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TOPICAL REVIEW

From Smart Grids to Super Smart Grids: A Roadmap for Strategic Demand Management for Next Generation SAARC and European Power Infrastructure

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ABSTRACT Due to an increasing of demands of electricity in a world on regular basis, different continents will initiate a step towards transforming their smart grids infrastructure into super smart grids (SSGs), in which various countries in a continent will take a step towards an interconnection of their power system networks with one another to manage their futuristic demands conditions. The concept of SSGs system is predicated due to extensive use of modern technology, digital communication, machine learning and modern information techniques for the present power generating system to be more accurate and feature on balancing demand and supply. The SSGs uses renewable energy resources to support power system of multiple countries by reducing the greenhouse gases emissions. The main purpose of transforming smart grids into SSGs is to balance the demands and supply between multiple countries, if each country is not able to manage their own demands profiles. The environmental conditions, lack of energy management, intermittent nature of renewable energy resources and line losses are the major hurdles to provide regular supply. This research work focused about the hurdles in the form of technical challenges that will be arises in case of developing a futuristic SSGs for European and SAARC continents, and thus provide a valuable solution for it along with discussion about the future research directions. Moreover, although SSGs ideas have received positive reviews from many technical experts, but there development in future is still a challenging research issue due to lack of simulation based models of SSGs in the current literature. To deal with this issue, finally a fuzzy logic using hybrid cluster model of SSGs consisting of two clusters and a renewable wind energy system is successfully presented in this research paper. This model can be utilized in prospective for transforming any smart grids power infrastructure based on one country power network to futuristic SSGs power infrastructure based on multiple countries power networks for SAARC and European continents. The simulations of clusters and wind system are performed by the MATLAB. The suggested model of SSGs consisting of eighteen bus networks provides regular supply of energy between two countries interconnecting in the form of two clusters, whenever one or both countries lies in the region of SAARC and European continents faced some kind of fault.

INDEX TERMS Super smart grid, power system, renewable energy resources, greenhouse gases, fuzzy logic, hybrid system, MATLAB.

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I. INTRODUCTION

Nowadays the developed and developing countries are facing several problems present by energy sources. The problems such as absence of adequate and secure energy sources, environmental losses by oil and coal based energy sources, location of energy sources far from the consumption centers, intermittency, energy losses, load shedding, lack of modern sensors, two way communications, less reliability and energy efficiency. So, there is a deep need of energetic development in energy sectors to improve the load shedding and energy losses. The new smart grid technology can be used to avoid all the problems in energy sectors. Smart grid ensures the stability regardless of the working conditions and it can integrate more energy sources to the grid and can solve the problems of intermittency [1]. Today, the power grid has become the smart grid or bright electrical network to produce the sustainable, more stable, more accurate and low economy electrical power. The smart grid had attracted the attention of researcher and engineers from the last few years. The fact is that the smart grid is based on data and Communication techniques to ensure the permanent availability of electric supply and balance. Smart grid is the mixture of control methods, modern sensors, communication devices and advanced technologies [2]. On the other hand, the super smart grids (SSGs) is a self-sufficient system that guarantees the balancing condition between the demand and supply, if a demand cannot be fulfilled through smart grids environment. In other words, brings down the work force and targets the safe, reliable and sustainable electric supply [3].

SSGs are a hybrid system that is the combination of two or more supply of energy [4]. This system may combined electrical source of power with renewable power sources, either independently or in conjunction with the grid's existing supply system [5]. In a hybrid system, the storage battery can indeed serve as a power origin [6]. In case of excess of power, batteries can store energy and distribute energy in the event of an oversupply of energy demand. The battery or wind driven system can be integrated with the hybrid system [7], [8]. The hybrid system removes the fluctuation in supply, deficient in production by primary sources. Further it makes it smooth by taking energy from auxiliary source [9].

To design such a hybrid grids for a transformation of smart grids to SSGs, the concepts of such futuristic grid can be tested by simulation before its actual implementation in future, which needs the integration of communication simulator and electrical simulator. So, co-simulations have been developed by the researcher to satisfy the expected demands. In co-simulation, the connection is used to couple the more than two simulators. The futuristic SSG simulation's primary goal is to increase the robustness, flexibility and to combine the energy sources by planning, designing and validating the capabilities of the grid system. For the designing and communication networks of SSGs or power grid, the simulation is better software [10], [11]. Simulation is very crucial to analyze system effectiveness and reducing the expense of upgrading the infrastructure of communication network and power system. Simulators can improve the accuracy of analysis of energy flow, short circuits, harmonics and over-voltages in energy sources. MATLAB/Simulink, Power World, PSS/E, Open DSS, Modelica and Positive Sequence Load Flow are the electrical network simulators that will be used in SSGs co-simulation and electrical simulation in order to network planning, price forecasting and operations [12].

For optimal energy management, the computational abilities must be integrated in SSGs power infrastructure, where an operator of grid monitor, control and optimize the efficiency of the electric utility system [13], [14]. There is a deep need to improve the energy management in terms of distribution and loss in transmission by the electric companies to reduce the operational cost [15]. This helps to reduce the burden of heavy electric bills of consumers and to monitor and control the energy resources [16], [17]. The communication architectures and protocols are evaluated and developed by the simulators for the simulation of communication network. The successfully widely used simulators in smart grid are OMNeT++, OPNET Modeler, Network simulator 2/3 and NeSSi [18]. Reference [16] proposed the MATLAB/NS-3 co-simulation for the framework of smart grid. To put the suggested co-simulation into practise they integrated two simulators. MATLAB and NS-3 simulators for electric grid and network connectivity were used for the simulation, respectively. Each of the following simulation platforms will also be utilized to provide an optimal energy management in futuristic SSGs power infrastructure.

Moreover, for strategic demand management in futuristic SSGs, fuzzy logic based controller will be a more suitable option, as compared to other control topologies [19]. The human operator's knowledge and experience are utilized by the fuzzy logic controller to develop a control system that will regulate the application process. The fuzzy rule base system is crucial example of fuzzy logic or fuzzy set application. The fuzzy sets and fuzzy numbers that may be specified in linguistic parameters were defined using fuzzy logic approaches. Fuzzy logic techniques can be used to deal with input and output variable inaccuracy. The rules-bases fuzzy technique is verbally constructed and covers the whole parameter space. Numerical interpolation is used to regulate the challenging non-linear relationship. Fuzzy rules often have the form "IF A Then B" where A and B are linguistic variables that include propositions. In [19], the authors used fuzzy logic based hybrid system, which can be utilized for an efficient transformation of smart grids environment into futuristic SSGs. The suggested method provided a linear energy flow, maximum energy management and lower requirement of battery storage. As long as the sufficient charge is hold by the battery, the proposed system remains self-sufficient. During the irregularities, for instance, when batteries are not charged, then grid provides the power. The outcomes of the simulation showed that the steady state and transient efficiency of the system remained within the limits. Load current's harmonic distortions were also in accepted range. The fluctuation and variations of current at load end were also in acceptable bounds.

TABLE 1. Advantages and drawbacks of power flow control methods for stability enhancement in smart grids and SSGs.

