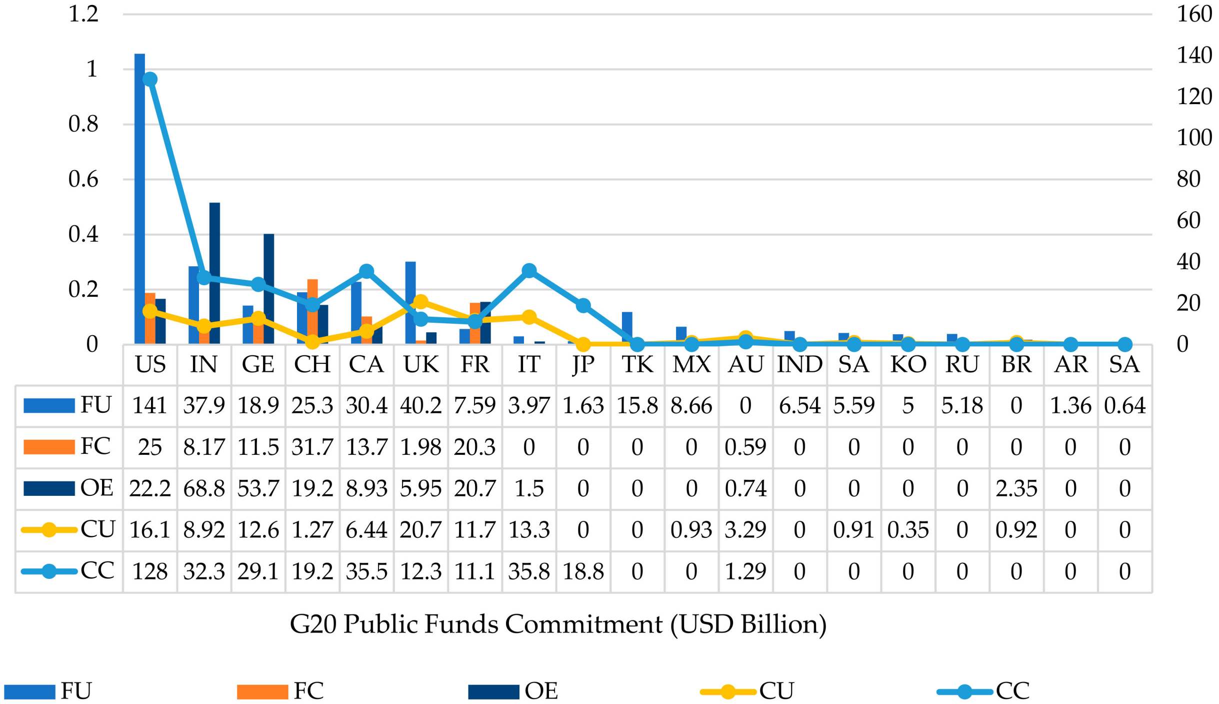
In addition to many other programs, the government also pledges substantial sums of funds to support various forms of energy. In Table 4, fossil unconditional takes the largest share, whereas clean unconditional takes the least.

Figures 5 and 6 outline the different post-COVID-19 public investment commitments by energy type from the G20 (excluding the entire EU) extracted from the energy policy tracker [38]. In Figure 5, a considerable amount (highlighted in Table 4) of the public funds are committed to clean energy investment. It is distributed across the G20 countries alongside the other three energy types of public investment funds. However, the investment values have shown that all these countries' commitment to fossil investment is higher than their commitment to clean energy, except for Germany, Italy, Japan, and Australia, which have a greater percentage share in clean energy investment, with a total clean investment of 33.16%, 89.98%, 92.03%, and 77.50%, respectively, of their total energy investment. However, these clean investments with higher shares are conditional; for instance, Japan's investments are more on nuclear and do not specify and quantify how much carbon footprint could be reduced in the implementation process. At the same time, other countries' commitments, such as Italy and Australia, lack the same target quantification but only indicate support for a transition away from fossil dominance.

The total amount allotted to clean energy is 38%, smaller than fossil fuels at 43%, while other energies are 19%, as depicted in Figure 6. Energy investments, especially those in fossil fuels, are fraught with risks that may be mitigated by private funding for clean energy development. Tackling issues such as policy consistency, regulatory predictability, and regional inequities is crucial for maximizing the positive effects of the contribution that private finance makes to the energy industry. For a sustainable energy future that protects investor interests and promotes economic growth, striking this balance is essential.

Energy development projects financed by public funds have created opportunities for private sector investments in renewable energy, green technologies, and related industries. Integrating sustainable energy investments into global portfolios has become more attractive to investors seeking long-term returns and aligning with environmental, social, and governance (ESG) principles.

Public finance for renewable energy is crucial due to the better value for money and environmental benefits it provides. In 2010, the global investment value of renewable capacity was USD 210 billion, with 88 GW added, while in 2019, twice as much new renewable energy production capacity was put into operation, with overall investment only rising by one-fifth to USD 253 billion. In addition, utility-scale solar PV dominated deployment capacity, accounting for 60% of all solar PV investment in 2019, whereas investments peaked in 2013 for CSP, hydropower, and biofuels [39]. These investment values of added RE installations are shown in Figure 7a. In contrast, the investment commitment for energy projects is compared to RE and fossil fuels in Figure 7b, with Figure 7c highlighting the investment cost distribution across the different industrial sectors, with projections made for the current year 2023.



	US	IN	GE	CH	CA	UK	FR	IT	JP	TK	MX	AU	IND	SA	KO	RU	BR	AR	SA
FU	141	37.9	18.9	25.3	30.4	40.2	7.59	3.97	1.63	15.8	8.66	0	6.54	5.59	5	5.18	0	1.36	0.64
FC	25	8.17	11.5	31.7	13.7	1.98	20.3	0	0	0	0	0.59	0	0	0	0	0	0	0
OE	22.2	68.8	53.7	19.2	8.93	5.95	20.7	1.5	0	0	0	0.74	0	0	0	0	2.35	0	0
CU	16.1	8.92	12.6	1.27	6.44	20.7	11.7	13.3	0	0	0.93	3.29	0	0.91	0.35	0	0.92	0	0
CC	128	32.3	29.1	19.2	35.5	12.3	11.1	35.8	18.8	0	0	1.29	0	0	0	0	0	0	0

Figure 5. Distribution of public funds commitment to energy investment (between 2020 to 2021). Data extracted from the energy policy tracker in [38]. US (United States), IN (India), GE (Germany), CH (China), CA (Canada), UK (United Kingdom), FR (France), IT (Italy), JP (Japan), TK (Turkey), MX (Mexico), AU (Australia), IND (Indonesia), SA (South Africa), KO (South Korea), RU (Russia), BR (Brazil), AR (Argentina), SA (South Africa). The legend FU, FC, OE, CU, and CC are for fossil unconditional, fossil conditional, other energy types, clean unconditional, and clean conditional, as explained previously in Table 4.

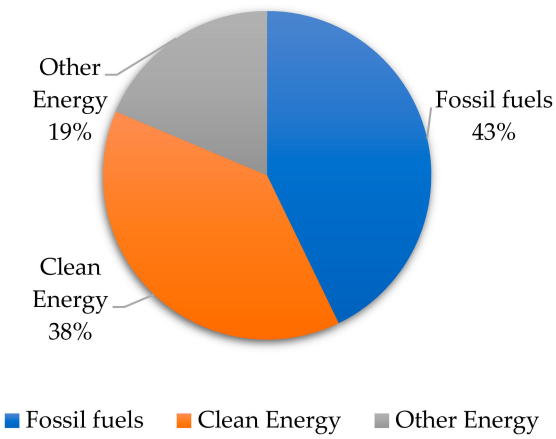
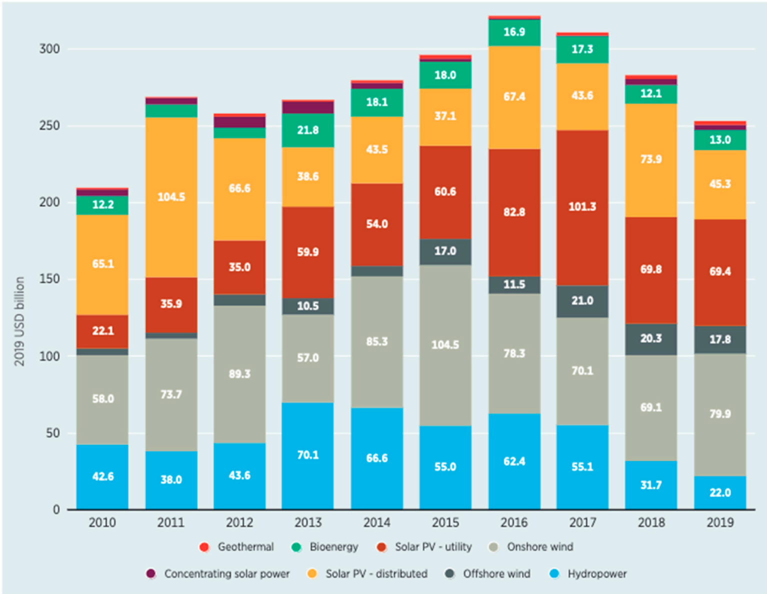
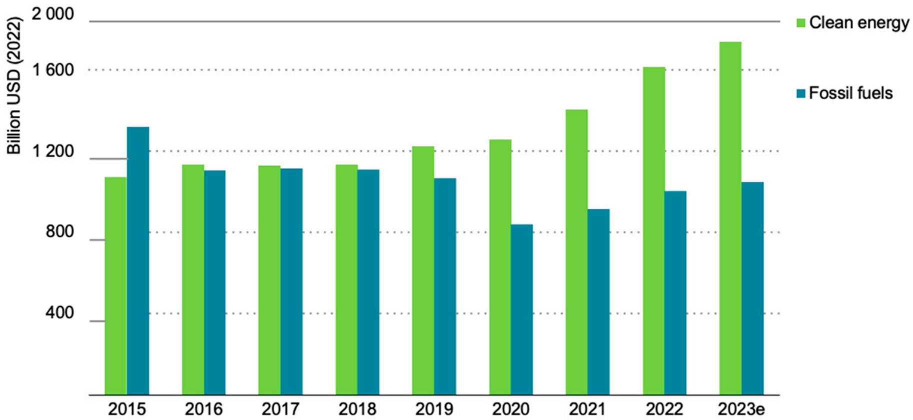


Figure 6. Total share of commitment of public finance to energy investment (1.09 USD Trillion) (in 2020–21) Source: Authors' elaboration.



