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Review

The Global Electricity Grid: A Comprehensive Review

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Abstract: Renewable energy includes a wide variety of technologies that may provide electric energy without releasing greenhouse gases. However, due to the intermittent nature of renewable energy sources, relying on a single source cannot ensure a steady energy supply, making it essential to combine multiple renewable energies with thermal generators to meet the required energy demand. Furthermore, the economic feasibility of renewable energy can vary significantly across different geographical regions. These challenges can be addressed successfully through the global electricity grid concept. It enables the efficient transmission of clean energy over long distances, and it allows nations to capitalize on their unique renewable energy strengths, facilitating the seamless exchange of clean energy to meet global demand while optimizing the use of renewable resources worldwide. This paper examines global and regional initiatives aimed at fostering a sustainable energy future, highlighting the benefits and challenges associated with globally interconnected power grids and intercontinental transmission networks. Although the challenges and opportunities of the global electricity grid are well understood, the quantification of its costs, benefits, and environmental impacts remains in its infancy, leaving a significant gap in the current literature.

Keywords: the global grid; renewable energy; electricity transmission network; world energy interconnection; power transmission; climate change

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1. Introduction

Climate change poses a substantial worldwide environmental concern. The possible consequences of its impact on society and biodiversity include significant threats to the global economy, the potential for international disputes, and the possibility of political catastrophes [1]. Various pathways have been introduced to illuminate how society might reconfigure its energy systems to align with the ambitious objectives outlined in the Paris Agreement [2]. These analyses emphasize that increasing renewable energy (RE) adoption and enhancing efficiency are essential prerequisites for restraining the global temperature increase to below 2 °C throughout the century [3]. Based on this evaluation, it is estimated that the threshold of 1.5 °C will be reached by the beginning of 2030, while the objective of 2.0 °C is anticipated to be achieved by 2050 [4]. In view of this, various studies have emphasized the necessity for all nations to reassess their commitments in 2018 to genuinely achieve the objectives set forth in the Paris Agreement. According to a study conducted in 2022 by International Energy Agency (IEA), the percentage of fossil fuels used in the worldwide energy portfolio has consistently elevated, staying at about 80% for a significant period of time [5]. Nevertheless, as per the Stated Policies Scenario (SPS) prediction, it is expected that this percentage will decrease to less than 75% by 2030 and 60% by 2050. According to the SPS, the peak of global CO_2 emissions is projected to occur in 2025, with an annual amount of 37 billion tones, followed by a decline to 32 billion tones by 2050. This trajectory would likely lead to an increase of approximately 2.5 °C in world temperatures by 2100 [6]. When analyzing worldwide total consumption of energy, electrical energy accounted for 18.1% of the energy; however, it was responsible for 35.2% of worldwide overall CO_2 emissions [7].

Harnessing RE offers opportunities, such as mitigating environmental damage and waste, lowering GHG emissions, expanding energy resources, and maintaining sustainability. Photovoltaics (PVs), wind energy (WE), and hydroelectric energy (HE) are essential technology options for enabling the paradigm shift to a decarbonized energy infrastructure. Although there has been a significant increase in the use of PV and WE over the past decade, there are still various underlying challenges that prevent the widespread implementation of these REs. The primary challenges in implementing the REs are prioritization of RE resources, identification of appropriate resources, site selection (SS), and determination its generation capacity [8]. Among these steps, RE site selection is crucial when constructing a RE power plant, since it has a direct impact on the capacity for electricity generation and possible socioeconomic advantages in the future. Therefore, the careful selection of sites for RE projects is highly significant. To date, numerous approaches have been developed to tackle decision-making problems, such as identifying promising resources and minimizing the cost of production while considering social and environmental impacts. Therefore, additional study is essential for optimizing RE site selection in order to maximize the use of sustainable energy. The first objective of this study is to analyze the previous research to identify the trends and similarities in the literature on RE site selection and offer guidance for future researchers in this area. Figure 1 presents the projected use of RE for energy generation in 2050. Within the total RE supply, 58% is expected to be allocated to electricity generation, 13% to transportation, and the remainder to heating and direct applications [9].

The global electricity grid (GEG) refers to a transcontinental network of interconnected power systems that enable the seamless exchange and distribution of electricity across countries and regions worldwide [10]. Unlike existing national or regional electricity grids, which are primarily confined within specific geographic boundaries, a global electricity grid aims to integrate renewable energy resources from different parts of the world, leveraging time zone differences and geographic diversity to optimize energy availability and efficiency. By enabling long-distance transmission of electricity through advanced technologies such as ultra-high voltage (UHV) transmission lines and smart grids, a global grid seeks to address critical challenges like energy access inequality, resource optimization, and climate change mitigation. This concept envisions a sustainable energy future where clean energy generated in resource-abundant regions can be transmitted to areas with high demand, creating a unified, resilient, and efficient global energy system.

The GEG is mainly powered by collecting RE from remote areas, with long-distance transmission lines (TLs) serving as its essential infrastructure component. Currently, HVDC cables are the only feasible solution for long-distance submarine transmission. HVAC cables are constrained to a maximum of 60 km without reactive compensation, and gas-insulated lines (GILs) are restricted to distances below 100 km due to technological limitations [11]. In addition, the long-distance HVDC lines experience lower thermal losses compared to HVAC lines. Furthermore, the non-synchronous areas can be interconnected while minimizing the risk of regional power failures spreading [10]. As advancements in HVDC technology continue, it is expected to play a critical role in the development of the GEG, facilitating the transition to a cleaner, more resilient energy system. Therefore, additional study is essential for developed HVDC technology and HVDC transmission lines to efficiently capture energy from remote locations. Therefore, the second objective of this study is to analyze the previous research to identify the trends and similarities in the literature on HVDC technology and TLs developed and offer guidance for future researchers in this area.

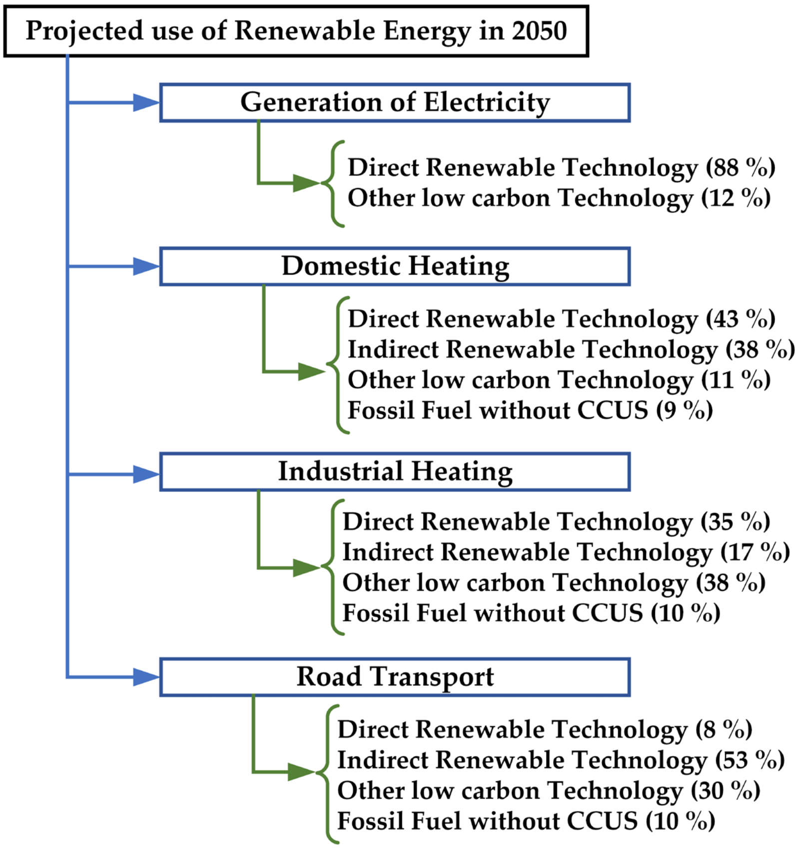

Figure 1. The projected use of renewable energy in 2050.

The increased prominence of renewable energy sources (RESs), especially in the last two decades, may be attributed to their contribution in mitigating climate change, minimizing the impact on the environment, promoting economic opportunities, and supplying power to remote and underserved areas [12]. Due to the intermittent nature of RESs, relying on a single source cannot guarantee a stable energy supply, making it crucial to integrate multiple RESs with thermal generating units to ensure consistent power generation. Moreover, the economic feasibility of RE varies by region, as factors such as local resources, infrastructure, and investment costs influence its viability [13]. This emphasizes the need for adaptable, region-specific energy strategies to maximize the effectiveness of RE adoption globally. Therefore, this article envisions a future where the global energy network evolves into a GEG, interconnecting power plants across the world with abundant renewable resources. However, energy trading also plays a crucial role in the GEG as it helps balance supply and demand, allowing regions to share excess power and address shortages [14]. It promotes cost efficiency by enabling areas with lower production costs to supply energy to those with higher costs. Additionally, trading enhances the integration of RESs, supporting sustainability and reducing reliance on fossil fuels.

Ultimately, it stimulates economic growth and investment in clean energy infrastructure, fostering a more resilient and efficient energy system. Therefore, the third objective of this study is to analyze existing research to identify trends and commonalities in the literature on global energy trading, providing valuable insights and guidance for future researchers in this field.

The idea of an interconnected grid originated in the early 20th century with RESs as the backbone. However, it was considered impractical at the time due to power transmission being limited to around 600 km [15]. Over the past few decades, there have been notable advancements in HVDC technology, resulting in more power capacity, improved efficiency, and enhanced grid protection mechanisms. The enhancements have rendered a GEG a viable option for establishing the intercontinental grid, which could significantly enhance global economic growth. The Secretary-General of the United Nations has acknowledged that the potential advantages of a worldwide grid are in line with the United Nations' 2030 Agenda for Sustainable Development and its objectives regarding climate change [16]. Although there are compelling arguments supporting the GEG concept, its application has been restricted so far. The current transcontinental connections are still limited to some regions of Eastern Europe and Central Asia [17]. However, S. Chatzivasileiadis et al. proposed a concept of a GEG in 2013 and discussed its potential benefits and feasibility [10]. This paper presents a comprehensive planning of the development of the GEG. Since then, several grid interconnections have been developed, numerous plans are currently underway, and research in this area has significantly increased.

This study provides an in-depth analysis, inspection, and comparison of advancements in the GEG, exploring their potential as a means to achieve decarbonization in future power systems. To date, no such overarching review exists in the scientific literature, making this work a pivotal resource for understanding the role of a GEG in the energy transition. By addressing critical gaps in research, this study highlights the transformative potential of interconnected power networks and provides a roadmap for future innovations that could reshape global energy systems toward a more sustainable and resilient future.

The article is structured as follows: Section 2 presents a detailed review of the GEG and summarizes its key aspects. Section 3 offers an overview of key initiatives and compares various projects and development trends aimed at promoting and advancing the GEG. Section 4 evaluates the arguments presented in the literature in support of these developments, along with the associated advantages and disadvantages. The review concludes in Section 5 with a discussion of the overall research findings and potential areas for future research.