	Methods	Advantages	Drawbacks	Functions
1	Data-driven	A quick calculating speed is utilized and a robust capacity for learning.	Inadequate description and response to the topological transition.	Level of stability can be investigated through the transient stability assessment model.
2	Direct method	Have quick calculating speed and sufficient margin for stability.	Conserved in outcome evaluation and have complexity in energy function.	Can assess and improve the stability transition.
3	Simulation method	Reliable results and scalability.	The outcomes of calculation can affect the accuracy of the system.	Differential and algebraic equations defined the dynamic of the system.

Based on the above explanations, in this research work, the authors first discussed various methodologies exist in literature for optimal power flow control demand management in smart grids, and how these topologies can be further upgraded into futuristic SSSs power infrastructure. Then after this, a comprehensive overview of futuristic SSGs for SAARC and European continents will be explained in detail along with the technical challenges and future research directions. Finally, a simulation based model of two clusters, which represents an interconnection topology between two countries based on SSGs power infrastructure will be designed in simulation section to provide an optimal demand management between any two countries of SAARC or European regions. The need of simulation model is due to the fact that although SSGs power infrastructure received a positive response from many scientific researchers, however, there development is still a very challenging issue due to the lack of availability of simulation models in the current literature. Thus there is a need to address this challenge, which is the primary focus of this suggested study. For simulation model, a fuzzy logic based hybrid system consisting of two clusters and wind power has been suggested for SSGs power infrastructure. As, the variations in weather conditions and the discontinuity of power generation from energy sources offer unbalanced power for consumers in SSGs power infrastructure. Therefore, the primary goal of the research is to manage the energy flow and ensure that smooth flow for the consumers. The final proposed system keeps the stability among the power use and supply. MATLAB software has been used for the analysis and simulation of the clusters and wind power station in SSGs power infrastructure.

II. METHODS FOR POWER FLOW CONTROL STABILITY ENHANCEMENT

A stable and modern smart grid or SSGs system can be evaluated by the power flow control stability enhancement. Three categories are used to understand the techniques of power flow control stability enhancement for demand management in smart grids or SSGs power infrastructures. These include data-driven systems base artificial intelligence, direct procedures, and time-domain simulation techniques. The advantages and drawbacks along with functions of these mentioned methods are described in table 1. To implement the numerical algorithm in data driven method is the main focus in order to solve the algebraic differential equations. It has also been noted that the power sector firms primarily use this technique.

Additionally, the multifunctional methods for solving the differential algebraic equations are observed in simulations models for power flow control management in power system networks [20]. The power flow control stability is assessed by Lyapunov theory based energy functions. Also, the direct methods use Koopman model to investigate the power flow control management for stability enhancement was proposed in [21]. The algorithm's strength is that it doesn't need any challenging time-domain model following a failure. In [22], [23], and [24], the authors proposed simulation model to assess the power flow control stability by phasor measurement units (PMUs) and dynamic state estimators (DSE) in order to collect the data. All of these techniques, which were already successfully utilized in smart grid environment, will be implemented in futuristic SSGs power infrastructure for optimal demand management requirements.

III. ADVANCE POWER STABILITY ENHANCING TECHNIQUES

The literature [25], [26], [27], [28], [29], [30], [31], [32] explores much technique to improve the energy flow control balance in power networks. The instability stability complexities cause disruptions in power quality, which leads to variability's in demand profiles, which can be enhanced by two strategies. The first way uses FACTS devices, for example UPFCs, to make a power angle network stable and synchronized in the wind turbines at the production sides. This can restricts the changes in position and speed of rotor caused by any type of fault or overloading conditions in power system networks, so reduces the difficulties of instability conditions at power grids. The second way to regulate the energy flow in a network for stability enhancement is to reduce disruptions of power quality; i.e., to install the FACTs UPFC device closes to faulty area or over the receiving unit of smart grids [33]. The main issue in power system is balancing in the transient oscillations brought on by various defects, which leads a variation in demand profiles of whole power system networks. The power system of renewable wind turbines is affected by the fault conditions [34]. In case less severe fault, there occur small changes in position and speed at the receiving side of smart grid which cause fewer problems in quality of power supply. But in case of severe fault, fluctuations in rotor speed cause severe problems in power quality, and that will ultimately leads to instability conditions in demand profiles. The schematic of strategic demand response for smart grids infrastructure is described by [30]. The power stability is increased by a closed loop control system based on probabilistic model. UPFC and smart node shaped closed loop is used for continuous monitoring of power system. In result of which appropriate right action is executed to balances the stability and mitigate the instability conditions. In case of less sever fault, power grid is improved by smart node to make balance in load flow. In more sever fault case scenario, the power system is improved by injecting a UPFC device into the transmission network to bring balance in order to reduce the energy supply instability conditions [31].The proposed work in [30] and [31] will be easily transformed to provide stability enhancement in futuristic SSGs power infrastructure.

A. MULTI-AGENT-BASED TECHNIQUE

By continuously assessing a system's critical clearance time (CCT) for generation load fluctuations and varying levels of wind energy penetration at different defective areas, a smart multi-agent-based method for enhancing power reliability is presented in [29]. One of the major hazards contemporary Power systems is power instability, which may be prevented by appropriately coordinating the protective relays of the network with the associated CCTs. These are significant power stability indicators because they examine whether the system can keep running smoothly and in balance following a different fault conditions [30]. Numerous more strategies are employed, such as the agent-based ones described in [31], [32], [33], [34], [35], [36], [37]. In order to increase system reliability, new strategy points are used to control the turbine valve [31]. The method for controlling the turbine upon the emergence of a defect is depicted in [32]. To maintain power stability, authors in [33] defined the use of a multi-agent based algorithm for wind turbine control. To enhance system stability, a multi-agent system approach is developed in [34] to devolve coordinated control. Authors in [35] describes a method for dynamically evaluating the critical clearance time in the event of a sudden genset fluctuation and the integration of renewable power sources with the genset using a multi-agent framework. Its structure is composed of global agents (GA) and local agents (LA), who employ an approach to correctly offer cooperation with the defence systems and their associated crucial clearing times (CCT). With the steady flow of CCT information, the agents continuously update the system's data to improve transient response by promoting the online capacity and flexibility of real-time agent-based protection device cooperation. The LAs uses communication language to communicate and negotiate with one another to link the system's safety framework by auto-reclosing and tripping its circuit breakers (CBs) with their corresponding CCT information to improve the system's performance for power flow control demand management. The GAs can monitor and evaluate a system's present condition using the physical characteristics of its system and then rapidly investigate the CCT as problems happen. The analogous agents cooperate to select the appropriate real-time safe instrument network to increase the power balancing of the structure when interruptions such three-phase faults or sudden load changes happen in an SGs [36], [37]. These advance smart grids stability enhancement techniques will be easily transformed for SSGs power infrastructure for optimal strategic demand management control in SSGs environment.

B. INCORPORATION OF FACTS DEVICES

In a power grid, FACTS devices are used to increase the transmission line's ability to transport power and to optimize voltage regulation, thermal restrictions, voltage stability, and transient stability for optimal power flow control management. These components serve as the system's actual median for system stability. The system can become unstable due to the transients, and an unstable system can result in disturbances in the electrical grids. Any state's electrical grids are of highest importance. The capability of the FACTS devices to maintain system stability is also researched in [38], [39], [40], [41], [42], [43], [44], and [45]. Before the invention of power electronics switches, these problems were dealt with by connecting reactors, capacitors, or synchronous generators using mechanical switches. However, employing mechanical switches has a lot of drawbacks. Mechanical switches are prone to wear and strain and react relatively slowly. These techniques are unreliable for improving the stability and controllability of the transmission line. After the development of power electronics switches with high-voltage application capabilities, such as the thyristor, power electronics-based FACTS controllers were developed. The types of the FACTS devices are as follows:

1. Static compensators (STATCOMs);
2. Unified power flow controllers (UPFCs);
3. Static synchronous series compensators (SSSCs);
4. Thyristor controlled shunt reactor (TCSR).