(**a**)



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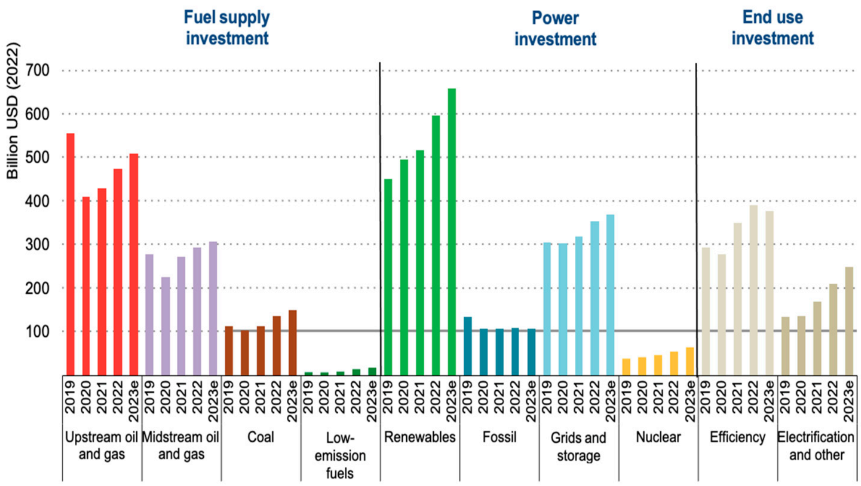


(**c**)

Figure 7. Global energy investment. (**a**) Investment value of newly installed RE capacity (2010–2019), according to the IRENA report in [39]; (**b**) global total investment commitment for clean energy versus fossil fuel projects (2015–2023), according to the IEA report in [40]; (**c**) global investment distribution for clean energy versus fossil fuel projects (per industry/sector) (2019–2023), according to the IEA report in [40].

In 2022, the global expenditure on energy transition technologies reached an unprecedented sum of nearly USD 1.6 trillion (i.e., USD 1,600 billion, as in Figure 7b). However, to adhere to the objective of limiting global temperature rise to below 1.5 degrees celsius, it is necessary to increase this annual investment [1,2,40,41], with [41] suggesting a cumulative amount of USD 150 trillion; hence, the projected expenditure to achieve this objective is estimated to surpass USD 5 trillion annually from the present time until the year 2050. In sustaining the current investment trajectory, securing an additional cumulative investment of USD 47 trillion is necessary by the year 2050. This amount is in addition to the estimated investment of USD 103 trillion, as projected in the Planned Energy Scenario, as shown in Figure 8. The annual investment of nearly USD 1 trillion in fossil-fuel-based technology should be redirected towards energy transition technologies and infrastructure [41].

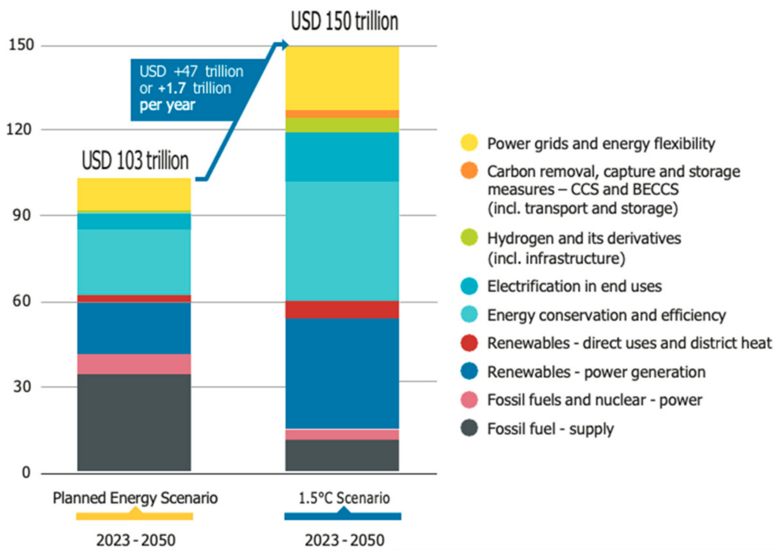


Figure 8. Global energy investment (Planned Energy Scenario versus 1.5 °C scenario), according to the IRENA report in [41].

The relationship between public finance commitment to energy development and global investment portfolios is intricate and increasingly relevant in the context of climate change mitigation and sustainable development. Understanding this connection becomes essential as governments prioritize energy transition and investors seek to align their portfolios with environmental goals. Research and analysis in this field can help policymakers and investors make informed decisions that balance financial objectives with sustainability and long-term economic stability.

Based on Figure 6, which shows a total amount of USD 1.09 trillion in public finance commitment by the G20 to global energy investment, the amount is believed to facilitate progress towards energy security. However, in the context of the transition to clean energy utilization, we assume the possibility of the total public commitments going into clean energy, such contributions being made annually. By continuous annual contribution between 2023 and 2050, a total of USD 29.43 trillion can be gained for clean energy investments. This amount is compared with the two scenarios in Figure 8 and represented in Figure 9 for comparative purposes.

Given the difference between the total public investment contribution under the 1.5 °C scenario and the additional amount valued at 4.47 USD trillion per annum (i.e., about 80% more funding combined with the G20 commitment) until 2050, it could be useful in increasing clean energy initiatives and projects aimed at keeping global warming within the desired threshold.

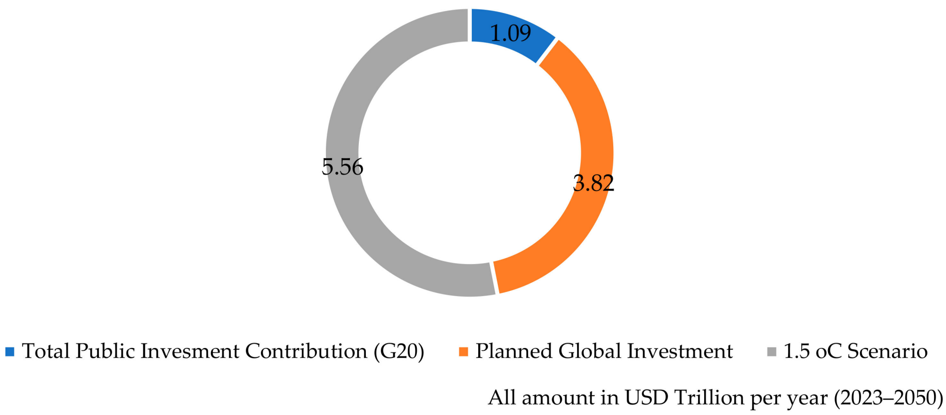


Figure 9. Global portfolio versus G20 public funds commitment to energy investment. Source: authors' elaboration.

5.1.1. Proximity to Reaching the 1.5–2.0 °C Scenario

Ecosystem biodiversity, human societies, diversified knowledge, climate change adaptation, mitigation, ecosystem health, and sustainable development are highlighted in the IPCC report [14]. By recognizing these interdependences, the value of various forms of knowledge, and the close links between them, this report reflects the increasing diversity of actors engaged in climate action. In a recent 6th Assessment Synthesis Report [42] released this year, the Intergovernmental Panel on Climate Change (IPCC) delivered a gloomy warning that left little space for dispute about the essential significance of taking rapid action and noted that it may be possible to limit the global temperature rise below the 2 °C scenario if there is success in reducing greenhouse gas emissions this decade. Within this time frame, only a dramatic increase in renewable energy and efficiency measures is possible [41]. IRENA's Director-General Francesco La Camera said, "The stakes could not be higher. The global energy system's profound and systemic transformation must occur in under 30 years, underscoring the need for a new approach to accelerate the energy transition". Finding ways to reduce the use of fossil fuels is seen as very important, but the current path of reduction is not enough to make the change to an energy system that works with fully or majorly green sources.

5.1.2. Response to the 1.5 °C Scenario Issues—Recent Policies of the top CO_2 Emitters

As a result of the 1.5–2.0 °C scenario issues raised by the IPCC, a few countries have gradually reviewed their existing energy policies to reflect this reality. Table 5 summarizes the progress made by the countries categorized as the top CO_2 emitters by energy. Europe is included in the list because of its observable large contributions towards the global transition to clean energy. It is important to note that some other countries still derive their measures from previously existing policies.

Table 5. Recent clean energy policies and NDCs of top CO_2 emitters (globally and in Africa) (2020–2023).