2. Literature Review

Global energy demand is rapidly increasing due to industrialization, population growth, and advancements in both developing and developed nations. Over the past 23 years, from 2000 to 2023, global electrical energy consumption rose from 15,276.96 TWh to 29,479.05 TWh [18,19]. In 2018 alone, this growth reached 2.9%. Figure 2 illustrates global energy consumption trends over the last 23 years. However, energy is essential for social growth and economic prosperity in contemporary civilization, and satisfying the continually rising global energy demand poses a major problem. Figure 3 and Figure 4 illustrate global energy generation, categorized by fuel types, from 1985 to 2023, emphasizing the persistent dependence on fossil fuels despite the increasing need for sustainable alternatives. In 1985, fossil fuels generated 64% of the world's electricity, nuclear energy contributed 15%, and RE accounted for 21% of total demand. By 2015, as climate change concerns intensified and the Paris Agreement was enacted, fossil fuel reliance rose to 66%, while nuclear energy declined to 11% and RE increased slightly to 23% [18–20]. In response, many countries implemented robust climate policies to shift toward RE [21], with the goal of limiting global temperature rise to below 1.5 °C from a projected 2.1 °C by achieving 80% RE generation by 2050. By 2023, these efforts had led to fossil fuels generating 61% of electricity, nuclear energy 9%, and renewables increasing to 30% of total demand [19,20].

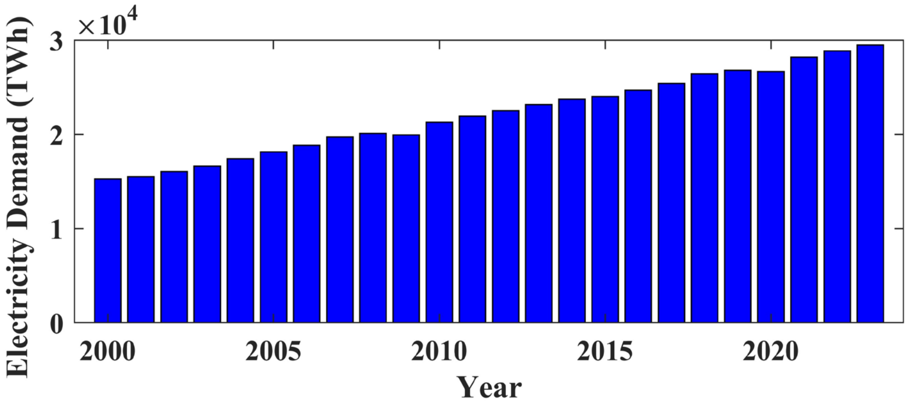

Figure 2. Global energy consumption trends from 2000 to 2023.

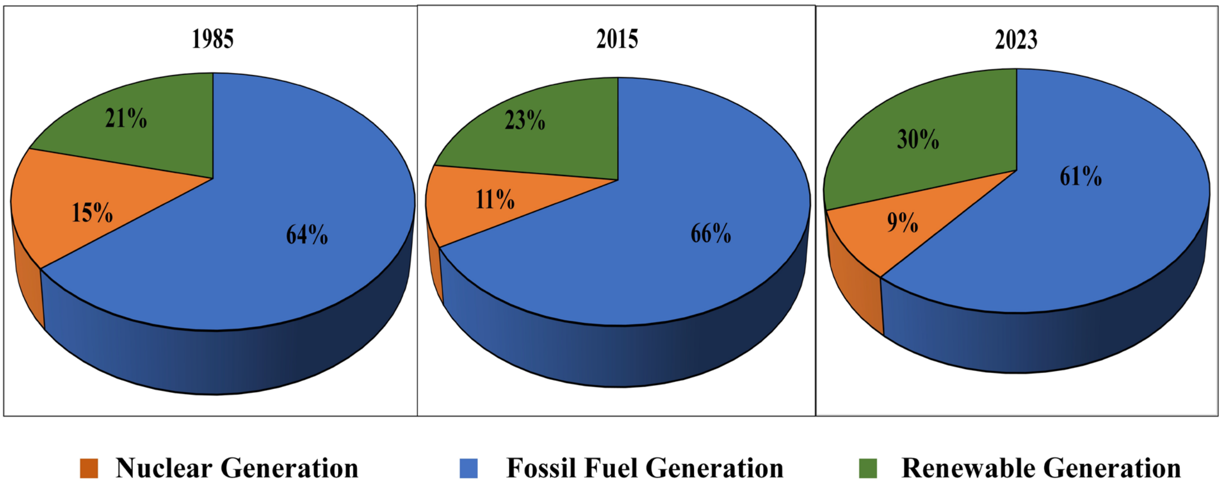

Figure 3. Global energy generation categorized by fuel type in 1985, 2015, and 2023.

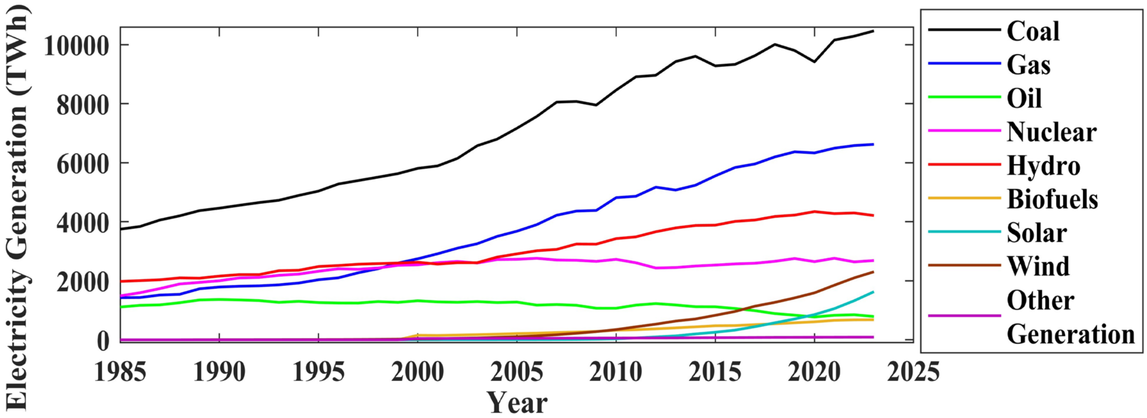

Figure 4. Global energy generation categorized by fuel type from 1985 to 2023.

Previously, hydro power plants (HPPs) were the most widely used form of RE, and they continue to be popular today. In 1985, energy generation from HPPs was 1979.24 TWh, which increased to 4211.01 TWh by 2023 [18]. However, over the past decade, solar PV and wind energy have experienced remarkable annual growth due to rapid technological advancements, significant cost reductions, and supportive government policies. Figure 5 illustrates the total installation costs of solar PV systems, onshore wind systems, and offshore wind systems for generating power per kW, measured in U.S. dollars for 2022. In 2010, the cost of generating 1 kW of power was USD 5124 for solar PV, USD 5217 for offshore wind, and USD 2186 for onshore wind [18,19]. By 2022, these costs significantly decreased to USD 876 for solar PV, USD 3461 for offshore wind, and USD 1274 for onshore wind, reflecting the impact of technological advancements, economies of scale, and increased market competition in driving down RE costs [19]. In 2000, the total installed capacity was 654.65 GW for hydropower, 796.7 MW for solar PV, 66.95 MW for offshore wind, and 16.89 GW for onshore wind. By 2023, this capacity had grown substantially to 1206.47 GW for hydropower, 1411.14 GW for solar PV, 73.18 GW for offshore wind, and 944.2 GW for onshore wind [18,20]. This growth highlights the significant global shift toward RE, with solar PV and wind experiencing particularly rapid expansion. Table 1 presents the global theoretical potential of hydropower, solar PV, and wind energy [18].

Table 1. The global theoretical potential of hydropower, solar PV, and wind energy.

	Hydropower		Solar		Wind	
Renewable Energy	**Total Installed Capacity (MW)**	**Global Share**	**Total Installed Capacity (MW)**	**Global Share**	**Total Installed Capacity (MW)**	**Global Share**
Asia	591,620.137	47.02%	62,5534.065	42.81%	439,687.044	48.70%
Africa	36,079.022	2.87%	12,646.002	0.87%	7744.853	0.86%
Europe	248,526.214	19.75%	625,534.065	42.81%	242,338.358	26.84%
Americas	368,005.195	29.25%	167,799.418	11.48%	200,078.499	22.16%
Oceania	13,939.462	1.11%	29,565.818	2.02%	13,034.611	1.44%
World	1,258,170.03	100%	146,1079.368	100%	902,883.365	100%

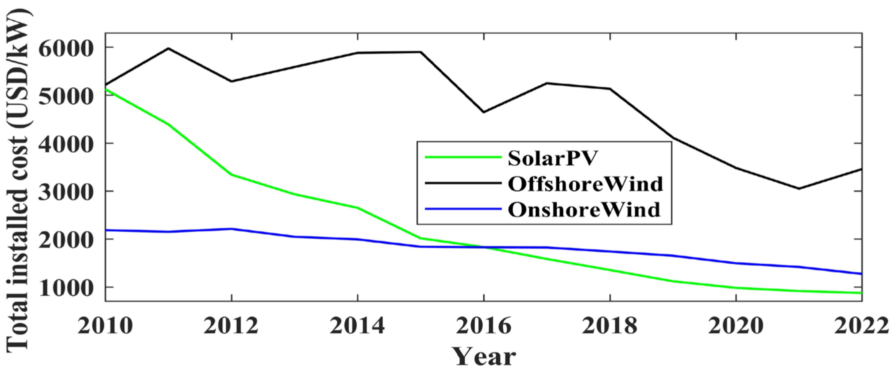

Figure 5. The total installation costs of solar PV systems and wind systems.

2.1. Global Grid

The intermittent nature of solar PV and wind energy presents a significant challenge to maintaining stability within the electricity grid. Vehicle-to-Grid (V2G) technology offers a promising and innovative solution to mitigate this issue [22]. By enabling electric vehicles (EVs) to both draw energy from and supply energy back to the grid, V2G systems can provide a dynamic and decentralized form of energy storage. This bidirectional flow not only helps stabilize the grid during fluctuations but also optimizes the use of renewable energy, reduces reliance on fossil fuel-based backup systems, and enhances overall grid resilience. This variability in generation impacts grid reliability and necessitates robust balancing measures, such as energy storage systems, demand response strategies, and enhanced grid interconnections, to ensure a consistent and reliable power supply [23,24]. Additionally, these measures are essential for maintaining stable inertia levels, which are crucial for grid stability and resilience in response to rapid changes in generation and demand [25]. Despite the challenges, various studies propose 100% RE scenarios, highlighting the potential of renewable sources for decarbonizing the power system, though practical implementation and reliability remain concerns; a diverse, flexible, low-carbon generation mix is essential for achieving emission targets while ensuring grid stability [26,27].

In 2009, H. Lund presented his first proposal for achieving 100% RE production in Denmark, setting initial targets for the years 2030 and 2050 [28]. In the study, it was proposed that by 2030, 50% of RE generation would be achieved through a combination of biomass, solar PV, wind energy, and wave energy, with the aim of increasing this to 100% by 2050. Inspired by this proposal, Ireland took significant steps toward achieving 100% RE integration into its national grid, which accounted for only 3% of the energy mix in 2007 [29]. At that time, Ireland generated just 6% of its energy demand from fossil fuels, while the remaining energy requirements were met through imports. However, RE is intermittent in nature, requiring reliable energy storage solutions to ensure a stable energy supply. As a result, numerous studies have also been conducted to explore the feasibility of achieving 100% RE integration with the support of energy storage systems [30].