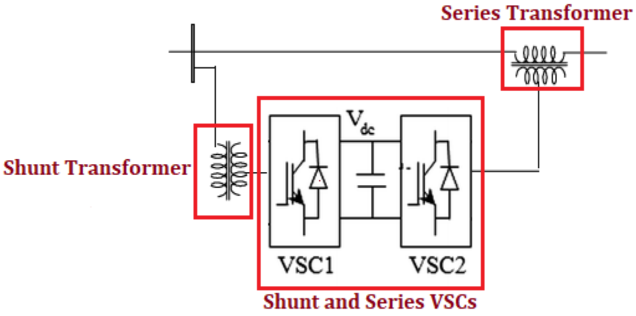

FIGURE 1. Representation of principle function of UPFC [57].

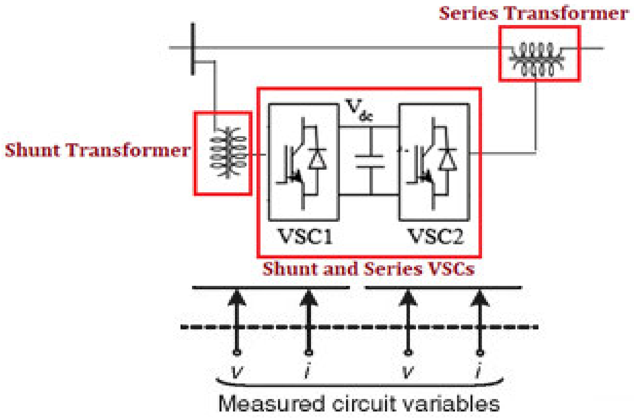

FIGURE 2. Block diagram of control system of UPFC series converter.

Regarding their integration into the renewable integrated power grids (RIPGs) to manage reliability problems in power systems, these FACTS devices are reviewed and investigated [46], [47], [48], [49], [50]. The universal type of UPFC is One of these FACTS controllers which can decrease the impact of voltage stability disturbances in an SG [51], [52], [53], which is one of most important power electronic device for transformation of smart grids infrastructure into futuristic SSGs.

C. INSERTION OF UPFC

UPFC incorporated 30-bus system was simulated and it is described in [54] for smart grid power infrastructure. The incorporation of UPFC in transmission line is also described in [55] and [56].

This demonstrates the basic operation of a UPFC, which consists of two inverters for shunt, two connected transformers, parallel and series branches, and series compensation managed by the references provided. According to [58], UPFC function in a number of ways. The way the shunt inverter functions especially makes it possible to inject regulated current into the power line. There are two parts to this current that relate to the voltage of the wire: the direct or actual part, which might be in phase with the voltage of the line or out of phase with it, and the reactive or quadrature part, which is in quadrature [59]. The direct component is dynamically controlled by the need to stable the series inverter's actual power. Instead, within an inverter's ability to either activate or generate reactive power via the line as necessary, the quadrature part can be separately tuned to any required amount of reference (inductive or capacitive). The block diagram is depicted in Fig. 2 to analyze the series inverter. How to operate the shunt inverter is illustrated in [60], [61], and [62]. Based on achieving the system reliability in a very little period of time, the UPFC is considered to be one of the versatile power electronic devices that can provide power flow control management between different countries power infrastructure that are ultimately interconnected in the form of SSGs power infrastructure to support one another in case of instability demand conditions.

D. UTILIZATION OF THE STATCOMS

Due to the margin for stabilities in the power stations, series compensation equipment like shunt compensation equipment and thyristor controlled series compensators (TCSC) like the static synchronous compensator (STATCOM) can enhance the stability by operating close to their limits [63], [64]. On the other hand, SSGs which are based on an interconnection between multiple countries could need even more than one compensator to achieve the needed performance. A thorough analysis of the system's stability state is necessary to comprehend the influence of FACTS devices. The transient energy function (TEF) technique is the common method for doing this [65]. By synchronizing generator and STATCOM stimulation, voltage regulation and power stability are also made possible [66]. The wide-area controlled static var compensators (SVCs) enhancement of network stability is demonstrated in [67] and was verified by hardware during loop validation. When STATCOM is used in conjunction with an power storage unit, the network reliability of electrical network with synchronous and induction generators are enhanced for power flow control management [68]. According to [69] and [70], UPFC significantly enhances preliminary swing network stability when compared to STATCOMS. By combining TCSC, SSSC and STATCOM, a power system with wind farms and photovoltaic improves its stability to the optimal range. Digital simulations, such as dynamic performance, network stability are used to comprehend the FACTS device's specifications functioning, which pertains to the formulation of product specifications. A method for creating a transmission SVC design utilizing common knowledge about thyristors is presented in [71], and it may be partially used in STATCOM and other instruments for an efficient integration for SSGs environment in order to achieve maximum stability in such futuristic power grids in terms of power flow control management.

IV. CHALLENGES AND CAPABILITIES OF POWER GRIDS IN SOUTH ASIAN ASSOCIATION FOR REGIONAL COOPERATION (SAARC) REGION

The limitations and potential of the current electricity systems in the SAARC nations are discussed in this section. The map of how SAARC countries futuristic SSGs will be developed