Country/Region	Summary of Energy-Related Policies for Climate Commitments	Addressing 1.5 °C Scenario Issues	Ref.
China	Increased RE Target in the National Grid • The 14th five-year plan raises the target for renewable energy to 30 per cent of total electricity consumption by 2025 (18 per cent for non-hydro renewables). Energy Storage/Hydrogen Roadmap Development • 50 GW new added battery energy storage capacity by 2025.	Partial	[40,43]

Table 5. *Cont.*

Country/Region	Summary of Energy-Related Policies for Climate Commitments	Addressing 1.5 °C Scenario Issues	Ref.
USA	Approval of the Inflation Reduction Act • Per-unit energy and investment tax credits for solar PV and wind energy systems are extended. • Battery storage and zero-emission nuclear power can qualify for an investment tax credit. • Investment in sustainable energy infrastructure and technology production. Energy Storage/Hydrogen Roadmap Development • 20.8 GW of battery storage by 2025, in addition to the 7.8 GW capacity at present.	Partial	[40,44]
India	Expansion of the Production-Linked Incentive (PLI) Scheme • 40 GWh of capacity to produce batteries. • Addition of 50 GWh of capacity to produce solar photovoltaic cells in the next three years. • Reduction of 50 Mtons annual emissions of CO_2 by 2030. Hydrogen Roadmap Development • 125GW Capacity of RE for green hydrogen by 2030.	Partial	[40,45]
Europe	Commitment to Increasing Offshore Wind Capacity • Nine EU member states have pledged more than 120 GW of offshore wind capacity installation by 2030 and more than 300 GW by 2050. Announcements by the European Commission—REPowerEU Plan, Net-Zero Industry Act Proposal, and other Potential Reforms • The European Union has proposed a few changes, including a faster permitting process. • An increase in the EU's 2030 renewables target to 45% by 2030 (total energy matrix, not just power). • An increase of around EUR 225 billion in loans for grids. Hydrogen Roadmap Development	Partial	[40,46]
Japan	• Reduction of Annual Emissions of CO_2 by 46% in 2030 from the 2013 levels. Planned Lifetime Extension of Nuclear Power Plants • The Japanese government is investigating the potential for extending the 60-year lifespan of nuclear power plants. Hydrogen Roadmap Development	Partial	[40]
Iran	-	None	
Canada	• Reduction of annual emissions of CO_2 by 40–45% in 2030 below the 2005 levels and net-zero by 2050. • Phasing out ozone-depleting substances included in the Montreal Protocol. • Adoption of the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) strategically aimed at reducing 2020 emissions by 347 Mt lower than 2015 projections and 36% below the 2005 levels. Hydrogen Roadmap Development	Partial	[47]

Table 5. *Cont.*

Country/Region	Summary of Energy-Related Policies for Climate Commitments	Addressing 1.5 °C Scenario Issues	Ref.
South Korea	Planned Production Capacity Reduction of Coal-fired Plants and Expansion of Nuclear Power Plants • Energy consumption from coal was cut by 15%. • From the current 10% share in 2021, renewables are expected to rise to 31% and nuclear power to 35% by 2036.	Partial	[40]
Indonesia and Southeast Asia	Indonesia-Introduction of Just Energy Transition Investment Plan (JETIP) • Achieve net-zero emissions in the electricity sector by 2050; increase the share of renewable energy in power generation to at least 34% by 2030; hasten the shutdown of coal-fired power plants. • Initial funding of USD 20 billion. Southeast Asia • From roughly 20% in 2021 to 35% in 2030 (and 50% in 2040), the Philippines has set ambitious targets for renewable electricity generation. • Under Thailand's new policy for renewable electricity procurement, the country's distribution companies are now required to pay feed-in tariffs and meet new capacity objectives (another 5 GW of biogas, solar, wind, and solar with storage).	Partial	[40]
Saudi Arabia	-	None	
South Africa	Introduction of Just Energy Transition Investment Plan (JETIP) • Increasing renewable energy projects between 2023 and 2027, aimed at achieving between 350–420 $MtCO_{2\text{-eq}}$ by 2030. • Considering how best to utilize and allocate the USD 8.5 billion on offer from the International Partner Group (IPG), made up of the United Kingdom, France, the United States, and the EU. • Approximately 2%, 8%, and 90% of IPG funding was allocated to electricity, new EVs, and green H_2 projects, respectively. However, the funding available can only reach 44% of the national financial target. • Reduction and complete phase-out of all coal-fired power plants by 2034.	Partial	[48]
Egypt	• Set targets to reduce GHG emissions in sectors (i.e., electricity, oil/gas, and transport) that contributed 43% of Egypt's total national emissions in 2015. • Reduction targets of 37%, 65%, and 7% in electricity, oil/gas, and transport, respectively.	Partial	[49]
Algeria	-	None	
Nigeria	Introduction of Energy Transition Plan (ETP) • Set targets to generate 30GW of electricity from renewables and reach net-zero carbon neutrality in sectors that contribute 65% of the total national emissions by 2062. • There is no clear investment commitment except the target for investors.	Partial	[50]
Libya	-	None	

Table 5. *Cont.*

Country/Region	Summary of Energy-Related Policies for Climate Commitments	Addressing 1.5 °C Scenario Issues	Ref.
Morocco	• A target GHG emission reduction of 45.5% by 2030, including an unconditional target of 18.3%. • The reduction objective is compared to the reference scenario, representing emissions under a business-as-usual (BAU) path. The mitigation scenario includes 34 unconditional and 27 conditional initiatives with regard to international finance.	Partial	[51]

NDC—nationally determined contribution is a form of GHG emission reduction commitment made by governments under Article 4(2) of the Paris Agreement [30].

As a result of the 1.5–2.0 °C scenario issues raised by the IPCC, a few countries have gradually reviewed their existing energy policies to reflect this reality. Table 5 summarizes the progress made by the countries categorized as the top CO_2 emitters. Europe is included in the list because of its observable large contributions towards the global transition to clean energy. It is important to note that some other countries still derive their measures from previous policies.

It can be observed from Table 5 that not all the top CO_2 global emitters have presented an updated plan to address climate change issues. In contrast, most of the emission reduction targets have only partially addressed the 1.5–2.0 °C scenario, as other factors and emissions from non-energy industries are hardly mentioned in the NDC commitments pledges found in the UNFCCC registry [29,31]. It is problematic that all the current policy plans and ongoing implementations may not achieve the UN SDG target of the world becoming a sustainable, developed society by 2030 while ensuring that the suitable global warming threshold is maintained. Therefore, and as has been previously discussed in this work, urgent but rational decisions and massive investment structures that match stated intentions with actions are required if this is to be achieved and spare the global population from the menace of climate change.

5.2. Uprising in 100% Renewable Energy System Possibilities and SED

There have been changes to the energy system, the economy, and the environment as the global energy system is transitioning towards renewable energy exclusively. The use of varying renewable energy sources, including solar, wind, hydro, geothermal, and biomass, is a great part of this shift, and a transition to 100% renewable energy would have positive effects on the environment, energy security, the economy, and the creation of jobs [52–54]. Table 6 shows the progress from 2018 to 2022 regarding the increasing penetration of RE in the national/regional energy mix of the G20 and the resulting contribution to reducing CO_2 emissions.

Table 6 presents the progression of either CO_2 emissions reduction or RE% increment for the G20 countries. For some years, there has been a retrogression in either the CO_2 emissions reduction or RE% increment, while only France and Germany have maintained consistent growth in both cases across 2018–2022. Emissions, particularly between 2020 and 2022, increased significantly across all the G20 countries except France, Germany, Indonesia, and Australia. The general increase is due to the re-opening of industries post-COVID-19. The year 2022 showed positive progress in the data available for the few countries that are the greatest emitters.

Table 6. RE penetration and CO_2 emissions reduction progress for G20 countries.

S/N	Country (G20)	Emission (CO_2) in 2018 Mt	Emission (CO_2) in 2019 Mt	Emission (CO_2) in 2020 Mt	Emission (CO_2) in 2021 Mt	Emission (CO_2) in 2022 Mt	RE in National Mix (%) in 2018	RE in National Mix (%) in 2019	RE in National Mix (%) in 2020	RE in National Mix (%) in 2021	RE in National Mix (%) in 2022
1	United States	5380	5260	4720	***4903***	***4970***	17.45	18.29	20.32	20.74	22.52
2	India	2600	***2630***	2450	***2701***	-	16.69	18.69	20.21	***19.38***	20.48
3	Germany	754.41	707.15	639.38	674.75	655.5	35.1	40.09	44.33	39.7	42.95
4	China	10350	***10,740***	***10,960***	***11,470***	11447	25.77	27	28.25	28.91	30.67
5	Canada	584.37	584.71	534.86	***545.63***	-	67.37	***67.17***	68.78	***68.17***	69.74
6	United Kingdom	379.73	364.75	326.26	***346.77***	331.5	33.29	37.46	42.86	***39.78***	41.45
7	France	322.53	316.39	280.03	274.4	269.7	19.73	20.01	23.76	22.23	24.54
8	Italy	349.01	339.23	302.28	***328.69***	317.7	39.81	***39.76***	42.04	40.62	***36.44***
9	Japan	1140	1110	1040	***1170***	-	18.14	19.42	21.32	22.61	23.63
10	Turkey	422.57	401.72	***413.43***	***446.2***	-	32.18	43.68	***42.02***	***35.56***	41.97
11	Mexico	475.27	472.19	391.71	407.21	-	17.7	18.55	21.26	23.94	***22.94***
12	Australia	416.28	***416.36***	399.92	391.19	-	17.15	21.38	25.05	29.13	32.3
13	Indonesia	603.66	***659.44***	609.79	***619.28***	-	17.05	***16.26***	18.13	18.17	19.62
14	Saudi Arabia	626.19	656.48	661.19	***672.38***	-	0.05	0.21	0.06	0.23	0.21
15	Korea, DPR	670.17	646.1	597.63	***616.08***	-	5.23	5.76	6.13	7.77	9.21
16	Russia	1700	1690	1620	***1760***	-	18.42	18.55	20.74	***19.96***	***18.36***
17	Brazil	477.1	475.1	442.31	***488.88***	-	82.92	***82.85***	84.64	***76.77***	86.94
18	Argentina	180.6	178.51	169.26	***186.45***	-	25.02	26.01	26.71	***25.35***	31.43
19	South Africa	435.24	***466.92***	435.83	***435.93***	-	5.16	5.36	5.78	7.56	9.09
20	European Union	3050	2910	2620	***2740***	2730	32.29	34	38.45	***37.34***	38.36

Data for RE% and CO_2 emissions were extracted from [55], and [56], respectively. The text in italics and bold indicates a decline in the progression of either increase in CO_2 emissions or RE% reduction from the previous year, respectively.