In a further study, it has been observed that the use of batteries may not be the most cost-effective option, and the efficiency of existing energy storage technologies remains relatively low. In response to these challenges, S. Chatzivasileiadis et al. proposed the concept of a global power grid, interconnecting the grids of multiple nations, allowing them to leverage time zone differences for more efficient energy distribution [10]. The global grid would eliminate the need for extensive energy storage by enabling global energy trading, allowing countries to share excess RE and balance supply and demand more efficiently. Since then, numerous studies have been conducted to advance and implement the proposal successfully.

To address the global perspective on the challenges and opportunities of a global electricity grid, this paper incorporates case studies from underrepresented regions to provide a more balanced analysis. For instance, the Southern African Power Pool in Sub-Saharan Africa highlights the challenges of infrastructure gaps and funding shortages in regional integration. In South Asia, India's energy trade with Nepal, Bhutan, and Bangladesh illustrates the role of cross-border electricity sharing in managing renewable energy fluctuations. Additionally, the Andean Electrical Interconnection System in Latin America showcases the potential for renewable resource sharing across borders, despite geopolitical complexities. These examples enrich the discussion by presenting diverse regional approaches to addressing the technical, regulatory, and geopolitical barriers in global energy integration.

G. Plebmann et al. evaluated a global, decentralized scenario for achieving a 100% RE supply, identifying optimal combinations of solar PV, concentrated solar power (CSP), wind energy, and electricity storage across roughly 15,400 regions in 163 countries [31]. This approach underscores the potential for tailored regional energy solutions that leverage diverse renewable resources and storage options to enhance energy resilience and sustainability globally. C. Wu et al. assessed the economic benefits of a GEG powered by 100% RE using HVDC transmission technology [32]. Their study modeled 14 regions with 20 potential interconnection routes, aiming to evaluate cost efficiencies and grid stability enhancements achievable through global interconnections. In 2015, the Paris Agreement provided a significant boost to this study, further emphasizing the global commitment to RE integration and climate action [3]. S. K. Chaharsooghi et al. developed four scenarios—Green Path, Standardization, Fossil Energy, and Non-Targeted Subsidy—to enhance RE generation, aiming for a 10% increase by 2025 [33]. Similarly, Libya and Tunisia have set a goal of generating 30% of their energy from renewable sources by 2030 [34,35]. Numerous studies have also been conducted by the European Union (EU) to increase the capacity of RE and interconnect neighboring countries, including France, Germany, Jordan, Sweden, and Denmark. These efforts are aimed at achieving 100% RE integration by 2050.

In 2020, A. Aghahosseini et al. conducted a feasibility study on achieving 100% RE generation in Middle Eastern and North African countries by 2030 [36]. The sectors considered in the analysis include power generation, non-energetic industrial gases, and seawater desalination. The UK, USA, and Japan are also rapidly expanding their RE installation capacities to meet the targets outlined in the Paris Agreement. C. F. Heuberger et al. discussed the real-world challenges of achieving 100% RE generation and proposed potential solutions to address these obstacles [37]. Meanwhile, W. J. Cole et al. discussed the real-world challenges for the USA [38]. Recently, numerous studies have been conducted on the feasibility, techno-economic challenges, and benefits of the GEG. With strong initiatives like the International Solar Alliance (ISA) and the One Sun One World One Grid (OSOWOG), India is actively promoting solar energy deployment and advancing transnational grid connectivity to enable efficient electricity sharing across time zones [39,40]. Similarly, China's Belt and Road Initiative (BRI), launched in 2013, complements this vision by supporting the development of the GEG [41]. Table 2 provides a comprehensive overview of the advancements and proposals made by various countries to date in support of the GEG concept. This summary emphasizes the growth in RE generation as a key approach through which countries have started to support the concept a GEG. These initiatives reflect a growing recognition of the need for international collaboration to harness renewable resources effectively, reduce reliance on fossil fuels, and transition towards a more sustainable and interconnected global energy system.

Table 2. Comprehensive overview of the advancements in global grid.

Authors	Year	Initiative Taken by Country	Percentage of RE	Target Year
H. Lund et al. [28]	2009	Denmark	100%	2050
D. Connolly et al. [29]	2011	Ireland	100%	-
B.V. Mathiesen et al. [42]	2011	Denmark	100%	2050
B. Elliston et al. [43]	2012	Australia	100%	-
B. Cosic et al. [44]	2012	Macedonia	100%	2050
M. Esteban et al. [30]	2012	Japan	100%	-
C. Bussar et al. [45]	2014	Europe	100%	2050
G. Plebmann et al. [31]	2014	Global	100%	2050
A. Charles [46]	2014	Nigeria	100%	-
D. Connolly et al. [47]	2014	Global	100%	2050
S.K. Chaharsooghi et al. [33]	2015	Iran	10%	2025
B. Brand [35]	2016	Algeria	27%	2030
A.M.A. Mohamed et al. [34]	2016	Libya	30%	2030
B. Brand [35]	2016	Tunisia	30%	2030
D. Bogdanov et al. [48]	2016	North-East Asia	100%	-
V. Krakowski et al. [49]	2016	France	100%	2050
A. Kilickaplan et al. [50]	2017	Turkey	100%	2050
H.C. Gils et al. [51]	2017	Canary Islands	100%	2050
T.S. Uyar et al. [52]	2017	Global	100%	-

A. Blakers et al. [53]	2017	Australia	100%	-
A. Khoodaruth et al. [54]	2017	Mauritius	100%	2050
U.B. Akuru et al. [55]	2017	Nigeria	100%	2050
A. Gulagi et al. [56]	2017	India	100%	2050
S. Chatzivasileiadis et al. [57]	2017	Global	80%	2050
H.C. Gils et al. [58]	2017	Brazil	100%	2050
A. Gulagi et al. [59]	2017	India and SAARC Countries	100%	2030
L.S.N.S. Barbosa et al. [60]	2017	South and Central America	100%	2030
M. Child et al. [61]	2017	Finland	100%	2050
U. Caldera et al. [62]	2018	Saudi Arabia	100%	2040
IRENA [63]	2018	Egypt	42%	2035
A. García-Olivares et al. [64]	2018	Global	100%	-
M. Esteban et al. [65]	2018	Japan	100%	-
A. Sadiqa et al. [66]	2018	Pakistan	100%	2050
S. Zapata et al. [67]	2018	Colombia	100%	2040
M. Child et al. [68]	2018	Europe	100%	2050
REN21 [69]	2018	Iraq	10%	2030
REN21 [69]	2018	Morocco	53%	2030
C.F. Heuberger et al. [37]	2018	United Kingdom	100%	2050
A.S. Oyewo et al. [70]	2019	South Africa	100%	2050
W. Zappa et al. [71]	2019	Europe	100%	2050
T. Luz et al. [72]	2019	Brazil	100%	2050
M. Child et al. [73]	2019	Europe	100%	2050
K. Hansen et al. [74]	2019	Germany	100%	2050
P. Moriarty et al. [75]	2019	Global	100%	2050
A. Blakers et al. [76]	2019	Global	100%	-
A. Aghahosseini et al. [36]	2020	Middle East and North Africa	100%	2030
M. Alves et al. [77]	2020	Islands	100%	-
A. Aghahosseini et al. [36]	2020	Israel	17%	2030
S. Kiwan et al. [78]	2020	Jordan	100%	2050
D. Bogdanov et al. [79]	2021	Global	100%	2050
L. Al-Ghussain [80]	2021	Jordan	100%	2050
J. Zhong et al. [81]	2021	Sweden	100%	2040
N. Reyseliani et al. [82]	2021	Indonesia	100%	2050
A. Gulagi et al. [83]	2021	Philippines	100%	2050
P. Denholm et al. [84]	2021	United States	100%	-
W.J. Cole et al. [38]	2021	United States	100%	-
C. Cheng et al. [85]	2022	Japan	50–60%	2050
I. AL-wesabi et al. [86]	2022	Yemen	15%	2025
IEA50 [87]	2023	Oman	10%	2025
H. Yang et al. [88]	2023	Global	100%	2050
Q. Hassan et al. [89]	2024	Global	100%	2050
J. Huber et al. [90]	2024	Global	100%	2050

From Table 2, it can be observed that several countries have begun taking their initial steps toward developing a GEG by significantly increasing their RE installation capacity, aiming for an ideal target of 100%. This trend can be traced back to 2009, when Denmark made a landmark decision to increase its RE installation capacity to 100% [28]. Following Denmark's lead, several EU countries adopted similar strategies, setting ambitious targets to increase their RE capacity to 80–100% by the year 2050. These efforts mark a significant shift toward sustainable energy integration and global collaboration in achieving carbon neutrality. In addition, the concept of a GEG, which was introduced in 2013 [10], and the Paris Agreement on Climate Change, adopted in 2015 [4], have significantly accelerated efforts toward global energy interconnection. The GEG aims to promote the seamless integration of RE across continents, while the Paris Agreement has set ambitious climate targets, urging nations to transition toward sustainable and RE solutions. Together, these initiatives have provided both a framework and momentum for advancing the development of a unified global energy network. Several steps have been taken so far to support the development of global grid interconnections. However, many countries are still in the early stages of expanding their RE capacity.

Most nations primarily focus on wind energy and solar PV systems to meet their load demands. While these sources are crucial, T.S. Uyar et al. highlight the potential advantages of integrating hydrogen energy into the energy mix, offering a promising pathway toward achieving a truly interconnected GEG [52]. Hydrogen energy can serve as a flexible and sustainable storage and transportation medium, addressing intermittency issues and complementing RESs in the transition to a global energy network. In the South Asian region and European region, numerous countries are already interconnected through regional power grids, and efforts are accelerating to achieve full interconnection with a 100% RE target by 2050. Since 2015, significant progress has been made in developing the concept of a GEG. This includes conducting techno-economic analyses, optimizing RE mixes and exploring cross-border energy trading (CBET) opportunities. Various strategies and frameworks have been developed, particularly focusing on advancing RE adoption and ensuring sustainable and efficient energy sharing across borders.

2.2. Renewable Energy Site Selection

When formulating future global energy policy, accurately forecasting the energy mix, technology costs, and potential generation site selection is crucial [91]. This forecast must account for fluctuating demand levels and the growing supply of RE, both of which can vary significantly across different regions and time periods [92]. Furthermore, the analysis of energy policies, the identification of the most suitable RESs, the evaluation of different RE options, the determination of optimal locations, and the choice of the best alternatives simultaneously increase the complexity of the process. This complex approach is essential for ensuring the effective integration of RE into the overall energy system [93,94]. Multi-attribute decision-making (MADM) techniques are being employed to solve these types of problems [95]. O. Erol et al. developed sustainable and resilient energy policies in Turkey by evaluating various RESs and non-RESs using the Analytic Hierarchy Process (AHP) [96]. H.I. Cobuloglu et al. identify the most sustainable biomass crop type for biofuel production by employing a stochastic AHP [97]. This proposed approach effectively addresses uncertain information and assigns weights to factors classified as economic, environmental, and social. M. Berger et al. used a critical time window framework to determine the suitable locations to install wind turbines in South Greenland and France [98]. In 2022, D. Radu used a complementarity-based siting scheme as well as a production-based siting scheme to determine the suitable locations to install offshore wind turbines in Europe [99].