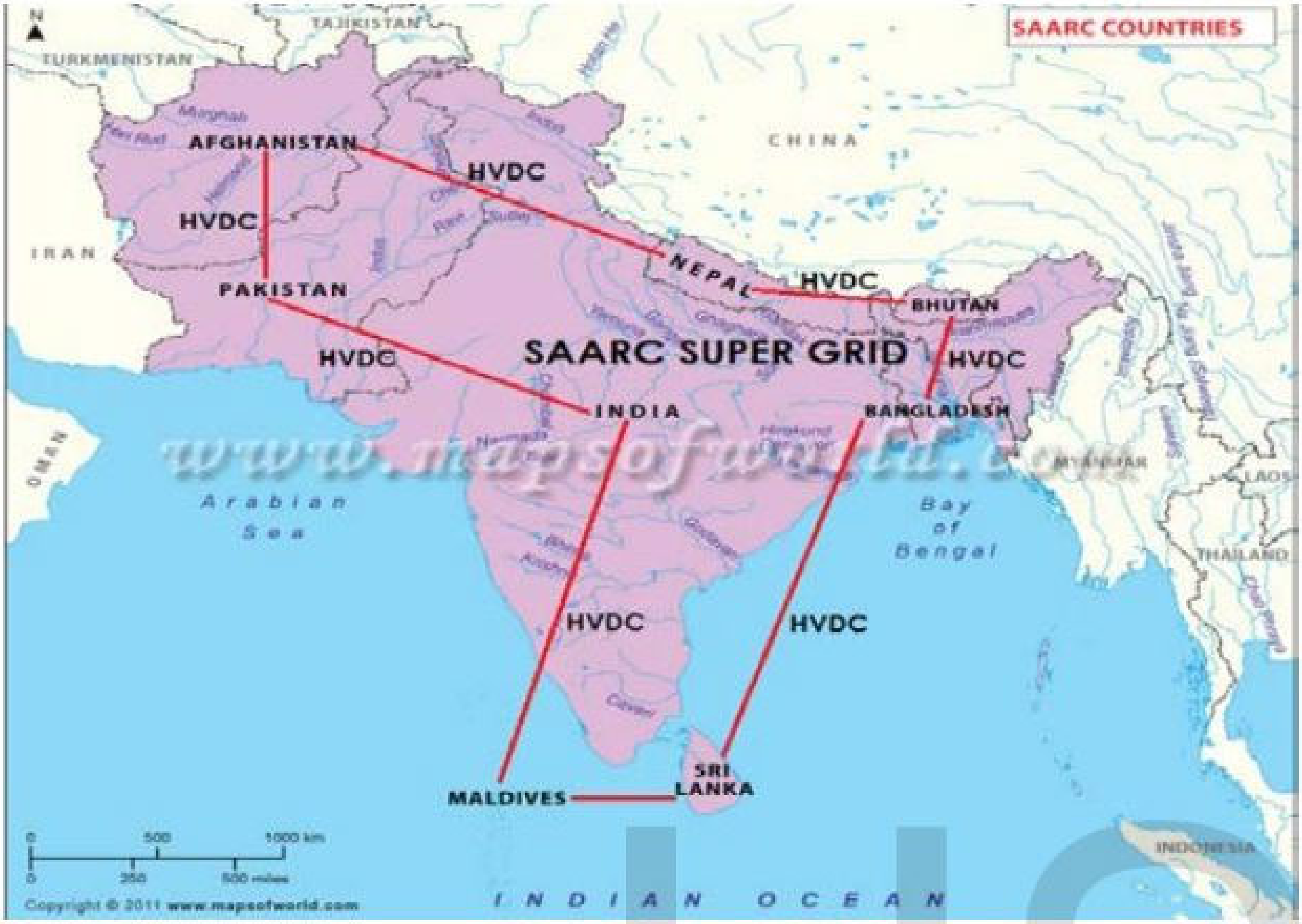

FIGURE 3. Map of SAARC countries.

are shown in Figs. 3 and 4. The integration of these nations' power grids could have a number of advantages, including the shared construction of transmission and power plants infrastructure, poverty reduction by reducing and sharing of electric bill, renewable energy-based generation of power, and fewer conflicts as a result of the prosperity of the region. However, serious issues can be created by many challenges. For example, as compared to the other countries, the SAARC countries have a small surface area (3.5%). The surface area and population of India is largest as compared to its population density. But Bangladesh and Maldives have large population densities. These are the hindrance in the way of constructing commercial scale solar, biomass, hydro, wind power plants. The skylights solar photo voltaic can offer the most advantages in this situation. The following section identifies the capabilities and challenges faced by SAARC power systems.

A. AFGHANISTAN

Due to numerous major issues, such as the dispersed infrastructure [72], the inconsistent power supply [73], and the frequent power outages [74], In Afghanistan, barely 30% of the country has a connection to the national grid. Only 10% to 15% of the population, however, has regular access to electricity. In rural places, this number declines even more [75]. The national grid also offers very poor voltage stability with frequent voltage changes in addition to load shedding. As a result, the oil/diesel generators must be kept in Afghanistan's industrial and commercial sectors as a reserve resource [76]. The ongoing wars in Afghanistan have seriously harmed the country's current power structure [77], [78]. Threats to the national grid still remain a possibility [79]. A regular power system's creation in Afghanistan is also a difficult task because of a number of obstacles, including political, geographic restrictions [80] and other economic, financial, and legal problems. Afghanistan may thus have a higher chance of distruption in the power-sharing function of the super grid's. Afghanistan either produces with diesel generators or buys electricity from its neighbors. Pollution is being caused by the increased usage of diesel generators [81]. The possibilities for renewable energy in Afghanistan are very high. An excellent solution for Afghanistan's electrical crisis and environmental problems is the use of RERs. However, its government is unable to fund the larger investments in projects based on renewable energy. As a result, one of the main issues preventing the

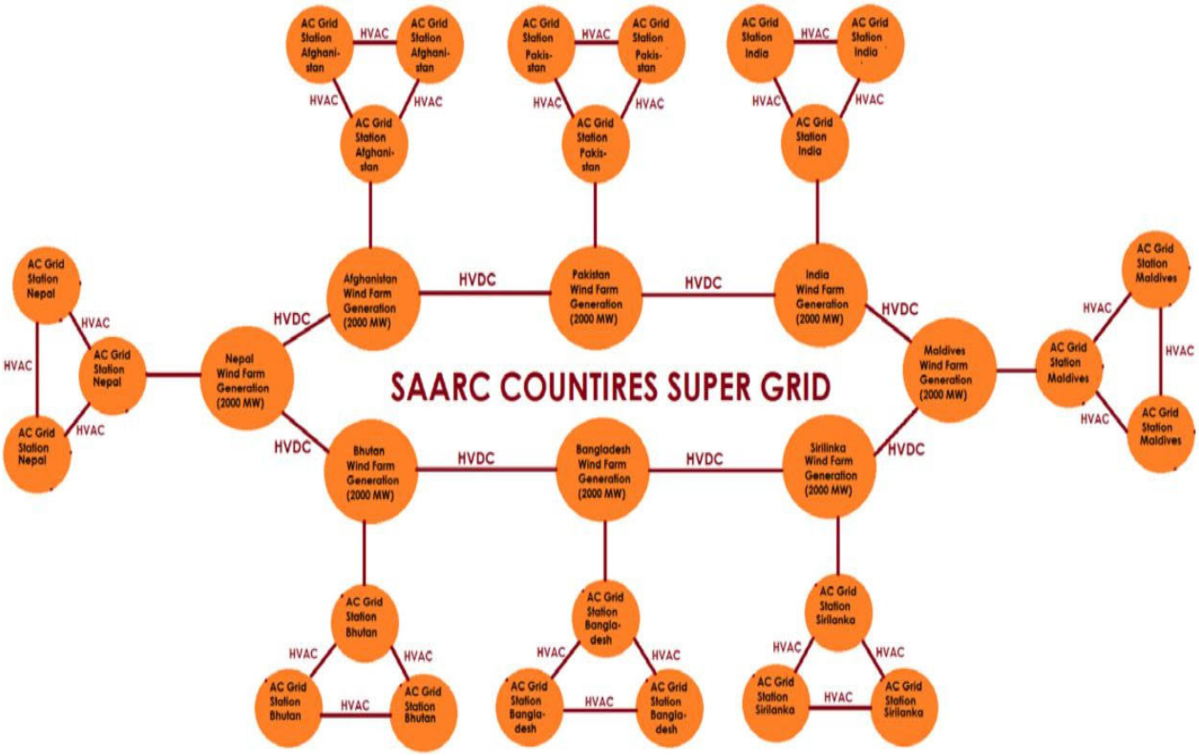

FIGURE 4. Development of futuristic SAARC Super Smart Grids.

extension, advancement, and safety of Afghanistan's national grid is a lack of financial resources [82]. In the long run, Afghanistan seeks international assistance to expand its electrical infrastructure. Integrating the power network with neighboring nations is one option. Afghanistan's location to other South Asian nations may make power sharing easier. For the benefit of their shared economic development, Afghanistan can trade electricity with South Asian nations. Afghanistan and the other SAARC members have stopped sharing authority in recent years. The SAARC body and Afghanistan's collaboration may make power sharing easier. Afghanistan can create affordable electricity in this way to support financial stability and economic growth, which may lead to fewer conflicts [83].