According to the IEA CO_2 emissions report of 2022 in [56], trends in energy-related CO_2 emissions were observed as follows:

- Energy-related global CO_2 emissions climbed by 0.9%, or 321 Mt, hitting a new high of more than 36.8 Gt.
- Difficulties in 2022 had an impact on the rise in emissions. Overall, 60 Mt CO_2 of the 321 Mt CO_2 increase is attributable to the requirement for cooling and heating during severe weather, while another 55 Mt CO_2 is associated with the shutdown of nuclear power plants.
- Energy combustion emissions increased by 423 Mt, while emissions from industrial processes decreased by 102 Mt.
- The increased usage of sustainable energy technologies, including heat pumps, electric vehicles, and renewable energy sources, helped prevent an extra 550 Mt of CO_2 emissions.
- Oil emissions climbed by 2.5%, or 268 Mt, compared to coal emissions, to reach 11.2 Gt.
- Despite the switch from petrol to coal in many countries, the global growth in emissions was less than expected in a year marked by energy price shocks, rising inflation, and disruptions to conventional fuel trading patterns.
- Due to supply issues made worse by Russia's invasion of Ukraine, natural gas emissions declined by 1.6%, or 118 Mt. The highest decrease in petrol emissions (−13.5%) was seen in Europe. Significant drops (−1.8%) were also noted in the Asia-Pacific region.
- A significant growth in renewable energy sources significantly decreased the revival in coal power emissions. Last year, renewable energy sources generated 90% of the additional electricity used worldwide. A new annual record was set by an increase in wind and solar PV generation of almost 275 TWh each.
- Except for China, emissions from emerging markets and developing economies in Asia increased by 4.2% or 206 Mt CO_2 in 2022, outpacing emissions from all other regions. The region's emissions increased by more than half because of coal-fired power generation.
- The combined production of wind and solar PV electricity surpassed gas or nuclear power for the first time.

Figure 10 shows 30 countries whose primary energy is at least 50% renewable energy. Nations such as Nepal, Iceland, Bhutan, and Albania have successfully attained a complete reliance on renewable energy sources, with consumption rates approaching 100%. In Ethiopia, DR Congo, Norway, Costa Rica, Namibia, Kenya, and Uganda, energy generation consists of between 70 and 99% RE. However, the measure of the population with electricity access is not 100%, as depicted in Figure 9.

As can be noted from Figure 10, even though electricity generation is nearly 100% RE in the countries presented, not all the population has access to electricity. Of the 30 near 100% RE countries, with a total population of 0.865 billion, 20% have no electricity yet, mainly in developing countries. From Figure 10, almost all the African countries in the list have a very large proportion of the population with no electricity access. Ethiopia, DR Congo, Kenya, and Angola, with populations of 120.3, 95.9, 53, and 35.6 million, respectively, have populations with electricity access of only 54.2%, 19%, 76.5%, and 48.2%. In comparison, the other countries with almost 100% electricity access, apart from Brazil, have lower populations compared with the near 100% RE African counterparts.

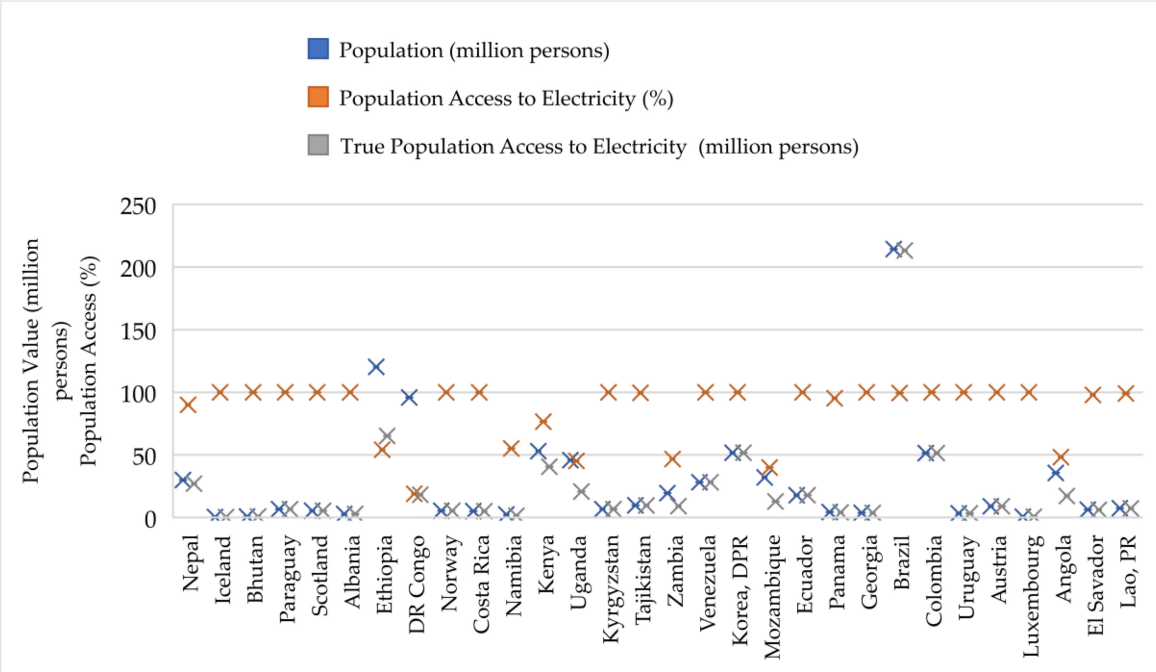


Figure 10. Population with true access to electricity in countries with high RE (70% or higher). Data from [28,57].

Implementing a completely renewable energy system has the potential to significantly impact the communities in these countries that currently do not have access to electricity [58]. This impact can have positive and negative consequences depending on many factors and circumstances. These are discussed further and summarized in Table 7.

Table 7. Possible impacts of increasing energy accessibility in developing countries. Source: authors' elaboration.

Impact	Highlights
Positive	1. Ease of facilitation in achieving the 100% RE vision. 2. Substitution of high infrastructural cost using microgrid powered by RE. 3. Jobs and economic development.
Negative	1. Human capacity and technical challenges with deployment. 2. Energy storage challenges to manage intermittency and reliability in supply. 3. Environmental impact from land and water uses for installation and operations. 4. Energy affordability issues with the high cost of RE.

The emphasis on prioritizing power access to remote and underserved areas may be heightened to complete a transition to renewable energy sources. The decentralization of renewable energy sources, such as solar and wind, enables electricity distribution to previously inaccessible areas hindered by the connectivity constraints of traditional centralized power grids. Renewable energy technologies are often deemed appropriate for deployment in smaller-scale systems, such as microgrids or off-grid installations. These systems have the potential to be deployed in isolated areas that have limited connection to larger power grids, therefore facilitating the utilization of energy resources without necessitating extensive infrastructure. The deployment of renewable energy infrastructure possesses the capacity to create job prospects and stimulate economic development within the community. The possibility to improve living circumstances exists through energy distribution to populations that previously lacked access. The preliminary costs of establishing renewable energy infrastructure, such as deploying photovoltaic panels and wind turbines, can be significant. The possible hurdle to the adoption of these technologies by poor groups may be mitigated with substantial external help.

Some geographical regions may have restrictions in terms of the necessary infrastructure and technical expertise needed for the effective deployment of renewable energy solutions. To ensure successful implementation, training and capacity-building programs must be offered in order to address the intermittency and reliability of various renewable energy sources, including solar and wind. Providing reliable electricity can pose challenges, particularly in regions where a consistent power supply is vital for critical sectors such as healthcare and education. The integration of renewable energy sources relies heavily on energy storage, as it facilitates electricity supply during periods characterized by limited solar irradiation or wind activity. Deploying reliable energy storage systems in remote areas may pose diverse obstacles and substantial financial consequences. When transitioning to renewable energy, it is imperative to consider the influence of cultural and social issues because adopting renewable energy may necessitate adjustments in local lifestyles, energy consumption patterns, and even traditional practices. Achieving a harmonious equilibrium between these modifications and preserving cultural values is necessary. Installing large-scale renewable energy projects gives rise to environmental and land use concerns, which have the potential to result in substantial consequences for local ecosystems and land use. Including thorough environmental assessments and active involvement of local communities are essential components within the decision-making framework.

In summary, the potential ramifications of implementing a comprehensive renewable energy initiative for populations lacking access to electricity depend on several factors, such as the selected approach, technological advancements, government support, financial capabilities, and community involvement.

It is crucial to recognize and address impediments while tailoring solutions to accommodate the unique needs mentioned in this section and the conditions of certain geographical areas, which have become rising issues in SED. The next section discusses selected emerging challenges and directions of SED.

6. SED Progress

6.1. Emerging Issues and Directions in SED

6.1.1. 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.

6.1.2. 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 8, and the rating is summarized in Figure 11. 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.

Table 8. Performances of energy storage pathways. Source: authors' elaboration.

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]
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 [59]. 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 11.

From Figure 11, 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, as noted in Table 5. 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.

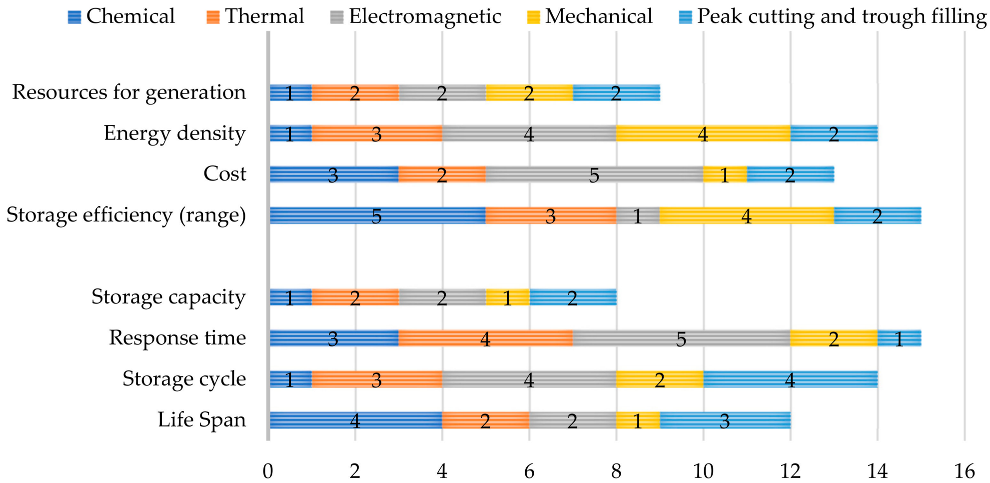


Figure 11. Performance rating of energy storage pathways. Source: authors' elaboration.