In the site selection process, RESs prioritize different objectives depending on the type of energy being harnessed. Generally, two major criteria determine the suitability of sites for RE development: exclusion criteria and evaluation criteria [8]. The exclusion criteria are used to identify and eliminate sites that are unsuitable for the installation of RE technology. These might include areas with legal restrictions, incompatible land use, or geographical limitations. On the other hand, evaluation criteria are applied to assess and rank the remaining eligible sites that pass the exclusion stage. These criteria are typically categorized into four key aspects, such as technical, economic, environmental, and social aspects [100]. Technical criteria assess factors like resource availability and infrastructure feasibility, while economic criteria consider cost-effectiveness and financial viability. Environmental criteria evaluate the impact on ecosystems and biodiversity, and social criteria take into account community acceptance, land acquisition issues, and social benefits or challenges. A well-balanced combination of these criteria ensures that the selected sites are not only technically and economically viable but also environmentally sustainable and socially acceptable.

Once the criteria for RE site selection are determined, the necessary data for these criteria are collected [101]. These data may have numerical value or subjective opinions that make the decision-making process complex. Additionally, due to variations in direction and dimension, these criteria are often not directly comparable. Therefore, it is essential to normalize both quantitative and qualitative criteria into directionless and dimensionless values, making them operable for further processing. This process is known as criteria value normalization [102].

The normalization of quantitative criteria values can be approached using two fundamental methods [103]. The first method involves a two-step process, first addressing the directionlessness and then addressing the dimensionlessness. The second method streamlines the process by achieving both directionlessness and dimensionlessness in a single step, providing a more integrated approach to normalization. The criteria may be categorized into benefit criteria and cost criteria [8]. Benefit criteria such as wind speed and solar radiation, etc., positively influence site selection, and cost criteria such as land costs and operation and maintenance costs, etc., negatively impact site selection. This means that, in the benefit criteria, higher values are more desirable, while in the cost criteria, lower values are more desirable. To streamline decision-making and ensure a consistent evaluation process, cost criteria can be mathematically transformed into benefit criteria through specific treatments, allowing the criteria system to achieve directionlessness. Furthermore, the differences in dimensions across numerous criteria make them incomparable, thereby affecting accuracy of the overall evaluation [104]. Therefore, it is essential for the criteria to be dimensionless. Methods of dimensionless transformation remove the impact of the dimensions of the original criteria by mathematical conversion, ensuring a more consistent and comparable evaluation. Some common and representative methods for achieving dimensionlessness in data processing include standardization, extremum processing, linear scaling, vector normalization, and the majorant operator.

Qualitative criteria are used less frequently due to the inherent challenges in measurement and comparison [105]. One commonly used method to address this challenge is expert scoring, which is a simple normalization technique for qualitative criteria. In this approach, experts assign evaluation values to the criteria based on their experience and objective data, effectively transforming qualitative factors into quantitative scores. This process achieves the quantification, standardization, and dimensionlessness of qualitative criteria in a single step, making them comparable and usable in decision-making frameworks.

Simple linear transformation methods have traditionally been used to normalize quantitative criteria in GIS and non-GIS environments [106]. While these methods can function independently, they are often incorporated into more complex decision-making frameworks to improve accuracy and reliability. For large-scale site selection with GIS, the fuzzy membership functions and reclassification are widely utilized techniques. On the other hand, for small-scale site selection without GIS, linguistic variables, expert scoring, and fuzzy theory are the most widely used techniques. The selection of an appropriate normalization method primarily depends on the application of GIS, fuzzy theory, and the nature of the criteria involved [102]. Therefore, before deciding on a normalization method, it is essential to carefully consider the scale of the site selection process and the specific characteristics of the criteria. Additionally, a thorough comparison of the strengths and weaknesses of the available normalization methods is crucial to ensure the chosen approach aligns with the objectives and requirements of the study.

Each criterion has its own internal impact on the decision-making process, making it essential to determine the degree of influence each criterion exerts on the results [107]. To reflect their relative importance, weights are assigned to the criteria. These weights must be rational and accurate to ensure a reliable decision-making outcome. Three key factors are typically considered when determining such weights: the degree of variance of the criteria, the level of independence between the criteria, and the subjective preferences of decision-makers [104]. Accurately balancing these factors is critical for achieving robust and effective decision-making. Determining the weight coefficient of each criterion is a critical and challenging aspect of MADM methods. These weights play a pivotal role in influencing the final decision outcomes. Generally, there are two primary approaches for assigning weights: equal weighting, where all criteria are treated as equally important, and rank-order weighting, which prioritizes criteria based on their relative importance [8]. In general, rank-order weighting can be divided into six categories. Figure 6 illustrates the classification of the most commonly used rank-order weighting methods.

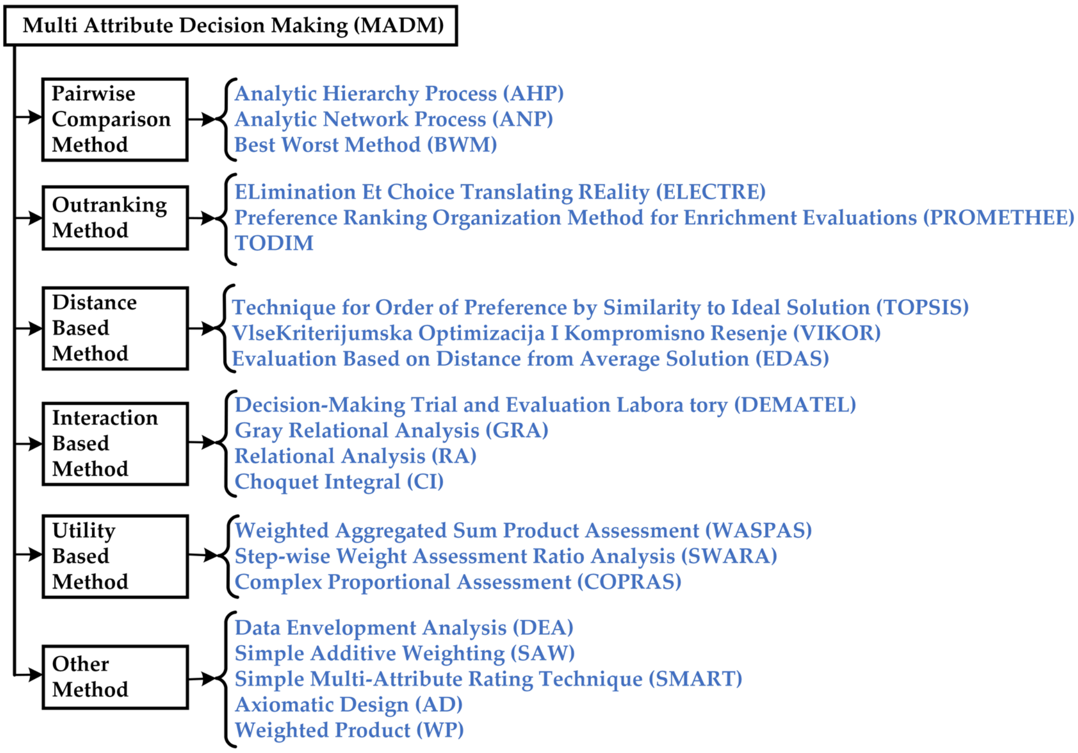

Figure 6. .The Classification of MADM methods.

The classification of MADM methods is based on their underlying principles, mathematical frameworks, and approaches to solving complex decision-making problems. Pairwise Comparison Methods (e.g., AHP, ANP) simplify decision-making by comparing criteria or alternatives in pairs, making them effective for strategic planning and subjective judgments. Outranking Methods (e.g., ELECTRE, PROMETHEE) focus on dominance relationships without aggregating scores, suitable for handling imprecise or conflicting data in areas like environmental management. Distance-Based Methods (e.g., TOPSIS, VIKOR) evaluate alternatives based on their proximity to ideal solutions, often applied in engineering and performance benchmarking. Interaction-Based Methods (e.g., DEMATEL, GRA) emphasize the interdependencies and causal relationships between criteria, making them valuable in systems analysis and network design. Utility-Based Methods (e.g., WASPAS, COPRAS) aggregate criteria into utility scores, optimizing decisions in fields like finance and resource allocation. Lastly, Other Methods (e.g., DEA, SAW) include diverse approaches tailored to specific contexts, offering flexibility in operational research and cost-benefit analysis. This classification ensures decision-makers can choose methods suited to their problem's complexity, data availability, and decision context, addressing diverse challenges across various domains.

Previously, E. Ilbahar et al. conducted a detailed review of RE site selection up to the year 2018 [95]. Building on their work, this study provides a comprehensive review of developments from 2019 to 2024, offering updated insights and advancements in the field. By focusing on recent studies, this paper highlights the evolving methodologies and trends in RE site selection, further supporting informed decision-making for sustainable energy development. Table 3 provides an overview of the methods used in these studies, offering a clear comparison of the various approaches applied in RE site selection for this period.

Table 3. Comprehensive overview of the advancements in renewable energy site selection.

Authors	Year	Proposed for	Method Used	RE
M. Argin et al. [100]	2019	Turkey	WA	Offshore wind
D. Messaoudi et al. [108]	2019	Algeria	GIS and AHP	Solar Hydrogen production
S. Ali et al. [101]	2019	Thailand	GIS and AHP	Wind and Solar
C. Emeksiz et al. [109]	2019	Turkey	Novelty Hybrid Site Selection Method (NHSSM)	Offshore wind
I. Konstantinos et al. [110]	2019	Greece	GIS and AHP and TOPSIS	Wind
D. Schitea et al. [111]	2019	Romania	WASPAS, COPRAS and EDAS	Hydrogen mobility roll-up
O. Nematollahi et al. [112]	2019	Iran	GIS	Solar/wind and Hydrogen production
O.N. Mensour et al. [113]	2019	Morocco	AHP	Solar PV
J. Zhang et al. [114]	2019	China	Extended PROMETHEE combined with ORA and Fuzzy	Ocean thermal energy
J.R.S. Doorga et al. [115]	2019	Mauritius	GIS and AHP	Solar PV
M.K. Firozjaei et al. [107]	2019	Iran	GIS and Ordered Weighted Averaging (OWA)	Solar PV
Y. Wu et al. [116]	2019	China	λ-fuzzy measure AHP	Pumped hydro storage station
M. Giamalaki et al. [117]	2019	Mediterranean	GIS and AHP	Solar PV
S.N. Shorabeh et al. [118]	2019	Iran	GIS and OWA	Solar PV
U. Nzotcha et al. [103]	2019	Cameroon	AHP and ELECTRE	Pumped hydro-energy storage
D. Messaoudi et al. [119]	2019	Algeria	GIS and AHP	Wind-powered hydrogen refuelling
G. Pambudi et al. [120]	2019	Indonesia	Hierarchical fuzzy data envelopment analysis	Wind
D. Majumdar et al. [121]	2019	USA	GIS and Multi-Criteria Analysis	Solar PV
Y.A. Solangi et al. [122]	2019	Pakistan	AHP and Fuzzy VIKOR	Solar PV
M. Giamalaki et al. [117]	2019	Greece	GIS and AHP	Solar PV and CSP
V. Sammartano et al. [123]	2019	England	GIS	Hydropower
Y. Khchine et al. [124]	2019	Morocco	Weibull analysis	Wind