B. BANGLADESH

Bangladesh is able to provide power to all of its citizens. For example, the nation's overall ability to generate power in 2020 was 20383 MW, which was 7483 MW higher than the necessary amount [84]. However, the distribution and transmission of power in Bangladesh is plagued by numerous problems with quality and dependability. Due to the multiple distribution and transmission constraints, the electrical supply to customers is inefficient. For example, it was predicted that transmission and distribution losses will be 10% by 2020 [85]. 92% of the electricity needed in Bangladesh is produced from fossil fuels. Hydropower and present RERs produce only 3% of theirs total energy [86]. Bangladesh's capacity to create hydropower is relatively low [87]. Additionally, the issue of land scarcity may restrict the usage of solar for power generation. The severe climatic circumstances could reduce its ability to produce wind power. The potential for biomass is also pretty small [88]. As a result, Bangladesh cannot meet its increasing need for electricity without heavily relying on fossil fuels. To satisfy future demand, Bangladesh has a goal to increase its capacity for energy production to 60,000 MW by 2041 [89]. The gradual consumption of fossil fuels could, however, lead to significant issues such as the highly paid imported fuels, system loses, less efficient plant, electricity theft, shortage of funds for power generation and increase in emission of CO_2. Bangladesh should put more effort into researching renewable resources to meet this challenge. For instance, Bangladesh has more potential for the use of geothermal energy, but no progress has been made in determining its entire potential. Integrating Bangladesh's power grid with those of other countries with higher RER potential is the best way for Bangladesh to deal with its current electricity crisis. There is already indication of Bangladesh importing electricity from India. It is indicated that according to their power sector master plan, the renewable energy resources can generate 3.6 MW of electricity. It is also described that 1.9 MW from wind power and 15 MW from solar energy is generating from Feni and Kutubidia.

C. BHUTAN

In Bhutan, grid access is available to 99.5% of the population. Some villages are not linked to the grid. PV systems and diesel generators are used to meet this demand [90]. In order to connect these settlements to the national grid, the electricity transmission system has to receive more funding. Bhutan has a lot of hydroelectric potential. It almost completely covers the energy demand during peak hydropower periods. During the dry period, hydropower production declines to 20%. Therefore, there is a chance that the disruption risk will be increased if hydropower production suddenly declines as a result of water constraint. Bhutan exports 70% of its hydropower to India and uses 30% of it locally when hydropower production is at its highest. Bhutan, in contrast, gets electricity from India when the hydropower is low. The non-renewable resources used to generate this imported electricity. Bhutan also buys fossil fuels to generate electricity when the availability of hydropower is low [91].

D. INDIA

India currently supplied around 79% of the total electricity required in South Asia. India has a huge electricity infrastructure that uses more fossil fuels than other countries. In the mix for generating energy, coal accounts for more than 50% [92]. The coal supplies could run short within the next 50 years, according to expectations [93]. Therefore, the shortage of fossil fuels may result in serious issues, such as difficulties meeting demand. India is expanding its capacity for the production of renewable energy in order to address these issues [94]. With RERs, India has a great potential for electricity production. There is indication, for example, of solar power producing projects in India that will produce 2100 GW of electricity [95]. India has an unreliable power system. For example, grid outages of four to eight hours are typical throughout much of India [96]. As a result, the Indian electricity system is constantly interrupted. However, compared to other SAARC countries, it is more capable of handling this problem. India should quickly switch to RERs as its non-renewable energy resources are decreasing faster than those of other nations. Additionally, RERs will replace fossil fuels, reducing CO2 emissions more than other SAARC countries. Regarding this, the super smart grid presents a fantastic opportunity to exchange the power based on renewable energy with other nations. As of 30 June 2022, India's national power grid had a capacity of 403.759 GW. Considering, National Electricity Plan of 2022, until 31st, March, 2027, the nation will not need more fossil fuel power plants, with the beginning of 25,580 MW coal-based electric plants that are currently being built after the superannuation of nearly 4,629 MW old coal-fired plants and an inclusion of 187,909 MW total renewable energy capacity. Non-fossil fuels are expected to make up around 44.7% of the world's gross energy output by the year of 2029–2030.

E. MALDIVES

Given its isolated geographic location, the Maldives has a restricted capacity for electricity sharing with SAARC nations. Because of its far position, it might experience some trouble with long distance connectivity. Additionally, the country's geography shows a little window for an effective electricity distribution system. There are 1192 islands in the Maldives, which makes it difficult to build a power network with SAARC nations [97]. The internal electric grid is dispersed, which raises the cost of fuel transportation. Almost all of the Maldives' electricity needs are covered by the import of oil and diesel. In this aspect, the cost of generating is impacted by changes in the price of fossil fuels. Domestic fossil fuels are not owned by the Maldives. Additionally, the potential for wind, solar, hydro, and biomass electricity is minimal. The Maldives' small surface area limits the potential of solar PV projects [98]. The SAARC body should assist the Maldives in integrating its electricity grid with that of other nations in the region in order to address the aforementioned issues. As a consequence, the Maldives may reduce their electricity generation costs and significantly reduce emissions.

F. PAKISTAN

Over 25 million Pakistanis live without access to power [99]. Additionally, the majority of rural areas are suffering from load shedding. The big reasons are insufficient attention paid to RERs, the poor utilization of resources, delay in construction of megaprojects, and outdated distribution of power system for the energy crisis in Pakistan. Additionally, Pakistan needs a digital technology based energy strategy and enough funds from the government [100]. In Pakistan, fossil fuels account for the majority of the electricity supply [101]. The capacity to generate renewable energy from solar, biomass, hydropower and wind is larger in Pakistan. Pakistan did not take benefits from RERs due to lack of funds, low interest, corruption in country, lack of interest, lack of modern technology, ineffective utilization of sources and higher costs. Geothermal, wave energy and tidal resources are rich in Pakistan and can help the country solve its energy crisis. Still Pakistan have no master plan except China Pakistan Economic corridor plant to utilize its RERs in order to generate power. Insufficient power is generated in Pakistan from hydropower but it is needed to enhance it. Presently, the main sources in Pakistan are gas, oil and coal to generate power. These sources are polluting the environment badly. Recently in Pakistan had completed the following RERs projects: 1000MW Quaid-e-Azam Solar Park (Bahawalpur), 50 MW Hydro China Dawood Wind Farm, Gharo, Thatta, 100MW UEP Wind Farm, Jhimpir, Thatta, 100MW Three Gorges Second and Third Wind Power Project. The under construction projects of Pakistan are 884MW SukiKinari Hydropower Project, KP, 300MW Coal-Fired Power Project at Gwadar and 330MW HUBCO Tha lNovaThar Coal Power Project. Pakistan is considering the following projects:50MW Cacho Wind Power Project, 50MW Western Energy (Pvt.) Ltd, 1320 MW Thar Mine Mouth Oracle Power Plant & surface mine, 1124MW Kohala Hydropower Project, AJK, 700.7MW Azad Pattan Hydropower Project, AJK/Punjab and

Wind Power Project. Conventional source can't support the SAARC mega power system since there isn't enough of them to supply the rising demand for electricity.