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 [60], 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 [61]. The article by N. H. Afgan et al. in [62] discussed the potential for multi-criteria evaluation of hydrogen systems based on performance, environment, market, and social aspects. H. Zhao et al. [63] 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 [63]. 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 [64].

In IRENA's report in [65], 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 9.

Even in the absence of many new governmental initiatives on energy storage, existing patterns of technical innovation and diffusion are continuously on the rise, as in the case of Hydrogen. P. Saha et al. [66] 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 [67], recent advances in green hydrogen technology were reviewed. Such advances include the hydrogenation of captured CO_2 in [68], green hydrogen from multi-renewable energy systems, as seen, for instance, with hydrogen from wind + geothermal in [69], wind + solar + electrolyzers + fuel cells in [70], and solar + electrolyzer + absorption chiller + electric + thermal energy storage in [71].

Table 9. 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, direct use of thermal energy	Long life span Fast response	Seconds to minutes	Low
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 [59].

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. Therefore, given the viability of the massive adoption of the hydrogen energy stream as a more promising option, Table 5 also indicates the countries with a hydrogen roadmap. 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.

6.1.3. 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 [53,72,73], 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 10 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 10. Issues and constraints surrounding SED decarbonization strategies. Source: authors' elaboration.

Category	Issues and Constraints	Related SED Themes (from Tables 2 and 3)
Institution and Politics	• Challenging support policies for increasing penetration of RE. [5,7] • Less government financing and subsidy. [10] • Energy wars. [1] • Rise in the disintegration of international treaties (uprise of the BRICS group versus G7, G20). [1]	5, 7, 10, 1
Technology Systems	• Challenges in maintaining grid stability because of varying RE in the existing conventional national grid. [1,6] • The initial cost of decentralized energy generation and storage. [8,10] • Challenging energy storage trade-offs (less storage cycle, high levelized storage cost). [7,10] • Challenges with high energy requirements for existing direct carbon capture and sequestration technologies. [6,7,8,10]	6, 1, 8, 10, 7
Climate Change Concerns	• Deforestation issues in the event of sudden utilization of forest resources for the energy transition. [8] • 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). [8,10] • Heat waves—intermittent cooling and heating needs of the population. [2,4,8]	8, 10, 2, 4
Public Opinion	• Energy markets (dwindling public trust for complete transition into 100% RE, less affordability, regional energy trade competitions). [3,5,10] • Adaptation issues with changing job and skill requirements for the new energy paradigm. [9] • Rising demand for energy accessibility in developing countries. [3,9,10]	3, 5, 10, 9

The numbers 1 to 10 are nomenclatures used to show the commonality and similarities with each sub-theme in Tables 2 and 3.

The constraints listed in Table 10 can all be categorized under the 10 themes of SED that this study earlier identified in Section 2. 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 11.

Table 11. Selected emerging decarbonization strategies for power and other sectors. Source: authors' elaboration.

Sector	Emerging Energy-Related Decarbonization Strategies	Merits	Demerits	Technology Maturity Level	Ref.
Power	1. Bioenergy with the capture of resulting CO_2 emissions. 2. Capture of CO_2 from fossil fuel emissions. 3. CO_2 methanation-energy resource (methane) recovery using the captured CO_2 as a feedstock. 4. Green hydrogen production and storage 5. Composites and materials hybridization for solar cell efficiency optimization.	1. Reduced CO_2 deposition in the atmosphere. 2. Alternative energy generation. 3. Improved generation efficiency.	1. High operational cost. 2. High energy requirement. 3. CO_2 storage constraint and durability of the reservoir. 4. Many hybridizations of materials as a composite are still at trial/experimental stages of development.	low	[67,74–77]
Industrial processes	1. Net-zero carbon and energy-intensive cement production using basalt and other calcium oxides (replacing limestone). 2. Industrial symbiosis (the waste in one industry becomes a resource for another). 3. Composite materials and intelligent manufacturing techniques.	1. Possibility of replacing 98% of cement production from limestones with CO_2 emission avoidance. 2. Waste reduction with energy savings and CO_2 emission avoidance.	1. Uncertain solutions (i.e., limestone replacement not yet tested at industrial scale). 2. Many hybridizations of materials as composites are still in the trial/experimental stages of development.	low	[78,79]
Transport	1. Use of vehicle-to-grid (V2G/G2V) for electric vehicle (EV) charging and energy trade. 2. Smart mobilities such as vehicle-to-vehicle (V2V) and autonomous vehicles. 3. Battery management system and solid-state batteries for EVs. 4. Sustainable aviation fuels (SAF) for commercial purposes are made from CO_2 via RE plus water synthesis. 5. Conversion of petrol/diesel to compressed natural gas (CNG) engines.	1. EVs are eco-friendly during their operational phase. 2. Reduced CO_2 deposition in the atmosphere with CNG use. 3. Reduced carbon intensity requirement and performance optimization mid-term trade-off for V2G, V2V, EV, SAF, and CNG.	1. High initial purchase cost. 2. The use of EVs requires grid stability and the right charging mechanisms. 3. EV battery materials resources' availability is not location-specific. 4. High conversion cost. 5. High safety handling requirements for CNG vehicles.	low	[80,81]
Building	*Innovative Active Cooling/Heating* 1. Use of heat pump, solar, and geothermal heating. 2. Alternative cooling technologies, such as vortex tubes. 3. Decentralized district heating and cooling using microgrids. 4. Intelligent and user-responsive cooling/heating using ML/AI techniques. *Passive Cooling* 5. Efficient building envelope designs and retrofitting. 6. Phase-change materials for cooling and heat storage.	1. Reduced CO_2 deposition in the atmosphere. 2. Alternative cooling and heating during intermittent seasonal demands.	1. High operational energy requirement for some alternative cooling/heating techniques. 2. High initial cost of installation and commissioning.	low	[82,83]

ML/AI—machine learning/artificial intelligence.

7. Discussion

The importance of energy in accomplishing the objective of sustainable development has been emphasized ever since it was placed on the international policy agenda [3]. To begin with, international conventions and treaties such as the UN Framework Convention on Climate Change and the Kyoto Protocol [15,18] have reframed energy development as a tool to reduce emissions of greenhouse gases and combat climate change. Energy problems were not found to be related to any other aspects of progress [8]. A new development paradigm that considers energy development's economic, environmental, and social impacts was mentioned in the IEA report in [2], which had its genesis in the UNDP's 2000 World Energy Assessment (WEA) study. According to the same IEA report, maintaining energy systems within the "carrying capacity of ecosystems" is essential for continuing economic growth and social fairness. The UN 2030 agenda report in [26] underlined the need for reliable, low-cost energy to meet these targets. Over the past three decades, SED has expanded to become an international, all-encompassing policy goal across more than 190 countries that are members of the UNFCCC and signatories to the Paris Agreement.

Each country and its energy system have unique difficulties and solutions for SED [8,84]. The article by P. Nejat et al. in [85] compares the situation of energy use, CO_2 emissions, and energy policy around the world using China, the US, India, Russia, Japan, Germany, South Korea, Canada, Iran, and the UK as the benchmark cases since they account for two-thirds of global CO_2 emissions. Along with these ten countries, the world's household energy consumption grew by 14% between 2000 and 2011, with most of this rise occurring in developing countries due to urbanization, increasing population growth, and other factors. Currently, traditional biomass makes up 40% of the world's residential energy market, followed by electricity (21%) and natural gas (20%). Strong energy policies, such as energy codes for buildings, subsidies, and energy labels, are necessary to control energy consumption. Nevertheless, because there is no comprehensive, efficient approach, countries such as China, India, and Iran continue to see huge increases in GHG emissions and energy consumption.

Consequently, this has necessitated the drive for massive adoption of renewable energies. To promote the widespread adoption of renewable energy sources in the Gulf Cooperation Council (GCC), the work by Z. Abdmouleh et al. in [86] provided regional decision-makers and international stakeholders with a collection of policy suggestions. A high-level summary of the RE goals of the GCC countries (Saudi Arabia, United Arab Emirates, Qatar, Kuwait, Bahrain, and Oman) was provided, focusing on the primary projects and strategies designed to kick off this shift. An evaluation of the regional RE potential, an analysis of the current installed RE capacity and project pipeline, and a review of institutional and commercial frameworks were all part of this study's in-depth investigation of the GCC countries' renewable energy (RE) situation. Key financial, economic, political, legislative, technological, and environmental factors impeding RE implementation in the region were identified and explored. G. Muhammed discussed these countries' and America's respective RE efforts [87]. Linear regression analysis determined how policies affect RE in the three selected countries. The findings showed that while policy assistance and regulatory instruments have the most effect, economic mechanisms are the most effective at increasing installed RE capacity. The US explored renewable energy sources for the benefit of Pakistan's economy and provided new job possibilities. Ahmad et al., in [88], aimed to identify methods for ensuring sustainable energy production and financial benefits. The paper also suggested putting resources into renewable energy systems with the lowest operational and external costs. It indicated that the government of Pakistan should encourage technological advancement in the nation's biomass resources because of their high potential benefits from a policy perspective. In addition, another developing country, an ASEAN member, is interested in several energy sources, including solar, wind, hydro, and biomass. S. Mekhilef et al. work in [89] underscores the significance of investigating renewable energy solutions to the rising expense of fossil fuels and greenhouse gas emissions. Legislation encouraging the use of renewable energy sources in both household and business settings has been passed by the Malaysian government, and a report that offers a concise summary of renewable energy in Malaysia, including information on current projects, projections for the future, and alternative energy policies were presented in [89].

To promote "smart, sustainable, and inclusive" growth in the region, the Europe2020 Strategy was presented in 2010 by I. Siksnelyte-Butkiene et al. [90], using the state-of-the-art multi-criterion decision-making (MCDM) technique to assess countries' progress towards the strategy's climate change and energy goals. The advancement of various countries was evaluated and compared using kernel-based comprehensive assessment (KerCA). Insights gained from analyzing how well the strategy was implemented can help shape and manage the dynamics of climate change and energy policy issues in the region, even during crises such as the COVID-19 pandemic or the Ukraine invasion. The innovative approach taken in the research was that the work assessed how effectively the objective was reached and how much was achieved beyond the initial objective.