C. Wang et al. [125]	2019	Vietnam	Fuzzy AHP and TOPSIS	Biomass
G. Sasikumar et al. [126]	2019	Generalized	Fuzzy AHP and TOPSIS	Solar PV
Moradi et al. [127]	2020	Iran	GIS and AHP	Wind
J.R. O'Hanleya et al. [128]	2020	Brazil	ArcGIS and GRASS	Hydropower
S.H.A. Shah et al. [129]	2020	Pakistan	Fuzzy AHP data envelopment analysis (DEA)	RE
S. Seker et al. [130]	2020	Turkey	TOPSIS	Hydrogen
A. Guleria et al. [131]	2020	Global	(R, S)-Norm Pythagorean Fuzzy information measures and on VIKOR and TOPSIS	Hydrogen power
H.S. Dhiman et al. [132]	2020	USA	Fuzzy TOPSIS and fuzzy COPRAS	Wind
Y. Xu et al. [133]	2020	China	GIS and interval AHP	Wind
S. Rahimi et al. [134]	2020	Iran	GIS and Fuzzy group BWM-MULTIMOORA	Municipal solid waste
H.E. Colak et al. [135]	2020	Turkey	GIS and AHP	Solar PV
Y. Wu et al. [136]	2020	China	PROMETHEE and Fuzzy	Offshore wind
Y. Wang et al. [137]	2020	Pakistan	Strengths, Weaknesses, Opportunities, and Threats (SWOT) Fuzzy AHP	Solar PV and Wind
S. Ahmadi et al. [138]	2020	Iran	Hybrid fuzzy and AHP and VIKOR	Wind-powered pumped storage power plant
A. Khamis et al. [139]	2020	Malaysia	K-means Technique	Solar, Wind and Hydro
S. Sreenath et al. [140]	2020	Malaysia	ForgeSolar software	Solar PV
H.S. Ruiz et al. [141]	2020	Tropical countries	GIS and AHP	Solar PV
C. Kocabaldir et al. [142]	2020	Turkey	GIS and AHP	Solar PV
M. Li et al. [143]	2020	China	GIS and Fuzzy	Wind
F. Chien et al. [105]	2020	Vietnam	Fuzzy, ANC, and TOPSIS	Hydropower
J. Feng [144]	2020	China	Fuzzy axiomatic design approach	Wind
H. Peng et al. [145]	2020	China	BWM, DETMATEL, and TOPSIS	Nuclear
E. Tercan et al. [146]	2020	Turkey	GIS MCDM	Wind
M.K. Anser et al. [147]	2020	Turkey	SWOT-based AHP–F-TOPSIS	Solar PV
S.C. Rana et al. [148]	2020	India	AHP, WPM, and TOPSIS	Hydropower
A.G. Abdullah et al. [149]	2021	Indonesia	AHP, WPM, and TOPSIS	Wind
J. Gao et al. [150]	2021	China	Probabilistic linguistic term set (PLTS)	Compressed air Energy Storage
F. Guo et al. [151]	2021	China	Extended fuzzy PROMETHEE	Floating Solar PV
D. Kannan et al. [152]	2021	Iran	GRA, VIKOR	Solar PV
E. Ilbahar et al. [153]	2021	Turkey	Fuzzy linear programming	Waste-to-energy
S.K. Saraswat et al. [154]	2021	India	GIS and AHP	Wind and Solar
B. Karatop et al. [155]	2021	Turkey	Fuzzy AHP-EDAS-Fuzzy FMEA	RE
G.N. Yucenur et al. [156]	2021	Turkey	SWARA/WASPAS	Marine current energy
M. Deveci et al. [157]	2021	Turkey	BWM and MARCOS	Offshore wind
H. Lo et al. [158]	2021	Taiwan	Hybrid of Gray decision-making trial-and-evaluation laboratory-and ANP and Probability and GRA	Offshore wind
F. Ouchani et al. [159]	2021	Morocco	GIS	Solar PV
M. Deveci et al. [160]	2021	Global	Fuzzy logarithmic additive estimation of weight coefficients	Solar PV
O. Lindberg et al. [161]	2021	Sweden	GIS	Solar PV

O. Soydan et al. [162]	2021	Turkey	GIS and AHP	Solar PV
H. Eroglu [104]	2021	Turkey	GIS and Fuzzy AHP	Wind
R.S. Shahdabadi et al. [163]	2021	Iran	SAW, TOPSIS, and ELECTRE	Biomass
S. Tekin et al. [164]	2021	Turkey	MaxEnt model	Solar PV
M.A. Basset et al. [165]	2021	Egypt	AHP and PROMETHEE II	Offshore Wind
H. Yousefi et al. [166]	2022	Iran	GIS and AHP	Wind
C. Emeksiz et al. [167]	2022	Turkey	Novelty hybrid MCDM approach (NHMCDMA)	Bioenergy
E. Caceoglu et al. [168]	2022	Turkey	GIS and AHP	Offshore wind
Y. Noorollahi et al. [102]	2022	Iran	GIS and Fuzzy and AHP	Solar PV
J.M.S. Lozano et al. [169]	2022	USA	TOPSIS and VIKOR	Offshore wind
V.T. Nguyen et al. [170]	2022	Vietnam	Fuzzy AHP and WASPAS	Wind
B. Josimovic et al. [171]	2023	Kosovo	GIS and PROMETHEE	Wind
S. Yum et al. [172]	2023	South Korea	GIS-MCDA and big data	Solar based smart hydrogen energy
P. Jamodkar et al. [173]	2023	India	GIS and AHP	Solar PV
J. Ngethe et al. [174]	2023	Kenya	GIS and hybrid AHP–WASPAS	Geothermal
M. Uyan et al. [175]	2023	Turkey	GIS and BWM	Biogas
A. Sekeroglu et al. [176]	2023	Turkey	GIS and Fuzzy logic	Wind, solar, and biomass
G. N. Yucenur et al. [177]	2024	Turkey	ENTROPY and ARAS	Geothermal
K. Ransikarbum et al. [178]	2024	Thailand	Fuzzy AHP	Biofuel
G. Demir et al. [179]	2024	Turkey	GIS and Fuzzy SWARA	Wind
J. Gao et al. [180]	2024	China	GIS and Fuzzy BWM	Biomass
K.E. Okedu et al. [181]	2024	Nigeria	GIS and Fuzzy	Biomass
K. Koca et al. [182]	2024	Turkey	GIS and AHP	Geothermal

Table 3 illustrates that GIS and Weighted Linear Combination (WLC), especially AHP, are commonly used tools for evaluation, outperforming other methods such as TOPSIS, OWA, and ELECTRE in terms of usage frequency. Notably, WLC and GIS often appeared together in most articles, reflecting their strong collaboration. This combination has been the main choice for many researchers in recent years due to several reasons. WLC is an uncomplicated yet highly effective method for combinatorial analysis. Its simplicity and ease of implementation have made it one of the most commonly used and traditionally dominant GIS decision-support tools. WLC can be easily implemented through user-friendly GIS tools, such as the weighted overlay tool, which integrates evaluation criterion layers along with their assigned weights to produce a map layer. This simplicity and compatibility with GIS platforms make WLC particularly attractive to researchers. Consequently, OWA has also been applied in many GIS-based applications, benefiting from this conceptual alignment. On the other hand, in some studies, researchers have directly integrated GIS with TOPSIS and ELECTRE because these are not fully integrated into GIS platforms yet, making their implementation more complex or less clearly necessary [107,110,171]. However, there are advancements in integrating GIS with these methods.

In these studies, the researchers developed approaches where the feasible area was divided into a finite number of locations in the GIS environment, which were then treated as alternatives. The data for these alternatives were subsequently extracted into a decision matrix, enabling the application of MCDM methods like TOPSIS and ELECTRE. This novel integration approach demonstrates the potential for extending GIS capabilities by incorporating advanced MCDM techniques, although such practices are still relatively rare compared to the more traditional WLC and GIS combination.

2.3. Global Energy Treading

Interconnecting adjacent power systems helps address variability challenges associated with RE penetration by enabling electricity import and export during electricity generation surpluses and deficits [183]. Initially, transmission interconnectors were used to enhance system security, However, their role has expanded over time to facilitate global energy trading, integrate international electricity markets (EMs), and balance RE generation, becoming essential for modern grid stability [184,185]. The EU emphasizes the importance of market integration, setting a 15% interconnection target by 2030 for all member states, and it highlights transmission infrastructure's role in connecting high RE areas with main consumption centers [186]. Recent advancements between India and Nepal offer favorable prospects for enhanced CBET. These initiatives include Nepal's increased HPP capacity, coordinated operations to integrate India's wind and solar resources, and the potential for Nepal to export hydroelectric power to Bangladesh [187]. Figure 7 illustrates the total energy imported by each country in 2022, with green indicating the largest energy-supplying countries and red representing those with the highest energy imports. In 2022, Italy imported the largest amount of energy, totaling 42.99 TWh, while Canada exported the most energy, amounting to 51.11 TWh. In Canada, the major sources of energy generation include coal and peat (26,251 GWh), natural gas (82,524 GWh), oil (5367 GWh), nuclear power (87,239 GWh), wood waste (6031.78 GWh), hydropower (397,616 GWh), solar PV (5737 GWh), and wind energy (36,853 GWh). Among these, renewable hydropower contributes the largest share, followed by nuclear power and natural gas. In addition, other sources of energy generation include pumped storage (111 GWh), biogases from thermal processes (5.525 GWh), landfill gas (565.22 GWh), other biogases from anaerobic fermentation (141.002 GWh), sewage sludge gas (71.253 GWh), renewable municipal waste (169 GWh), black liquor (2018.269 GWh), and wood fuel (57.953 GWh). While these sources contribute smaller amounts, they play an essential role in diversifying the energy mix and promoting sustainability.

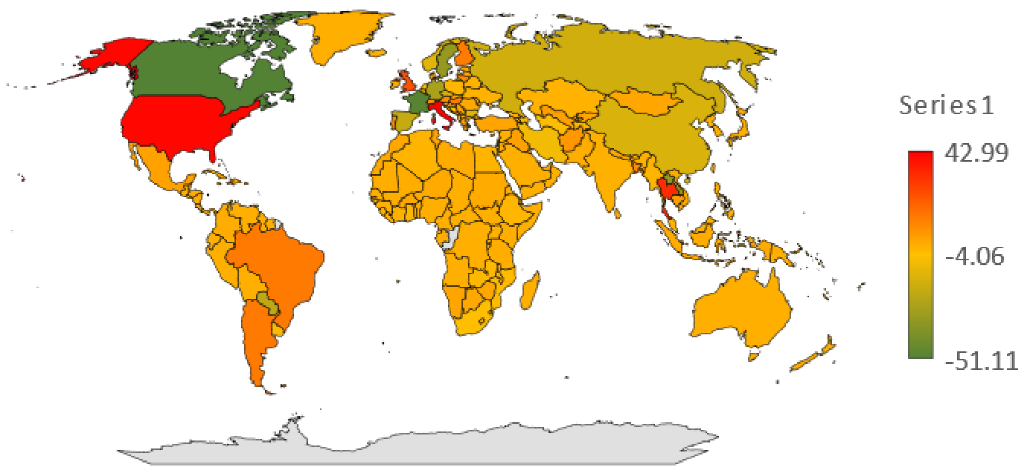

Figure 7. The total energy imported by each country in 2022.

In 2022, A.P. Jha et al. [188] discussed the role and benefits of CBET for the EU, and P. Thaler et al. [189] introduced the concept of the "Impossible Energy Trinity", which addresses the complex interplay between energy security, sustainability, and sovereignty in CBET. S. Saroha et al. discuss the opportunities, benefits, and challenges regarding international energy trading in South Asia [190]. In [191–193], a detailed review of the challenges and opportunities of the CBET between India and its neighboring countries as well as Africa is discussed.