G. NEPAL

Only approximately 280 MW of the nation's hydroelectricity potential—which is close to 83000 MW—has been achieved. Approximately 40% of the society has electricity availability in some form, although Only about 1.5% (613.5 MW) of the potential hydropower (32000 MW) has been produced.

H. SRI LANKA

Highest energy consumption in Sri Lanka for 2011 was 2163.1 MW. In order to meet that demand and Sri Lanka's need for electricity, 139 Grid-joined power plants with a combined generation capacity of 3140 MW were running in 2011. The Ceylon Electricity Board operated and owned 23 of power facilities, containing 16 hydro plants, 6 thermal plants, and 1 wind power plant.

I. FEASIBILITY OF SSGs BETWEEN SAARC REGIONS

Table 2 presents the feasibility of SAARC super smart grid for the utilization of high voltage transmission lines (HVAC). HVAC transmission lines can be utilized up to approximately 800 km distance between two countries. The direct HVAC connections of Pakistan are possible with India and Afghanistan. In addition, Pakistan can connect with other countries through India. For example, Pakistan can be connected with Nepal through India. More HVAC connections would be possible during the SAARC super grid evolution, because the distance between several countries is within the range of HVAC transmission. Some countries have common borders but the straight line distance between them is more than the HVAC range. In this case, HVAC transmission can be performed near borders. Hence, the utilization of HVAC transmission lines would be a major source of power flow management in SAARC super smart grid. In many cases, the utilization of HVAC seems infeasible. In these cases, HVDC transmission lines would be used.

V. LIMITATIONS OF THE EXISTING GRIDS AND NECESSITY OF A SSGs

The high-voltage grid in Europe is largely more than 50 years old. It was constructed in the 1970s and 1980s to connect lower voltage systems and act as a backup system to handle probable power plant breakdowns. It is based on a hierarchical, top-down flow and distribution of power flow. The electricity grid is still operated in the same way. Even if there are more clients and their demands have changed significantly over time, it has mostly remained the same. The transmission grid and connectivity to it have grown in significance because of the deregulation and liberalization of the electricity markets. Additionally, the grid's capacity limits are reached due to the quick increase of wind power in many locations with low load, which requires the construction of new power lines to connect the production sites to the load centers [102]. The demand for new connections will rise as offshore wind development is anticipated. The grid infrastructure is further strained by the changing trend of renewable energies. The growing trend of new power plants being constructed near pipelines or harbours rather than close to need centers puts additional strain on the grid. The existing transmission grid will not be adequate to meet future electricity needs due to the growing supply of renewable electricity, the spatial rearrangement of conventional power generation, and the anticipated rise in power demand.

VI. THE FUTURE POWER GRIDS

Whatever the circumstance—solving the issue of environmental change or preserving the availability of electricity—the grid has emerged as one of the essential requirements to meet both. There are two basic methods to renewable energy that are in contention:

1.) The extensive distribution of electricity
2.) Decentralized generation.

The Super Grid is the name given to the idea of distributing renewable electricity widely over very vast distances. The capacity for renewable electricity in Europe is considerable, perhaps even sufficient for an entirely renewable electrical supply, but it is highly unevenly distributed [103].

A vast expansion of an effective, wide distance electricity network in a broad supply system is a requirement for an electrical system entirely reliant on these sources. When viewed in a broader context, the wind and solar energy potential of the North African deserts' could easily supply all of the world's energy requirements. As a result, there may be plenty of low-hanging fruit for providing the rest of Europe with electricity as well. Power transmission over large distances, if necessary, from locations with favorable generation to those with high demand, is important for the broad supply of electricity. High voltage direct current (HVDC) lines are a form of transmission techniques that has been around for a long times. The Club of Rome's idea, which integrates the resources of North Africa (landscapes with enormous potential for renewable power), with the advantages of Europe, is one such Super Grid vision [104].

2.) A number of distributed generation (DG) facilities, such as low level wind turbines (WTs), fuels, gas turbines, fuel cells, micro turbines, photovoltaic (PV), methane digesters, etc., are the core of the decentralized system. Such Virtual Energy Plants or clusters are jointly managed by a central control unit that regulates the various power plants to govern the energy output from the cluster as a whole. The supply-controlled feed-in of wind, stochastic, and PV is successfully smoothed by the clustering of a variety of various renewable technologies, some of which should be technologies capable of producing electricity on-requirement like hydro or biomass power plants. This enables the control and maintenance of a steady level for the overall feed-in from the Virtual Power Plant. This method makes the cluster of renewable power plants as stable and controlled as a traditional thermal

TABLE 2. Straight line distance and common borders for SAARC countries.

	Distance (km)	**Common border**	**Possibility of feasible HVAC interconnections**
Afghanistan and Bangladesh	2380	No	No
Afghanistan and Bhutan	2103	No	No
Afghanistan and India	**1007**	**No**	**Yes (through Pakistan)**
Afghanistan and Maldives	3406	No	No
Afghanistan and Nepal	1710	No	No
Afghanistan and Pakistan	**369**	**Yes**	**Yes**
Afghanistan and Sri Lanka	3262	No	No
Bangladesh and Bhutan	**426**	**No**	**Yes**
Bangladesh and India	**1222**	**Yes**	**Yes**
Bangladesh and Maldives	2829	No	No
Bangladesh and Nepal	**676**	**No**	**Yes**
Bangladesh and Pakistan	2020	No	No
Bangladesh and Sri Lanka	2178	No	No
Bhutan and India	**1396**	**Yes**	**Yes**
Bhutan and Maldives	3110	No	No
Bhutan and Nepal	**433**	**No**	**Yes**
Bhutan and Pakistan	1734	No	No
Bhutan and Sri Lanka	2511	No	No
India and Maldives	2743	**No**	**No**
India and Nepal	**801**	**Yes**	**Yes**
India and Pakistan	**693**	**Yes**	**Yes**
India and Sri Lanka	**1428**	**Yes**	**Yes**
Maldives and Nepal	2902	No	No
Maldives and Pakistan	3287	No	No
Maldives and Sri Lanka	**770**	**No**	**Yes**
Nepal and Pakistan	**1347**	**No**	**Yes (through India)**
Nepal and Sri Lanka	**2382**	**No**	**No**
Pakistan and Sri Lanka	**3063**	**No**	**No**

power station. In order to connect with supply side loads that provide a range of options to improve the system load and the output more reliable, and modify the output to the demand correspondingly, the Smart Grid is provided with ICT-based optimization technologies. Since smart technologies allow for regulated flow management and switching, trigger able, and planned feed-in, they would permit a vastly greater share of renewable, fluctuating electricity in the system. A 100% renewable power generation will not be attainable without a significant upgrading to the current system and the adoption of Smart technology.