Global consumption of coal, oil, and gas has reached unprecedented levels, reflecting the high demand for these fossil fuels. In response to the pressing need for sustainable energy sources, countries such as the United States, the European Union, and others actively promote and support the transition towards alternative energy solutions [1]. There is a noticeable upward trend in climate ambition and action within the public and corporate sectors.

The global energy boom since 2020, coupled with the impact of the COVID-19 epidemic, has led to an unprecedented surge in coal and fossil fuel demand [2]. However, with the estimation of Figure 12, which shows predicted sectoral demand, a reduction in the coming years is expected as there has been a noticeable global economic recovery, with a growing refocused investment plan in clean energy projects. Post-pandemic combustible fossil fuel consumption is predicted to peak in 2023, with road transport in 2025 and total transport in 2026. This pressing need has sparked an unparalleled surge in investments directed toward advancing clean energy technology, and the imperative to achieve climate targets necessitates a substantial surge in renewable generation by 2050 [40].

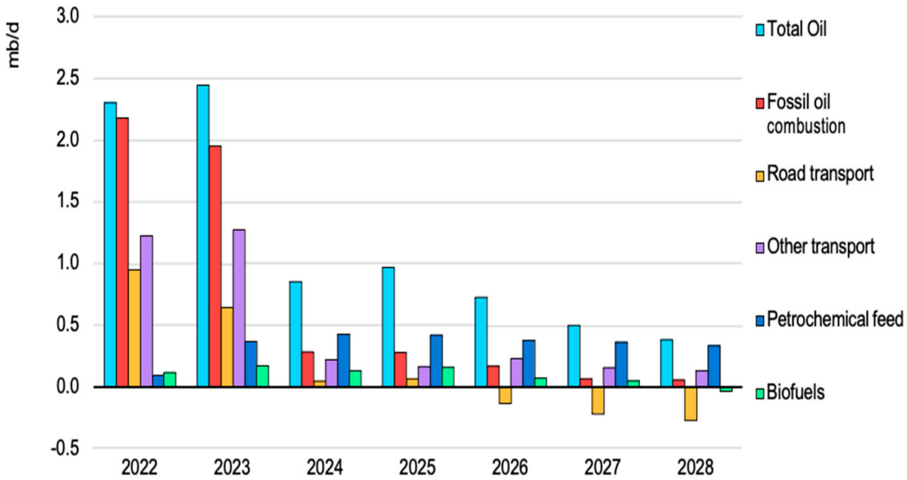


Figure 12. Forecasted growth in oil demand (per annum, between 2022 and 2028), according to IEA Oil Report in [2].

Sustainable development is closely linked to using renewable energy sources [91], as the economy relies on natural resources to provide consumer goods and services. The availability constraints and disadvantages of excessive use of these natural resources pose restraints to sustainable development. The UN's SDGs for 2030 established the need to address these challenges by setting targets for sustainable development, and in doing so, the critical link between renewable energy use and sustainable development became apparent. Among the 17 SDGs established by the United Nations is climate change action (i.e., Goal 13) through the promotion of environmental sustainability practices.

It has become necessary to stop or reverse the depletion of environmental resources by implementing national policies and plans prioritizing sustainable development. Goal 7 of the 2030 Sustainable Development Agenda established by the United Nations consists of the following [26]: universal access to affordable, secure, and modern energy services by 2030; strengthening international cooperation to facilitate access to renewable energy; increasing energy efficiency; and promoting investments in energy infrastructure and clean energy.

Achieving such a feat could significantly increase the share of renewable energy in the global energy mix by 2030 and double the global development rate to enable the population to afford the initial cost of the transition. The focus on renewable energy in SDG 7 is a prime example of this principle that synergizes the relationship between renewable energy and sustainable development.

7.1. Sustainable Energy Development Tracking and Assessment

To progressively achieve SED, methods of tracking sustainable development and gauging whether policies are fostering optimal growth are essential to develop in the form of indicators and targets. The necessity for sustainable development indicators that may be used to influence decision-making at all levels was emphasized in the United Nations' Agenda 21 [92].

Using the right sustainability indicators is essential for monitoring progress and informing policy choices. Several indices and indicators have been developed for use in the study of SED. Because they all measure various things and have distinct purposes, there is a huge variety of them. Disagreements on methodological approaches and whether stakeholders should be engaged in formulating indicators are two examples of the roadblocks that have slowed down these efforts. The success of renewable energy programs was examined by T. Horschig et al. in [93] using a variety of methodologies to assess energy policy. Modelling and analysis of the energy system are the most popular techniques.

The study by T. Horschig et al. in [93] also provided an overview of current modelling techniques for modelling renewable energy policies to assess their effectiveness and effects on other sectors. The benefits and shortcomings of various strategies presented in the same work resulted in a framework for deciding whether they are suitable for evaluating renewable energy policies. On the other hand, N. A. Spyridaki et al. in [94] provided a side-by-side comparison of qualitative and quantitative methodologies used to evaluate the interplay between energy and climate policies, illuminating important disparities and calling attention to the most serious challenges and limitations that have been overlooked thus far. Existing methods only partially consider the multi-actor, multi-level nature of interacting policy, and there is still a lack of variation in the evaluation of policy and research into cross-sectoral interactions is underutilized.

Therefore, in modern society, research should consider a wide range of national issues that address all three dimensions of sustainability while still recognizing the need to employ renewable energy for future generations. Figure 13 shows how the 17 UN SDGs relate to human well-being, material conditions, and the natural environment [95], together constituting sustainable development.

In addition to international treaties and other efforts to achieve sustainable development, measures have been implemented to track SDG progress, such as those found by R. Ritchie and O. Mispy and OECD in [28,96], respectively. Kumba H. et al. [97] used the SDG progress tracker to discuss renewable energy development in South Africa, with implications on the country's energy policy pathway towards the achievement of SDG 7.

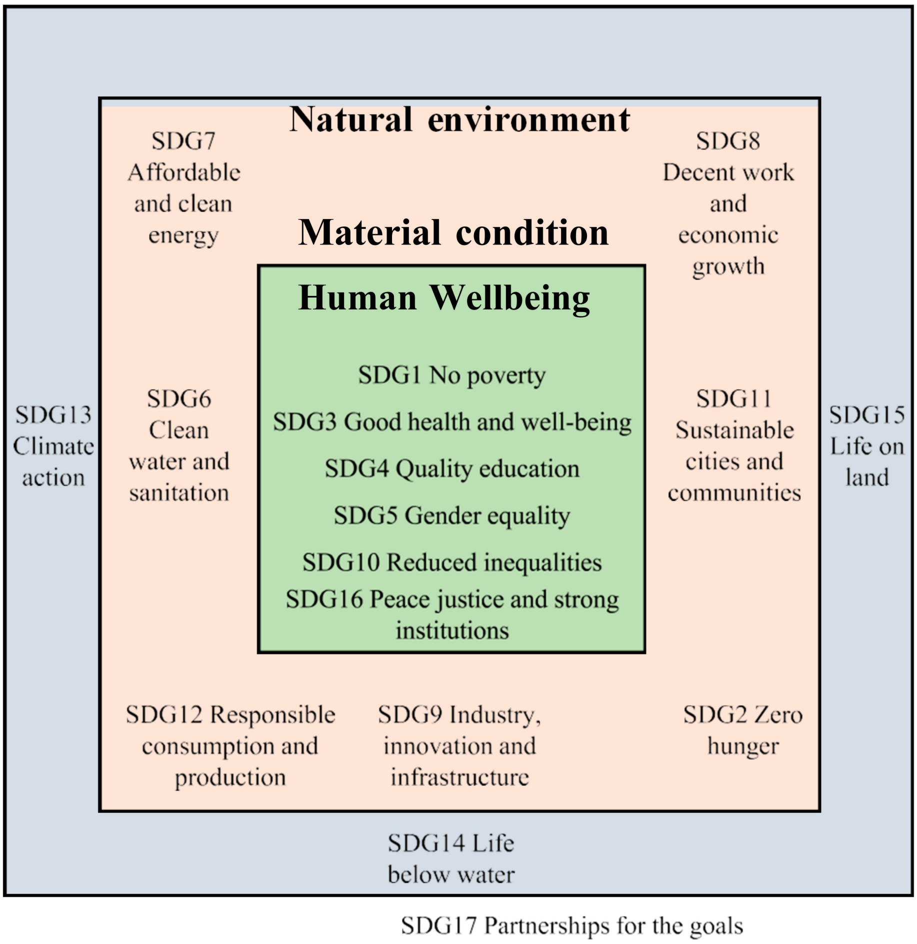


Figure 13. Nexus of the United Nation's SDGs, according to X. Pan et al. in [37], as modified from the summary by J. Waage et al. in [96].

The necessity for sustainable development indicators that may be used to influence decision-making at all levels was emphasized in the United Nations' Agenda 21 [93]. Using the right sustainability indicators is essential for monitoring progress and informing policy choices. Several indices and indicators have been developed for use in the study of SED. Because they all measure various things and have distinct purposes, there is a huge variety of them. For sustainable development goals to be achieved, energy policies must reflect the true value of energy to society [98–100]. Human well-being must be prioritized, the natural environment conserved, and the conditions of materials used to produce these energies are easily replenished to preserve world resources and defend against the consequences of climate change. The discussion surrounding climate change, energy, and sustainable development is presented in the next section.

7.2. Energy, Climate Change, and Sustainable Development

The global movement towards low-cost, environmentally friendly energy systems is gaining momentum, necessitating a better understanding of the interconnectedness of energy and sustainable development [58]. Climate change and energy variability severely affect human society, the environment, and development. Renewable energy investment is widely accepted as a strategy to reduce global warming impacts and ensure long-term economic growth sustainability. Sustainable energy development involves expanding energy supplies and regulating demand to meet societal energy needs while minimizing greenhouse gas emissions and climate change impacts [101]. The difficulties posed by climate change have been exacerbated by global anthropogenic activities that release harmful greenhouse gases (GHGs) into the atmosphere [11]. The use of fossil fuels as an energy source has come under increased scrutiny because of efforts to reduce climate uncertainty. All parts of the world are feeling the effects of climate change, and the energy industry has received much attention because it is responsible for a disproportionately large percentage of these emissions. Since energy consumption is so important to economic growth, experts have continuously stressed the importance of large utilization of renewable energy sources across the globe [102–109]. Currently, this has led several advanced countries to invest in several renewable energy projects while most developing countries are still striving to achieve 100% energy access and other development issues. Therefore, a growingly disproportionate share of global greenhouse gas emissions could be expected from developing countries should they follow the traditional path of industrialization towards achieving complete energy access [110].