In recent years, the concept of a GEG has gained significant attention. Many countries are already taking steps toward its development by interconnecting their national grids with neighboring nations. Such collaborations aim to enhance energy security, optimize RE utilization, and reduce reliance on fossil fuels. However, energy trading between multiple nations introduces new challenges and opportunities, including the need for harmonized regulations, advanced grid management technologies, cybersecurity measures, and equitable energy-sharing agreements. To support this transition, several policies, programs, and regulations have been implemented to promote and encourage the adoption of global energy trading.

In 2008, L. Parisio et al. developed equilibrium bid functions for domestic EMs and examined their adjustments when CBET is implemented through the implicit auction method [194]. Their study demonstrated that CBET can lead to price convergence across countries, redistributing gains and losses due to two simultaneous effects: the volume effect and bid effect. The volume effect occurs due to changes in demand and supply, while the bid effect occurs due to changes in bid functions. Recognizing the benefits of CBET, numerous models have since been developed to optimize electricity market integration within the European Union (EU), further enhancing energy security, price stability, and market efficiency across member states.

Recently, European energy markets (EMs) have experienced substantial developmental transformations, driving the continued liberalization of the energy sector [195]. Furthermore, the EU committed to achieve ambitious targets for 2050, focusing on increasing the share of RESs in the energy generation mix, as outlined in the European Green Deal. To address the challenges of the intermittent nature of RE and foster a more efficient energy market, European EMs are becoming progressively integrated, working toward the goal of a unified European EM [196]. Although Greece's EM is not coupled with its neighbors, it is expected to adopt it soon [197]. Additionally, European electricity market reports highlight that traded energy volumes exhibit a high degree of seasonality, driven by fluctuations in human activity, which typically slows during the summer months and picks up again afterward. This seasonality shows the importance of robust market mechanisms and interconnections to ensure a reliable energy supply throughout the year.

Countries within North America are adopting CBET policies while enhancing generation and transmission capacities to make those more efficient and adaptable. The successful implementation of the Nord Pool Network serves as a compelling example of the benefits that can arise from CBET [198]. Scholars have argued that the Nord Pool Network represents an exemplary model of an integrated electricity system, one that increases the aggregate efficiency and capacity factors of intermittent RESs, thereby improving grid stability and reliability. As a result, many researchers have identified EMs with high potential to achieve aggregate efficiency gains, both economically and technically, through expanded cross-border transmission networks [199]. To support these advancements, they have developed comprehensive economic, regulatory, and institutional models, considering both theoretical frameworks and real-world market conditions.

Extensive research has also been conducted on CBET and grid interconnection in the South Asia region. Several countries in this region are already interconnected, with India playing a pivotal role through initiatives such as the ISA and OSOWOG [39,40]. These initiatives aim to harness the region's renewable resources, particularly solar, wind, and hydropower, with the goal of connecting to the transnational grid. India has established power linkages with various neighboring nations, notably Bangladesh, Bhutan, and Nepal, to serve as a backbone for regional energy sharing [200–203]. An example is the India–Bangladesh grid link, which allows surplus electric power from India to be transferred to Bangladesh, so contributing to Bangladesh's increased energy demand [200,204]. In this example, India and Bhutan have long collaborated on HPP development, with Bhutan selling surplus energy to India to meet India's peak demand while providing Bhutan with critical revenue [202,203]. In the scenario of Nepal, the India–Nepal grid interconnection allows for such exchanges based on seasonal demand swings; Nepal would export hydropower in the rainy season and receive energy during dry seasons [202,205]. Such links contribute not just to energy security and grid stability but also RE integration in the region. Looking ahead, ISA and OSOWOG want to strengthen their links by incorporating solar power into the regional energy mix and establishing a single grid for multiple countries. Such efforts have the potential to make South Asia a paradigm for regional energy cooperation and sustainable development.

China is also taking significant steps in CBET under its BRI [41]. This ambitious project aims to extend regional and global energy cooperation through the development of intercontinental power grids. China has thus formed or planned grid interconnections with several neighboring countries that include Laos, Myanmar, Vietnam, and Mongolia, along with its influence extended all the way to Central Asia in Kazakhstan and Kyrgyzstan [206,207]. For instance, China has built HVDC transmission lines to draw hydropower from Laos and Myanmar. This enhances the country's energy use and shares economic interests as well. Central Asia presents the case where China's grid interconnections have enabled trade in electricity among Kazakhstan, which is wealthy in coal and renewable resources, and Kyrgyzstan, which contributes hydropower. This is all in the whole concept of making the power supply balance with demand so that energy security can be increased and RE integrated across borders. Beyond the closest neighbors, its efforts stretch to connect south Asia and potentially Europe into its network, which displays its vision for a worldwide energy network. These actions not only enhance China's energy security but also advance it as a leader of CBET and infrastructure development in the whole world.

S. Zhang et al. conducted a comprehensive study demonstrating the price formation approaches and correlations of cascade HPPs in CBET [207]. In this study, the researchers designed a bi-level optimization model to replicate the decision-making process, where each layer represented the interests of the two contracting parties. The study analyzed the electricity prices of Combined Heat and Power Systems (CHSs) in southwestern China under various pricing schemes and validated the findings using a real-world transaction case. The findings highlighted the complementarity between exporting countries, emphasizing the economic and operational synergies achievable through CBET. Moreover, the research identified the favorable pricing option for CBET, a unified price derived from marginal cost, which ensures efficiency and fairness in electricity trade.

Table 4 presents an overview of the developments and proposals made by various countries to date regarding global energy trading. This summary highlights the key initiatives, strategies, and collaborative efforts undertaken to advance CBET, promote grid integration, and support the transition toward a more interconnected and sustainable global energy market. It underscores the increasing focus on global energy trading as an essential element for enhancing energy security, facilitating the integration of RE, and achieving broader sustainability goals.

Table 4. The advancements in international energy trading.

Authors	Year	Countries Involved	Method Used
H. Fraser et al. [194]	2008	Arab Gulf States	Developed a legal and organizational framework
L. Parisio et al. [208]	2008	Europe	Used volume and strategy effects to regulate price in CBET
M. Watcharejyothin et al. [209]	2009	Laos and Thailand	Used a MARKAL-based model

S. Srinivasan et al. [210]	2013	India and Bhutan	Energy policy study
J.C. Richstein et al. [184]	2014	Europe	Agent-based approach
J. Torriti et al. [211]	2014	Europe	Used a bi-linear fixed-effects model for CBET
P. Higgins et al. [212]	2015	Europe	Optimization
P. Wijayatunga et al. [201]	2015	SAARC Countries	Performed a techno-economic analysis of CBET in SAARC Countries
W. Antweiler [213]	2016	USA and Canada	Two-way trade for optimization
M.O. Oseni et al. [214]	2016	South Africa, West Africa, and Central America	Investigation
J. Abrell et al. [195]	2016	Europe	Equilibrium model
T. Ahmed et al. [215]	2017	Southeast Asian Countries	An optimal power flow model is developed in MATPOWER
M.M. Sediqi et al. [216]	2017	Afghanistan and Pakistan	Used the Genetic Algorithm to minimize cost and maximize profit
S. Saroha et al. [217]	2017	South Asian Countries	Discussed the power system security, stability, and benefits of CBET
A. Singh et al. [218]	2017	South Asia Region	Review about barriers in CBET in the South Asia Region
M.M. Sediqi et al. [219]	2018	Afghanistan and Neighbor Countries	Optimal sizing of RE using the Genetic Algorithm
Y. Hou et al. [220]	2018	Northeast Asia	Consideration of the significance of the intermittent nature of wind energy while using CBET
H.M.E. Haque et al. [200]	2019	Bhutan, Bangladesh, India, and Nepal	SWOT-AHP approach
M.V. Loureiro et al. [221]	2019	Spain, Portugal	Nash–Coase or Nash bargaining
F. Chen et al. [183]	2019	Global	Optimized the resource allocation
C.A. Agostini et al. [199]	2019	Chile and Neighbor Countries	Used Surplus-based framework for CBET
S. Dhakal et al. [202]	2019	Bhutan, Bangladesh, India, and Nepal	Used SWOT-AHP model for CBET
A. Ulhaq et al. [222]	2019	SAARC Region	Used Technical Standardization and Power Pool Model
L.G. Montoya [223]	2020	Great Britain, France, and the Netherlands	Determined metrics
T. Mertens et al. [224]	2020	Belgium, the Netherlands, France, Germany, and Denmark	Used long-term energy-system optimization models for CBET
M.E. Islam et al. [225]	2020	India and Bangladesh	Discussed the economic benefits of CBET
G.P. Papaioannou et al. [197]	2020	Greece, Italy, and Bulgaria	Used Granger Causality Network Methods
D.I. Makrygiorgou et al. [185]	2020	Greece, North Macedonia, Bulgaria, Serbia, and Romania	Used the Available Transfer Capacity-Net Transfer Capacity (ATC-NTC) method
X. Gu et al. [226]	2020	Countries taking part in Belt and Road Initiative	BRI
M. Yuan et al. [227]	2021	New York and New England	Top-down approach
D.E. Boz et al. [228]	2021	48 countries across America, Europe, and Asia	Studied the effects of CBET on power production from various RESs
D. Schonheit et al. [196]	2021	Europe	Implemented a flow-based market coupling model
A.L. Kurian et al. [229]	2021	South Asia	Review of the functioning and significance of CBET
M. Yuan et al. [227]	2021	Northeastern region of USA	Used integrated top-down bottom-up modeling framework

S. Mukharjee et al. [203]	2021	India and Nepal	Study of present and future scenarios of CBET for India
Y. Pu. Et al. [230]	2021	Europe and Asia	Complex Network Perspective
M. Eghlimi et al. [231]	2022	Iran, Turkey, Iraq, Pakistan, Afghanistan, Armenia, Azerbaijan, and Turkmenistan	Multi objective particle swarm optimization algorithm
D.N. Dangal et al. [205]	2022	Nepal and India	Explored opportunities and challenges through data analysis and descriptive research methods
S. Zhang et al. [207]	2022	China	Bi-level optimization model is used to maximize income and minimize expenditures with the help of Karush–Kuhn–Tucker.
P. Shinde et al. [232]	2023	Europe	Proposed an agent-based model to analyze the trading behaviour in CBET
T.N. Do et al. [233]	2023	International Solar Alliance	Literature study
G.R. Timilsina et al. [234]	2024	South Asia	Discussed climate change and how climate change will be mitigated by using CBET
Z. Luo Et al. [235]	2024	China	Nash game and ARIMA-GARCH model
J. Shan et al. [236]	2024	Generalized	Developed an energy cross-border e-commerce optimization model
Z. Luo Et al. [237]	2024	China	Non-cooperative game approach
D.B. Diez et al. [238]	2024	India, Bhutan, and Nepal	Literature study about CBET

From Table 4, it can be observed that both the EU and South Asian countries are rapidly expanding their interconnected electricity networks and making significant progress toward the vision of a GEG. Numerous models have been developed to ensure the successful interconnection of national grids while maintaining safe and reliable operation. Additionally, various policies, programs, and regulations have been implemented to promote and encourage the adoption of global energy trading, highlighting the increasing importance of CBET. On the other hand, Middle Eastern countries are also making substantial efforts to enhance their RE capacity. These nations are working toward interconnecting their grids to support energy exchange while formulating policies that align with the global energy trading framework. This growing collaboration demonstrates the region's commitment to diversifying energy resources and contributing to the development of the GEG.