VII. SUPER SMART GRIDS

Many people believe that the small-scale decentralized Smart Grid and the large-scale centralized Super Grid are mutually exclusive. To assure a shift to a decarbonized system, we contend that the two ideas are compatible and may and must coexist. A Super Smart Grid is consequently necessary. The capability to handle both irregular supply and loads and the infrastructure to supply power generated from renewable sources from a number of large and small generation sites dispersed over broad areas. As the system's share of intermittent energy rises, the ideas of power storage and power management will be given more and more weight. The Super Smart Grid would make it possible to run Swiss pump storage plants with North African solar power, but it is challenging to store electricity directly. Pump storage hydro power plants are a convenient way to store energy. More crucially, the Smart Grid enhances another advantage of the Super Grid concept: the stochastic smoothing of feed-in of the supply-controlled wind and solar energy. It allows for the rerouting and control of power flow, as well as the focused grid management utilizing stochastic smoothing. Since the wind usually blows somewhere in a very big system, the feed-in peaks and valleys in the regional grid sections would be filled and the system's stability would be improved, necessitating less backup power or energy storage.

VIII. ALGORITHMS FOR POWER FLOW CONTROL IN FUTURISTIC SSGs

In the research, a number of strategies for improving power flow control balance are described. To increase the stability of the power system brought on by the presence of three-phase line-to-ground faults, it uses a genetic algorithm (GA), particle swarm optimization, current limiting methods, and adaptive input-output feedback linearization control (AIFLC). In [105] the stability is improved by employing a UPFC and the PS methods for a single interval three-phase problem. BY implementing different control schemes, as stated in [106], and [107], Instability caused by power system transients was examined in depth. A stability evaluation for less sever faults in the transmission system without FACTS controllers and with FACTS controllers is presented to explain the impact of less sever faults on wind turbine efficiency. The FACTS controller transient rating is underlined in [106] for the purpose of alleviating power balancing issues. Another viewpoint is to analyze several kind of oscillations brought on by the presence of a three-phase line-to-ground fault in a single cycle and to make a UPFC compensation for them. Similar to this, [107] describe utilizing a basic genetic algorithm (GA) to optimize a UPFC controller's to outputs in order to address transitory stability issues in the context of less severe problems. Additionally, a strategy called adaptive input-output feedback linearization control (AIFLC) using a STPF was proposed in [108] to suppress oscillations at earlier stage in multi-machine power generating systems by utilizing UPFC. A particular swarm optimization method based on the controller of the UPFC by adjusting its output feedback of it was utilized to examine the same problem of damping oscillations of lower frequency using a six-cycle fault. For the purpose of using FACTS devices to mitigate power quality issues, several tactics were applied to SGs by introducing minute delays brought on by faults. Probabilistic modeling can increase precision and decrease future power system instability brought on by various type of failure. The recommended method also makes it possible for the researcher to choose the optimal UPFC configuration in a synchronized network and a better control mode for various generating resources when a severe failure occurs in power system networks.

IX. POSSIBILITIES AND SYNERGIES OF A NORTH SEA OFFSHORE EUROPEAN SUPER SMART GRIDS

In the near future, there is a considerable potential for the growth of wind power, according to several scenarios produced in recent years. According to capacity projections for 2030, which were originally derived from the Trading Wind project [109], 94.6 GW of installed wind generating capacity in the North Sea by that year may be feasible. The entire capacity is split between Denmark (5.6 GW), Belgium (3.0 GW), Germany (25.4 GW), the Netherlands (12.0 GW), United Kingdom (43.3 MW), and Norway (5.4 MW). New balance and transmission capacity are required to fully use the North Sea's enormous potential. It would be a significant and costly undertaking to build the necessary long-term storage space the northern European grid will require over time. Researchers are investigating considering Norway's hydro power as a logical first step in balancing out fluctuating renewable sources. According to the CEDREN Hydraulic Balance initiative, southern Norway has at least 20GW of potential balance capacity [110]. A significant percentage of the renewable potential could be unlocked by using this resource in cooperation with nearby nations. Such a system may be the most affordable large-scale option currently available and cost-effective [109].There are many estimates of how much non - fossil capacity may be introduced, based on how this huge dispatch able source is utilized in the electricity grid. On days when there is no wind or sun, water power generation can be used to fill the gap and balance in the load and the production. According to an International Energy Agency (IEA) analysis, Europe will require around 100 GW of additional dispatchable power between 2016 and 2035 in order to maintain grid stability and accommodate the 250 GW growth in renewable capacity [111]. Therefore, a fifth of this capacity demand or requirement might be met by hydropower. However, only a small portion of the year is when there is a minimum generation of renewable energy. For the remaining period of time, hydropower might use its high level of flexibility as a backup to balance out anomalies in wind production brought on by inaccurate forecasts. Numerous elements, which won't be discussed in this article, affect forecasting error. Considering on forecasting inaccuracy and grid dependability level, studies show that the 20GW hydro capacity might fulfil the reserve needs for 60–250GW of new wind power [112], [113].The report's main scenario considers an expansion of 11.2 GW overall, of which 5.2 GW is newly pumped hydro energy and 6.0 GW is updated hydro capacity, out of the 20 GW extra capacity. Upgrading both current and new construction sites could bring the overall energy to 20GW.

The desire and interest in employing Norway as a stabilizing energy in the Northern Sea area is demonstrated by a study of various Norwegian stakeholders. However, the absence of a government policy and necessary legislation drew worry. The perceived risk is too great to begin planning and developing export balance energy for potential offshore grid situations in the absence of a national policy [109]. Wide grid developments are being proposed as a result of the anticipated rise in renewable energy in the European region. The Eurelectric, European Climate Foundation (ECF), and European Network of Transmission System Operators for Electricity (ENTSO-E) have all published reports on grid expansion [109]. The within country connections are given special consideration. An estimated 10,500 km of new HVDC inland or underwater cables will be installed for the pan-European region, according to the ENTSO-E 10-year development plan. A 23 billion euro market is represented by submarine cables. The North Sea offshore grid ''is likely to be beneficial in the long-term,'' it is further claimed. Still, funding for this kind of endeavor needs to be secured. Infrastructure initiative of this size are often at least partially co-financed by states.

X. ACCESS TO OFFSHORE NETWORK ELEMENTS IN EUROPEAN SUPER SMART GRIDS

A. CONVERTERS AND TRANSMISSION

HVAC cables are subject to very strict distance restrictions because of their ingrained features about reactive power usage. HVAC is therefore inappropriate for widespread application in offshore systems. The difficulties associated with long-distance transmission can be overcome through HVDC. HVDC is the most appealing choice in terms of expenditure and maintenance costs for offshore uses where distances are great. In actuality, the budget and conductivity losses of the cable are the only factors limiting HVDC transmission distance. Although energy losses in the DC units are larger than for comparable AC systems, HVDC provides reduced transmission losses. The fact that HVDC offers complete power flow management is a significant benefit [114]. The current source converter (CSC) and the voltage source converter are two main converter concepts for HVDC systems (VSC).A CSC technique ideal for the transport of large electricity is the line commutated converter (LCC). Its dependability and accessibility have been proven over a long period of time on installations on ground [115]. The LLC, however, has some limitations, including significant filtering requirements, an expanded footprint, and operating concerns [116]. Regarding these difficulties, the VSC has an edge over the CSC. Because of this, VSC technology is frequently chosen as the best option for an offshore infrastructure [117]. It is still unclear whether the offshore network of the future will use more than one converter technique or if both will coexist. Two-phase VSC, three-phase VSC, and modular multilevel VSC (MMC) are the three primary designs of VSC that can be categorized [118], [119].With regard to high-energy and greater voltages applications, the MMC is the latest current HVDC option and in some ways the most advanced design. The MMC lowers harmonic content and energy losses in the current and voltage waveforms [120]. Over years, extensive research has been done on the control schemes for LLC and VSC converters. A summary of LLC supervision may be provided in [121], as well as further study can be obtained in [122]. The most popular technique for VSC management is vector control. VSC vector control and HVDC system-related data can be discovered in [123] and [124]. A relatively new field of research, the regulation of the MMC converter is still being improved. However, it can be said that an MMC's high level control functions similarly to the VSC and substantially in the same way. An ENTSO-E study created by the NSCOGI (North Seas Countries' Offshore Grid Initiative) contains examples of completed HVDC installations, cost assessment data, and more details about offshore distribution technology [125].