Reviewing the literature using bibliometric analysis, X. Pan et al. [37] found that studies on the relationship between energy and sustainable development have increased rapidly in recent years. Low carbon emissions and efficient and sustainable energy systems provide great potential for advancing human flourishing, material prosperity, ecological equilibrium, and cooperative endeavours. To combat climate change, X. He et al. in [111] investigated whether countries with large investments in renewable energy should increase their spending on R&D. The findings demonstrate that investments in renewable energy generation can lessen the risks associated with climate change and cut down on export surpluses. Sustainable urbanization policies, improved use of natural resources, and more investment in renewable energy technology are all essential steps toward achieving SDG 13. Global leaders prioritize slowing climate change, urging both developed and developing countries to adopt low-carbon sustainable technologies that are both scalable and transferable. Numerous studies have investigated the potential synergies that could be realized on a national level and the trade-offs that must be made between the various aspects of sustainable development. Case studies on a national scale of Brazil, China, India, and South Africa are highlighted as examples from these studies, as summarized by K. Halsnæs et al. in [112].

Sustainable development has been advocated as a guiding principle to coordinate better efforts to tackle poverty and climate change. These countries may be able to accelerate their development efforts and reduce their carbon footprints at the same time if climate change is factored into their sustainable development strategies, developing adaptability in the face of climate change and the possibility of alternative national development plans for infrastructure [112]. China's energy demand, supply, and emissions, focusing on global, regional, and local environmental and health concerns, were analyzed by X. Ren et al. in [113] while addressing equity issues in climate change and the connection between redefining development goals and sustainable development. It discusses non-fossil fuels, natural gas switching, economic reorganization, and clean coal technologies for reducing emissions and energy security. It emphasizes improving energy efficiency and integrating renewable energy into rural development [114]. The study by S. S. Mutanga et al. in [114] showed that African countries need infrastructure for sustainable development goals such as human growth, poverty eradication, and climate change mitigation, and further stated that the G20 Agenda for Africa in [115] should align with African initiatives, the SDGs, and the Paris Agreement; promote low-carbon development; eliminate subsidies; establish a carbon price; and create a level playing field for low-carbon technologies. M. Tosam et al.'s work in [116] examined Africa's disposition to climate change and its potential for long-term development. Africa is the most susceptible region globally, facing starvation, illness, and financial loss due to environmental degradation and extreme weather events. The continent's fragile political and economic systems are threatened by climate change. It argued that investments in renewable energy, good governance, and traditional values, such as environmental preservation and women's economic empowerment, are essential for effective climate change mitigation and sustainable development [116]. With a focus on regional and local initiatives, D. Streimikiene et al.'s work in [117] analyzed Lithuania's national energy and climate change policy. It offered a framework for regional solutions to climate change mitigation in the context of national and transnational energy, climate change, and rural development policies.

For long-term progress in green energy economy for sustainable growth (EESG) domains [118], a country must shift to a green economy. Renewable energy is indispensable for sustainable development and the fight against global warming [119]. Enhanced energy resource potential forecasting, more reliable renewable energy resources, and energy efficiency incentives could support countries' policies for renewables in support of climate change actions [120]. Energy efficiency, renewable energy, mobility, and sustainable land use are only some examples of climate change policies that can help advance the sustainable development agenda [98,121–124], considering the distributive consequences of not making responsive and immediate plans to tackle climate change issues and the consequences on both social and economic development, vulnerability to climate change effects, and adaptive capability, future agreements on mitigation, public trust, and adaptation are needed.

To effectively combat climate change, it is crucial to comprehend the complexity, unpredictability, and hazards related to future climate change [125]. Following pertinent national green development strategies and policies, utilizing science, technology, finance, and city governance to actively address urban climate change issues, such as improved adaptation and mitigation measures, and carefully selecting development pathways can significantly improve climate resilience [125]. Income, poverty, water stress, food access, sustainable energy use, energy security, and ocean acidification are the only indicators of sustainable development and climate change that can be analyzed. K. Akimoto et al. [126] stressed the importance of a well-thought-out strategy for economic growth to deal with climate change and sustainable development indicators. Integrative assessment frameworks are often applied to analyze these metrics objectively [127–132]. Synergizing energy development with long-term sustainability is an area that necessitates more study and further investigation as the current global paradigm views energy as a subset of climate change policy's many related components. Therefore, national energy policy instruments and frameworks are crucial for mitigating global climate change by addressing fossil fuel geopolitics, renewable energy technology development, and national power system planning. Addressing core societal concerns such as energy security is essential for achieving climate goals and sustainable development.

The next section briefly presents cases of relying on national energy policy instruments, frameworks, and assets to manage energy security for sustainable development in the fight to mitigate global climate change.

7.3. Energy Security in the Context of Sustainable Development

Energy security and sustainable energy use are crucial for political stability, economic growth, and social well-being. In line with the UN 2030 SDG agenda, many countries are rethinking their energy development strategies to align with Agenda 2030 goals. For instance, L. Luty et al.'s research [133] examines EU countries' dynamic differences between energy security indicators (i.e., energy demand, productivity, and dependency), applying the TOPSIS methodology. Results showed no correlation between energy productivity (primarily based on foreign energy sources) and sustainable energy consumption. However, primary energy use and renewables' gross final energy consumption share were strongly linked to total energy import dependence.

A study by L. Zhang [134] presented a methodological framework for addressing energy security using quantitative and qualitative techniques. It interpreted the seven-part framework and 28 indicators, presented the GRA-TOPSIS hybrid model, and used fuzzy AHP to highlight dimensions and indicators. A qualitative root cause analysis using a Why-Why diagram was conducted. The framework highlighted the multifaceted nature of energy security, requiring enhancements in the technological, environmental, social, and political spheres. Using SOWA (subjective and objective weight allocation) and a balance score matrix, the study by Q. Wang et al. in [135] introduced a novel approach to evaluating energy security (ES). The report showed progress in building a secure energy system in 37 out of 162 nations (scoring 'Good'). Inadequacies in all three areas were highlighted, and suggestions for how countries can raise their scores were provided.

By converting vague ideas into quantifiable criteria and digging into the connections between causes and effects, J. Ren et al.'s research [136] tried to guide stakeholders in developing workable plans for strengthening energy security. The DEMATEL technique was used to rate the various approaches to energy security, and it was concluded that national measures emphasizing renewable energy development and diversity were necessary. The research also emphasized the significance of limited energy resource potentials, data accessibility, and cost in ensuring a nation's energy security. Limited resources and isolated power systems require energy security (ES) for sustainable growth. For instance, South Korean ES was evaluated from W. Chung et al.'s work [137] utilizing supply reliability, power generation economics, environmental sustainability, and technology complementarity. The proposed ES indicators could assist policymakers in assessing ES and deciding on regional disputes and climate change treaties. Combining indicators and analyzing the quantitative impact of microscopic elements on ES across time is useful in yielding comprehensive indicators. Energy consumption, final energy intensity, losses in transformation, RPR of crude oil and natural gas, net energy import dependency, and CO_2 emission per capita are significantly connected with the indicator.

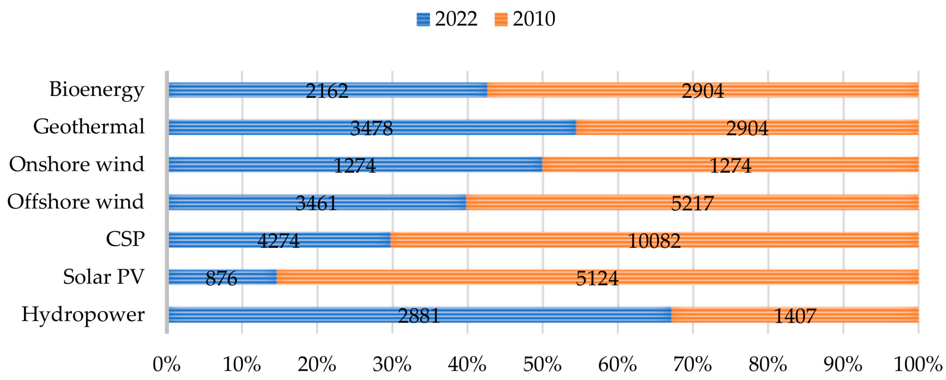
Consequently, Thailand's energy security was measured by its Aggregated Energy Security Performance Indicator (AESPI) from 1986 to 2030. The AESPI dropped from 9 to 7 between 1992 and 2009, but energy conservation maintained it [138]. For data accessibility, an approach for quantitatively evaluating energy security was presented in [139]. The methodology had been adjusted to fit Malaysia's and other Southeast Asian nations' sparse data availability. According to this framework, 5 fundamental characteristics and 13 sub-elements comprise energy security. As markers for these 13 components, 35 have been found. The study explained how the indicator data were normalized on a 0-to-1 scale to transform them into a common unit. The weights employed in the weighted-average method, which synthesizes normalized indicators into composite scores for the 13 elements, the 5 key features, and 1 overall energy security index, were also discussed [139]. B.W Ang et al. introduced a composite index and three sub-indexes in [140] to examine Singapore's energy security. These indices track the status of the economy, the supply chain, and the environment concerning energy safety. Despite a drop in economic factors, the findings indicated a rather constant state of energy security. For countries that must rely on imports to meet energy needs, this methodology helps identify power grid vulnerabilities.