2.4. HVDC Technology and Transmission Line Development

Over the past few decades, significant advancements in HVDC technology have led to increased power capacity, improved efficiency, and enhanced grid protection mechanisms [239]. These improvements have made a GEG a viable option for developing an intercontinental grid. Numerous HVDC interconnections and grids are currently either in the planning stages or under construction. The first commercial HVDC link was developed by ABB in Gotland, Sweden in 1954, which is known as the Gotland 1 link [240]. It was extended 98 km and transmitted 20 MW of power at 100 kV. HVDC transmission primarily relies on two key converter technologies, line-commutated converters (LCCs) and voltage source converters (VSCs), each offering distinct advantages for specific applications. An LCC excels in high power and voltage ratings, making it ideal for creating overlay grids. Currently, the LCC link has a maximum rating of 12 GW at 1100 kV [241]. Among VSCs, the largest operational installation is the Zhangbei 4-terminal HVDC grid, with a capacity of 3000 MW at ±500 kV [242]. Additionally, the largest VSC system under construction is the Kun-Liu-Long 3-terminal HVDC grid, with a capacity of 5000 MW at

±800 kV [242]. In 2017, the Cypriot government granted environmental approval for a 1518 km, 2 GW transmission link interconnecting Greece, Cyprus, and Israel [243]. In 2016, Trena, the transmission system operator of Italy, approved a 600 MW HVDC line to link Tunisia and Sicily [244]. In 2025, Saudi Arabia will be interconnected with Egypt via the largest HVDC transmission system in the Middle East, which will span 1350 km and have a capacity of 3 GW at a voltage of 500 kV [245].

By 2030, mass-impregnated (MI) cables are expected to support higher transmission ratings, reaching up to 750 kV at 3000 MW per bipole, especially in projects with underground or submarine cable sections [246]. However, MI cables are seeing a decrease in market share as cross-linked polyethylene (XLPE) cables continue to grow in popularity. XLPE cables are anticipated to reach ratings of 650 kV at 2600 MW per bipole by 2030, driven by advancements in VSC technology [247]. This increase in demand is fueled by the need for multi-terminal direct current (MTDC) links to support offshore wind farms and integrate RESs. Recently, high-performance thermoplastic elastomer (HPTE) cables based on polypropylene and rated at 525 kV have been developed, providing enhanced dielectric and thermomechanical properties [248]. GIL is still under research, and it holds the potential to achieve the low loss levels required for very long TL.

Overhead lines (OHLs), when combined with LCC and VSC technologies, facilitate the use of ultra-high voltage (UHV) by achieving insulation through increased distances between conductors and grounds [246]. The maximum rating of OHL-HVDC systems currently stands at 1100 kV. One of the main advantages of OHLs is their lower cost in comparison to underground and submarine cables (USCs). However, they are more prone to faults, including both pole-to-ground and pole-to-pole faults [239]. For a GEG, a combination of OHLs and USCs is expected to play a crucial role, especially due to the long land and marine routes connecting continents. Further research is needed to increase the voltage and power capacity of both OHLs and USCs to meet the demands of the envisioned GEG.

DC/DC converters will be essential for the future development of HVDC grids, facilitating the interconnection of HVDC lines and terminals with different voltage ratings [249]. These converters are particularly beneficial in a GEG, as they allow efficient integration of small RE generation sources or load centers. Additionally, DC/DC converters can incorporate functions like power flow (PF) control and DC fault handling, potentially reducing the need for separate PF control devices and DC circuit breakers. In a GEG, the selection of DC/DC converter technology will depend on the specific application, with considerations for factors such as voltage transformation ratio, PF controllability, isolation, fault-handling capacity, and efficiency [250]. These parameters will guide the design of converters to meet the diverse and evolving demands of future HVDC networks.

There are several HVDC interconnectors and grids, either in the planning stages or under construction, and these initiatives are expected to serve as the fundamental building blocks for the development of a GEG. Cross-border HVDC interconnectors have a proven track record of success and have been a key component of Europe's energy infrastructure for many years [251]. Since 2013, the European Commission has initiated several critical cross-border infrastructure projects under the Projects of Common Interest (PCI) framework to enhance energy connectivity in the EU [252]. Key initiatives include the North Sea Offshore Grid, which aims to integrate RESs, as well as the North–South Electricity Interconnections in Western Europe and Central-Eastern and Southeastern Europe, which are designed to improve the flow of electricity between regions [253]. Additionally, the Baltic EM interconnection plan focuses on strengthening electricity links in the Baltic Sea region. These projects have been identified as priority electricity corridors, with the goal of improving energy security, promoting market integration, and advancing the EU's transition to a low-carbon energy system. Another significant PCI is the Euro-Asia

Interconnector, which links the electrical grids of Israel, Cyprus, and Greece through a combination of USCs and OHLs [254]. This project plays a crucial role in advancing regional energy integration by enhancing electricity interconnections between these countries, thereby improving energy security, facilitating the sharing of RE, and contributing to the broader goal of creating more interconnected and resilient European and Middle Eastern EMs.

In recent years, China has emerged as one of the leading countries in the development of HVDC grid technologies, driven by critical problems like geographical energy imbalances and environmental concerns [207]. Another key factor behind the rapid advancement of HVDC systems in China is the country's rapid economic growth, which has facilitated the financing and execution of large-scale infrastructure projects. China operates the largest HVDC links in terms of both power and voltage ratings. It is also at the forefront of HVDC grid development and deployment [235,237]. In contrast, most RE integration and grid expansion efforts have been concentrated in North America, with the goal of enhancing economic competitiveness and grid reliability. The North American RE integration study is one such collaborative initiative between the United States, Canada, and Mexico, aimed at examining the interconnection of the grid of these three countries and exploring the potential to increase the use of clean energy across the continent.

India has previously commissioned numerous such HVDC linkages, including high-profile projects like the North-East-Northern Grid and the Vindhyachal HVDC link, which are known for efficient power transfer over great distances. India's government recognized the necessity of HVDC technology for future power grid growth, and current programs such as the National Electricity Grid and the Green Energy Corridor would help integrate RE into the grid via HVDC systems [255,256]. India is also building cross-border grid interconnections with neighboring nations such as Bhutan, Nepal, Bangladesh, and Sri Lanka using HVDC technology.

Technological advancements have made HVDC a key technology increasingly adopted by system operators worldwide. For a GEG, transmission distances could extend over several thousand kilometers, potentially resulting in considerable voltage reductions between converter stations. To mitigate these voltage drops, effective solutions include utilizing UHV levels, optimizing conductor designs, and incorporating superconducting TLs [246]. Additionally, converter transformers equipped with wide-range tap changers will be essential to accommodate the wide voltage operating range required for such extensive HVDC systems. Although GEGs do not yet exist on a global scale, significant progress has been made in taking the first steps toward their development. Real-world insights gained from projects like the Zhangbei, as well as multi-terminal HVDC projects in Europe and North America, are valuable assets in promoting the widespread deployment of GEGs.

Table 5 presents a year-by-year overview of the development and current plans for international HVDC transmission lines, outlining their specifications and the technologies used. This table highlights the evolution of HVDC technology, emphasizing advancements in design, efficiency, and capacity, along with key innovations that have influenced the growth of intercontinental transmission networks. The information provided offers valuable insights into the ongoing progress of HVDC technology, which plays a pivotal role in improving long-distance power transmission and promoting the integration of global energy systems.

Table 5. The advancements in international HVDC transmission lines.

Countries Interconnected	Length (km)	Technology	Power (MW)	Voltage (kV)	Status
South Africa and Mozambique [257]	1420 (OHL)	Thyrister	1920	533	Operating (1979)
France and the UK [258]	70 (USC)	Thyrister	2000	270	Operating (1986)
Denmark and Sweden [259]	61 (OHL) 88 (USC)	Thyrister	300	300	Operating (1988)
Germany and Sweden [260]	262 (OHL)	Thyrister	600	450	Operating (1994)
Denmark and Germany [198]	170 (OHL)	Thyrister	440	350	Operating (1996)
Poland and Sweden [252]	245 (OHL)	Thyrister	600	450	Operating (2000)
Greece and Italy [261]	310 (OHL)	Thyrister	500	400	Operating (2001)
Thailand and Malaysia [262]	110 (OHL)	Thyrister	300	300	Operating (2001)
Finland and Estonia [263]	105 (OHL)	IGBT	350	150	Operating (2006)
The Netherlands and Norway [198]	580 (OHL)	Thyrister	700	450	Operating (2008)
The Netherlands and the UK [264]	245 (OHL)	Thyrister	1000	450	Operating (2010)
Finland and Sweden [198]	303 (OHL)	Thyrister	800	500	Operating (2011)
Ireland and the UK [265]	130 (OHL)	IGBT	500	200	Operating (2012)
France and Spain [266]	64 (OHL)	IGBT	2000	320	Operating (2015)
Sweden and Lithuania [252]	450 (OHL)	IGBT	700	300	Operating (2015)
Denmark and Norway [198]	244 (OHL)	IGBT	700	500	Operating (2015)
India and Bangladesh [256]	1728 (OHL)	Thyrister	6000	800	Operating (2017)
Italy and Montenegro [267]	415 (OHL)	Thyrister	1000	500	Operating (2019)
Denmark and the Netherlands [251]	325 (OHL)	IGBT	700	320	Operating (2019)
Italy and France [261]	190 (OHL)	IGBT	1200	320	Operating (2019)
Belgium and the UK [268]	140 (OHL)	IGBT	1000	400	Operating (2019)
Belgium and Germany [253]	100 (OHL)	IGBT	1000	320	Operating (2020)
Norway and Germany [251]	623 (OHL)	IGBT	1400	525	Operating (2021)
Norway and the UK [269]	730 (OHL)	IGBT	1400	515	Operating (2021)
Kenya and Ethiopia [270]	1045 (OHL)	Thyrister	2000	500	Operating (2021)
Denmark and the UK [255]	740 (OHL)	IGBT	1400	525	Operating (2023)
India and Sri Lanka [256]	285(USC)	Thyrister	1000	400	Developing
India and Nepal [256]	85 (OHL)	Thyrister	700	400	Developing
India and Bhutan [256]	170 (OHL)	Thyrister	2000	400	Developing
Ireland and France [255]	575	Planning	700	500	Planning
Israel and Greece [254]	1208	Planning	2000	500	Planning
Egypt and Greece [254]	1396	Planning	2000	500	Planning
Germany and the UK [255]	725	Planning	1400	525	Planning
Lithuania and Poland [252]	330	Planning	700	320	Planning
France and the UK [255]	210	IGBT	1400	320	Planning
Morocco and the UK [271]	4000 (USC)	Planning	3600		Planning
Australia and Singapore [272]	800 (OHL) 4200 (USC)	Planning	1500		Planning

From Table 5, it can be observed that the EU is rapidly developing its HVDC networks, making significant progress toward the creation of a GEG. India is also making substantial efforts to develop their own HVDC networks. While many interconnections are established through overhead lines, some are also implemented using a combination of overhead lines and undersea cables. The primary technologies used for these interconnections are Thyristor and IGBT devices, which enable efficient and reliable power transmission across long distances.

3. Initiatives in a Global Grid

The Global Energy Network Institute (GENI), created in 1986, aims to investigate and promote Buckminster Fuller's innovative idea of a GEG, a system intended to link power networks across countries and continents [243]. This concept envisions a world where electricity produced from renewable sources, such as solar, wind, and hydro, may be effectively distributed across regions, optimizing resource utilization and minimizing energy waste. Since its establishment, GENI has focused on performing thorough research to assess the technical, economic, and environmental viability of cross-border and intercontinental energy transmission. The institute actively participates in public outreach and education to enhance understanding of the revolutionary possibilities of global energy integration. Furthermore, GENI collaborates with governmental entities, industry executives, academic institutions, and non-governmental organizations to promote policies and infrastructure investments that endorse this integrated vision [24]. GENI aims to tackle significant issues, including energy access disparity, the transition to RE, and the mitigation of greenhouse gas emissions, through the promotion of a seamless GEG. Their initiatives highlight the significance of global collaboration in establishing a sustainable, resilient, and inclusive energy future.