Many countries prioritize safeguarding their energy supplies by expanding renewable sources, improving energy efficiency, and reducing carbon dioxide emissions. Energy security indicators monitor these initiatives' effectiveness. However, conventional energy safety measures are often insufficient, with regulatory efforts varying in response [141]. Adaptation to climate change, water intensity reduction, oil dependence reduction, energy affordability, and access to modern energy services are among the five energy security strategies that were studied by B. Sovacool [142]. The research highlighted differences and parallels across the energy security indicators while arguing that the common "all of the above" perspective is flawed (i.e., expecting that a country can sufficiently meet the target of all the indicators at 100%). It was emphasized throughout the study that there is no such thing as complete energy security and that certain policy aims and plans should be prioritized above others [142]. The next part discusses key priorities (energy innovation and financing) to ensure that energy security and sustainable development are achieved globally while climate justice is upheld.

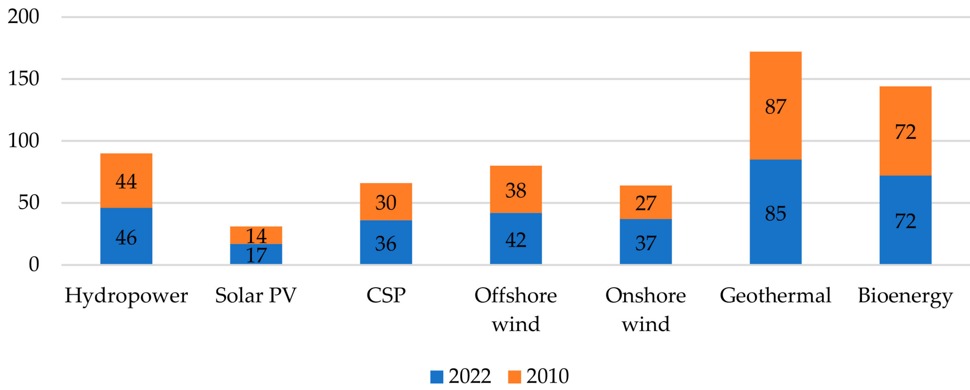
7.4. Energy Innovation, Financing, and Sustainable Development

A study on sustainable innovation tried to link financial growth with energy innovation and predicted that by 2030, energy finance could play a 40% essential role in the energy transition paradigm [143]. Proper energy financing is a key component of the framework of the study, which could benefit sustainable energy innovations that further energy development and the Sustainable Development Goals [143]. To assess the benefits of green energy finance (GEF) for green energy technology/innovation (GEI) and carbon efficiency, L. Pang in [144] looked at how it affects both areas. The link between these variables was evaluated using the wavelet-based quantile-on-quantile approach. The results indicated that, in the near to medium term, green energy finance could probably have compound impacts on GEI across various market sizes and conditions. In contrast, in the long run, the bull GEF market might be able to use the positive outcomes, while the bear market might take advantage of the drawbacks. The outcomes vary from short-term to long-term [144].

Because of the connection between innovation and environmental sustainability, many countries have prioritized renewable energy financing and technological innovation to these ends [11,145]. In addition, the emergence of new materials, increased production efficiencies, policy support, and the large benefits of renewables have greatly helped reduce the cost of renewable energy technologies. Examples of these cost reductions between 2010 and 2022 are represented in Figure 14 and Table 12 for the Levelized Cost of Energy (LCOE) of seven RE technologies.



(**a**)



(**b**)

Figure 14. Total installed costs and capacity factor of RE technology. (**a**) Total installed cost of RE (UDS/kW), according to IRENA report in [146]; (**b**) RE capacity factor, according to the IRENA report in [146].

Table 12. (LCOE) trends by technology, 2010 and 2022, according to the IRENA report in [146].

Energy Technology	LCOE (USD/kWh)	LCOE (USD/kWh)	
	2022	**2010**	**% Change**
Hydropower	0.061	0.082	25.61 decrease
Solar PV	0.049	0.445	88.98% decrease
CSP	0.118	0.380	68.95% decrease
Offshore wind	0.081	0.197	58.88% decrease
Onshore wind	0.033	0.107	69.16% decrease
Geothermal	0.056	0.053	5.666% increase
Bioenergy	0.061	0.082	25.61% decrease

The transition to a low-carbon society and sustainable development relies heavily on technological development since technological innovation in energy systems has been shown to minimize carbon emissions [147,148]. Eco-innovations in terms of increased energy-efficient systems contribute to economic growth and reduce environmental damage by decreasing emissions from energy use and promoting better resource utilization [124,149]. Such possibilities are easier with proper financing systems that support the investment of capital into such research and projects, as has been a consensus among the leadership of nations and international agencies/organizations/forums about energy financing. Recently, global leaders have made it a priority to promote the widespread use of low-carbon, sustainable technologies that are scalable and transferable in both industrialized and developing nations in the bid to meet the COP21 goals [150–152]. COP21 emphasizes the importance of carbon neutrality and environmental sustainability, and countries must shift to renewable energy, reduce emissions, and adapt to climate change through green investment and technological innovation. The study by K. Zhang et al. in [149] examines 49 countries that issued green bonds between 2007 and 2019, highlighting the connections between pollution, climate change, and renewable energy use and affirming that green finance is an effective strategy for combating global warming and environmental issues. Accelerating green finance growth is crucial for sustainable development, fostering collaboration among sectors such as innovation, renewable energy, environment, and climate [100].

Facilitating green finance is not without challenges; for instance, after the COVID-19 pandemic, the cost of green financing for renewable energy expansion, with private investment being a key factor in reducing greenhouse gas emissions, has increased. Therefore, the need for more private investment to assist green energy funds and encourage investment in clean technology has risen. In addition, only a few industrialized countries with high technological capacity receive most of the private investment in green finance despite its importance for sustainable development. Financing for technology transfer (TT) and supporting stakeholders in the energy sector in developing countries is crucial for the UNFCCC and Kyoto Protocol, enabling faster implementation of environmentally sustainable technologies, policies, and procedures across the different regions of the world. The work by C. Karakosta et al. in [153] analyzes the benefits and drawbacks of TT implementation and its impact on energy infrastructure. Innovation systems must actively cultivate economic and social capital through multi-stakeholder networks, as natural and social capital are not easily replenished. Power and lack of trust in markets can hinder progress, as seen in monopolistic electrical corporations' attitudes toward distributed energy and intellectual property. With proper financing and technology transfer, developing countries and smaller organizations can develop disruptive technologies due to the importance of domestic institutional frameworks and cultural norms. Factors influencing this green energy private financing and technology transfer/adoption include relative benefit, compatibility, complexity, observability, trialability, and risk. Addressing these factors and familiarity with new opportunities could make smaller-scale breakthroughs in energy technologies and implementations easier.

8. Conclusions and Prospects for Future Work

Given that the average energy generation life cycle is about 25–30 years, the world is just about one-quarter of an investment cycle away from 2030. This study emphasizes the urgency of addressing current and emerging energy issues within the updated themes of SED presented in this work and, more particularly, the importance of clean energy financing and renewable energy dominance. Any investments made in current energy generation must be able to work in concert to meet society's needs in the present while limiting any further carbon emissions to keep the environment protected for future generations. Hence, continuous investments in fossil fuels could lead to stranded assets and underutilization within the regular life cycle of electricity generation plant operations. Therefore, significant investment in clean and sustainable energy systems could ensure the operational longevity of generation facilities beyond the year 2030. With this in place, the global energy system can be sustainable, helping nations focus on the other key development needs of society that make up the other goals of the United Nations' SDG, as indicated in Figure 13 while reducing the impact of climate change through energy development.

The world's total energy development has continuously seen an increased growth rate of renewable sources' contribution to the total global energy mix during the past decade. However, the penetration of RE comes at a high initial cost that requires a large and unprecedented financial investment from government, private, and corporate entities. Consequently, countries and governments are required to assist this movement by developing policies that support the nationally determined contribution (NDC) initiative for each country to comply with the COP21 Paris Agreement's objectives for reducing greenhouse gas emissions and adapting to climate change. It is unfortunate that even though there are commitments by many of the countries making up the 195 members of the UNFCCC, as can be found in the NDC registry in [29]. Hence, there is a need for stricter policy measures, better Carbon budgeting and energy financing to reduce global emissions, as the current NDCs are not sufficient [154,155].

A recordable investment into fossil fuels continues, as can be seen in our analysis, where finance allocated by the G20 countries for clean energy constitutes only 38% of the total, which is somewhat smaller than the allocation for fossil fuels at 43%. The remaining 19% is designated for various other forms of energy that are either clean or fossil fuels, posing a continual challenge to ambitions addressing climate change.

Therefore, clean energy financing policies and support should be increased by developing an evaluation system and information disclosure criteria compatible with developmental issues and energy innovation to reduce emission levels in the drive for sustainable development. Such evaluation systems should employ an integrative approach in assessing and determining the right energy financing mechanisms for transition into globally sustainable energy systems and sustainable development. A typical example may be redefining NDC through a centralized emission budgeting strategy for global or regional stock-taking aimed at identifying the best options for emissions reduction investments. For instance, the NDC from the EU addresses greenhouse gas mitigation from a regional perspective. In this way, less adverse compromise on individual countries' developmental issues could be achieved through the right sharing ratio for both clean energy funding and emission reduction expectations. A possible outcome from such a regional evaluation system could help provide clarity on the exact percentage of renewables in both the national or overall global energy mix and the right energy finance investment options that put every country in an advantageous position to meet the goal of low-carbon economic transformation and to stay within the 1.5–2.0 °C scenario of the Paris Agreement.

Finally, considering these dynamics of cross-sectoral interactions and the interrelation between the SED themes as highlighted in this work, there is a need to explore timely strategies towards the 1.5 °C Scenario and SDGs' vision. In the current energy paradigm, SED themes involving emerging issues like energy storage and developmental indices such as energy accessibility, affordability, independency issues, and energy-X (where X can be other infrastructures or areas such as food, water, and land) nexus continue to be instrumental towards developing a comprehensive, integrated assessment approach to evaluate and manage multiple energy potentials, resources, and systems while creating a link between energy systems or policies and sustainable development goal 7 (clean and affordable energy for all), goal 13 (climate change action), and other relevant goals of the SDGs towards the 2030 United Nations' targets.

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