In 2013, S. Chatzivasileiadis et al. explored the potential benefits and feasibility of a GEG, presenting a comprehensive framework for its development [10]. This work marked a significant milestone in the conceptualization of a GEG. Since then, the momentum for creating a GEG has grown substantially. Today, numerous universities and research institutes actively conduct research and advocate for its advancement to address the rising global demand for electricity sustainably. The BRI, launched by China in 2013, complements the vision of global energy interconnection pioneered by the Global Energy Network Institute (GENI) [41]. The BRI focuses on building transnational energy infrastructure, including cross-border power grids, pipelines, and RE projects, to address global energy needs and accelerate the transition to sustainable systems. By advancing investments in solar, wind, and hydroelectric facilities, alongside technologies like smart grids and energy storage, the BRI enhances energy access in underserved regions, mitigates energy poverty, and fosters economic growth. However, its large-scale projects raise concerns about environmental sustainability, debt burdens for participating nations, and geopolitical tensions. To align with GENI's goal of an efficient and cohesive global energy grid, the BRI must prioritize clean energy, equitable collaboration, and a balanced approach. Together, these initiatives present transformative opportunities for fostering international cooperation, optimizing resource use, and addressing the challenges of a global energy transition. The Global Energy Interconnection Development and Cooperation Organization (GEIDCO), established in 2016, aligns with the vision of creating a unified global energy grid, similar to the goals of the GENI and BRI [206].

India is also making significant strides toward the development of a GEG, closely aligning with its commitment to sustainable energy and international collaboration, in parallel with BRI and GENI [40]. Through the launch of the ISA and the OSOWOG initiative, India is promoting solar energy deployment and advancing transnational grid connectivity to enable efficient electricity sharing across time zones [39,40]. The country is also expanding its RE capacity, aiming for 500 GW of non-fossil fuel energy by 2030, and strengthening regional energy cooperation through cross-border transmission projects with neighboring countries such as Bhutan, Nepal, Bangladesh, and Sri Lanka. The EU has achieved considerable advancements in the establishment of a global electrical grid [273]. The EU has led these programs, including the European Supergrid, which seeks to distribute 100% RE throughout Europe. Europe has emphasized the growth of its offshore wind energy capacity, especially in the North Sea, where nations such as the UK, Germany, Denmark, and the Netherlands are cooperating to establish extensive wind farms and interconnected networks [71]. These initiatives aim to facilitate the sharing of surplus electricity among adjacent nations, enhancing energy security and mitigating carbon emissions. The ENTSO-E plays a crucial role for coordinating the integration of European power grids and promoting initiatives such as the North Sea Wind Power Hub, aimed at establishing a central offshore wind farm hub to provide RE to multiple countries simultaneously.

Despite the endorsement of a GEG by various networks and organizations, there remains inadequate information to guide policy formulation and decision-making and substantiate the development of associated projects.

4. Benefits and Challenges in Developing a Global Grid

Assessing the potential benefits and challenges of a GEG is crucial for guiding decision-making processes essential to the development of a low-carbon energy system and the achievement of a sustainable global energy future. However, the development of a GEG presents considerable challenges. Several technical, economic, and geopolitical challenges must be addressed to achieve this objective. The primary benefits and challenges related to a GEG are discussed below.

4.1. Benefits in Developing a Global Grid

The disparity between primary consumption regions with existing grid infrastructure and places having abundant amounts of RE potential is often emphasized as a key argument for the benefits of a GEG. Considering the anticipated global need of RE capacity in accordance with the 1.5–2° climate target, there will be greater interest in connecting efficient, underdeveloped, and sparsely populated areas to facilitate RE integration [3]. This method facilitates enhanced usage of renewable resources in these regions while maximizing domestic RESs, presenting a viable solution for achieving global sustainability goals.

The inherent uncertainty in RE supply, combined with demand swings across several areas, may be alleviated by leveraging time-zone variation [10]. This may be accomplished by integrating electricity networks across various longitudinal and latitudinal areas via intercontinental interconnectors. Connecting areas across different time zones and seasonal variations allows more efficient balancing of production and demand, resulting in a more stable and consistent electricity supply.

A GEG improves supply diversity and security by interconnecting regions, which mitigates price volatility and results in more stable electricity price [32]. This stability offers consumers a dependable energy supply while reducing the risk of price volatility, thus enhancing both economic development and long-term energy security.

Numerous studies highlight the significant potential of a GEG and the need of RE imports from remote areas in assisting nations in achieving their energy targets. In addition to the energy-related gains, this transformation provides other socio-economic advantages [42]. Countries might improve their global position by transitioning from fossil fuel exporters to RE providers. This transition could encourage the development of green employment and enhance overall economic growth. Moreover, the environmental advantages are significant, since enhanced integration of RE into the grid would reduce reliance on fossil fuels for power production, resulting in a cleaner and more sustainable energy system.

A GEG optimizes the effective use of seasonal fluctuations in solar PV generation, which reduces the total storage capacity needed [91]. This will improve the grid efficiency and reduce costs related to energy storage equipment.

The potential to invest in regions with abundant, highly efficient RESs presents a significant opportunity for foreign investment in the RE sector, particularly in developing countries [10]. This influx of investment not only stimulates local economic growth but also fosters increased cooperation between regions. As these investments contribute to the development of infrastructure, job creation, and the expansion of the RES industry, they facilitate long-term commitments to sustainable energy practices. Moreover, such investments can strengthen regional partnerships, promote knowledge sharing, and enhance energy security, ultimately advancing global sustainability goals.

Some studies suggest that directly connecting regions with high RE potential could bypass local low-voltage grids [243]. For a GEG to operate efficiently, it is crucial that local transmission and distribution networks are strong enough to manage and distribute large electricity flows. Strengthening these local grids is essential to ensuring the smooth functioning and optimization of a global interconnected energy system.

4.2. Challenges in Developing a Global Grid

The development of interconnections between countries and continents holds great potential to promote regional cooperation and drive economic growth. However, a major challenge for transmission projects, especially long-distance and sub-sea interconnectors, lies in the substantial investment costs and the significant risks inherent in projects of this magnitude [274]. Transmission losses, typically assumed to be 3% per 1000 km, are a common consideration in studies of intercontinental interconnectors. In addition, the losses associated with a converter pair are estimated to range between 1.4% and 1.6%. The long-distance TLs provide a considerable constraint in assessing the overall viability of prospective intercontinental connectivity projects [243]. A GEG could also introduce high risks associated with increased dependence on non-domestic energy sources, particularly when these sources are situated in regions that are susceptible to political or economic instability. This dependence may render governments vulnerable to supply outages or price fluctuations, so jeopardizing energy security. These dangers highlight the need of strategic planning and diversification in the establishment of a global energy network [31].

The development of a global electricity grid and cross-border energy trading faces significant regulatory and geopolitical challenges [11]. Regulatory disparities, such as differing energy policies, market structures, and grid standards, complicate integration and cooperation. Geopolitical tensions, including disputes over resources, energy being used as a strategic asset, and sanctions, further hinder collaboration. Infrastructure and investment challenges, such as unequal development, high costs, and disagreements over cost-sharing, add complexity. Energy security concerns, including dependency risks and cybersecurity vulnerabilities, also create resistance. Environmental and social issues, like the impact of new infrastructure and the management of renewable energy fluctuations, require careful consideration. Additionally, the lack of unified international governance frameworks and political instability in certain regions exacerbate these difficulties. Overcoming these barriers demands global cooperation through standardized regulations, transparent policies, multilateral agreements, and investment in resilient infrastructure to ensure equitable and sustainable energy trade.

A significant challenge in a GEG is the integration of diverse EMs, each characterized by distinct regulatory frameworks, pricing systems, and operational standards. Combining these disparities necessitates synchronized international policies and agreements, with the establishment of adaptable market frameworks capable of accommodating diverse regional patterns. Handling these problems is essential for ensuring the effective and fair functioning of a GEG. Harnessing RESs in regions with high resource potential presents an attractive approach for advancing global decarbonization initiatives [246]. However, a growing body of research highlights a competing trend: the prioritization of decentralized RE systems. Some studies argue that decentralized RESs represent a cost-efficient solution, leveraging advancements in localized energy systems and reducing reliance on large-scale infrastructure. On the other hand, others emphasize societal preferences for utilizing indigenous resources, which can enhance energy security, support local economies, and foster community resilience.

The lack of experience with long-distance interconnection projects, particularly those involving subsea pathways, introduces uncertainties regarding how local environmental conditions, geography, and terrain could impact the feasibility of such projects [246]. These factors can significantly influence both the technical challenges and cost estimates, making it difficult to predict the overall success and sustainability of the infrastructure. As such, thorough site assessments and innovative solutions are crucial to mitigate these uncertainties. Another challenge is that integrating power systems can lead to a more balanced distribution of marginal electricity prices across regions. While this can reduce overall costs, it may also result in higher electricity generation costs and, consequently, higher prices for consumers in certain regions. Additionally, there are concerns around energy sovereignty, political influence over domestic energy policies, resistance from market players to new entrants, and local opposition to interconnector projects.

5. Conclusions

This paper provides an in-depth analysis of the available research on the idea of the global grid, a system that connects electricity networks across continents to facilitate the efficient sharing of RE. Furthermore, it examines existing initiatives that support this concept and evaluates the current state of intercontinental interconnection projects, highlighting their progress, challenges, and future prospects. It examines the progress made so far in steps toward realizing a global grid and evaluates key initiatives and intercontinental interconnection projects, assessing their current state, challenges, and opportunities. Additionally, the paper highlights and performs a comprehensive analysis of the three main pillars critical to the development of a global grid: RE Site Selection, which ensures optimal resource utilization; Global Energy Trading, which facilitates equitable and efficient energy exchange; and HVDC Technology and TL Development, which are essential for transmitting electricity over long distances with minimal losses.

The discussion of the challenges and benefits associated with a global grid is essential for understanding the key barriers and opportunities in achieving an interconnected energy system. Therefore, this study provides a thorough examination of these factors, offering a comprehensive analysis of their impact on the feasibility, scalability, and potential benefits of global grid development. By highlighting the technical, economic, and geopolitical considerations, the study offers valuable insights that can inform future research, policy-making, and practical strategies for realizing a sustainable, efficient, and resilient global energy infrastructure. These findings are crucial for guiding the transition towards a more integrated and low-carbon global energy future.

Recent trends in the evolution of the global grid concept indicate a significant reduction in the expenses associated with long-distance transmission technologies, especially land-based and subsea HVDC. This reduction is primarily propelled by the accelerated economic expansion and increasing energy demand, as well as by technological advancements and economies of scale. Furthermore, there is a discernible transition towards intercontinental interconnector initiatives with enhanced transmission capacities, addressing the difficulties encountered by earlier large-scale projects. These pragmatic projects emphasize enhancing feasibility, sustainability, and risk management. Initiatives promoting the global grid have gained substantial momentum in recent years, indicating heightened global interest, collaboration, and advancement towards a more integrated and resilient energy system.

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