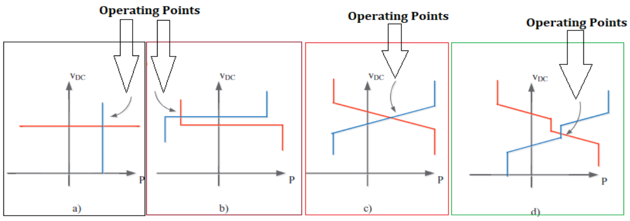

FIGURE 5. P-V characteristics of voltage and power control methods for multi terminal DC grids. a) master/slave mode b) voltage margin control c) DC droop control d) dead-band droop control (Figure original resource R. E. Torres-Olguin.et al. [128]).

B. CONTROL SYSTEM FOR MULTI TERMINAL HVDC (MT-HVDC) SYSTEMS

The interaction between voltage regulation and power balancing remains one of the most crucial concerns in the functioning of the MT-HVDC system [126]. The power converters completely regulate the power flows in DC grids. Each line's delivered power, however, cannot be directly managed; instead, the voltage at the nodes controls it. As a result, a DC grid may experience congestion. Opportunities for energy balancing across various converters are made possible by the accurate and systematic management of node voltages. The literature has examined a number of power balancing and voltage management techniques. The two basic approaches to control are centralized and distributed. Primary-secondary management and voltage-margin management, two examples of centralized control (figures. 5a and 5b), are thought to be simple to implement. The master node, sometimes referred to as the slack bus, is in charge of preserving the DC voltage at its own node in primary-secondary management. The other nodes function as nodes with continuous power.

The master node should be enlarged to secure operation inside the converter's technical constraints. Additionally, the master node or quick communication between nodes

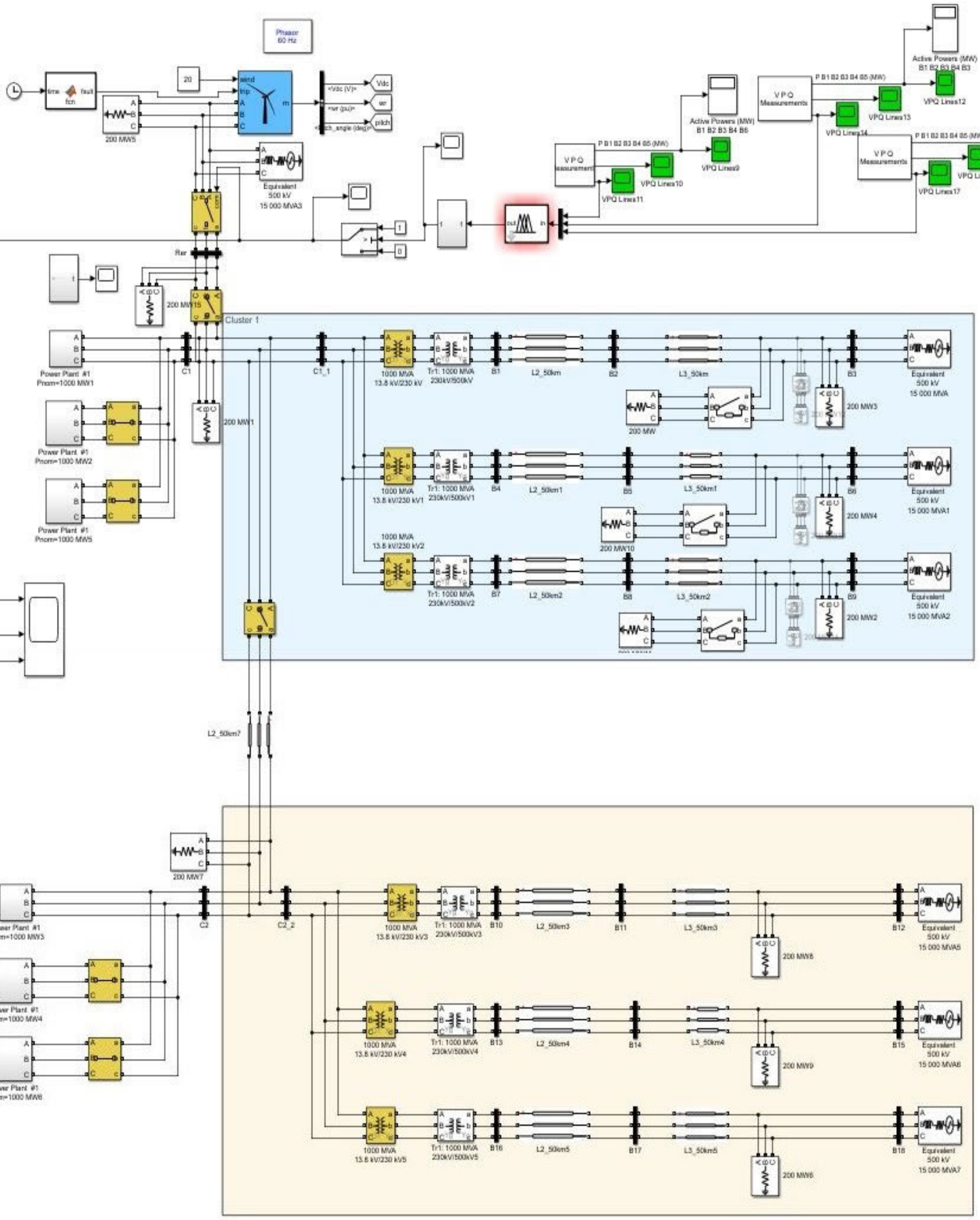

FIGURE 6. Schematic representation of proposed method.

has a significant impact on the system's dependability. A weak system is the end result. The majority of these characteristics apply to voltage regulation as well. As a result, dependability and oversizing suffer as a result of the simple installation of centralized systems [124], [127]. Every terminal is given a straight interaction between its DC power and the energy flowing into its terminals for the distributed voltage regulation theory in an MTDC system (figure 4c&d). Droop control is the more common name for this. In this approach, the terminals are responsible for both regulating the system voltage and balancing the electrical grid's immediate load. Furthermore, by adjusting the corresponding droop parameters offset of the translators, the power transmission for each individual line may be managed [128]. Furthermore, because the monitoring is dependent on local observations in this architecture, there is no a need for quick node-to-node communication. In conclusion, relative to a centralized control system, distributed control offers improved system

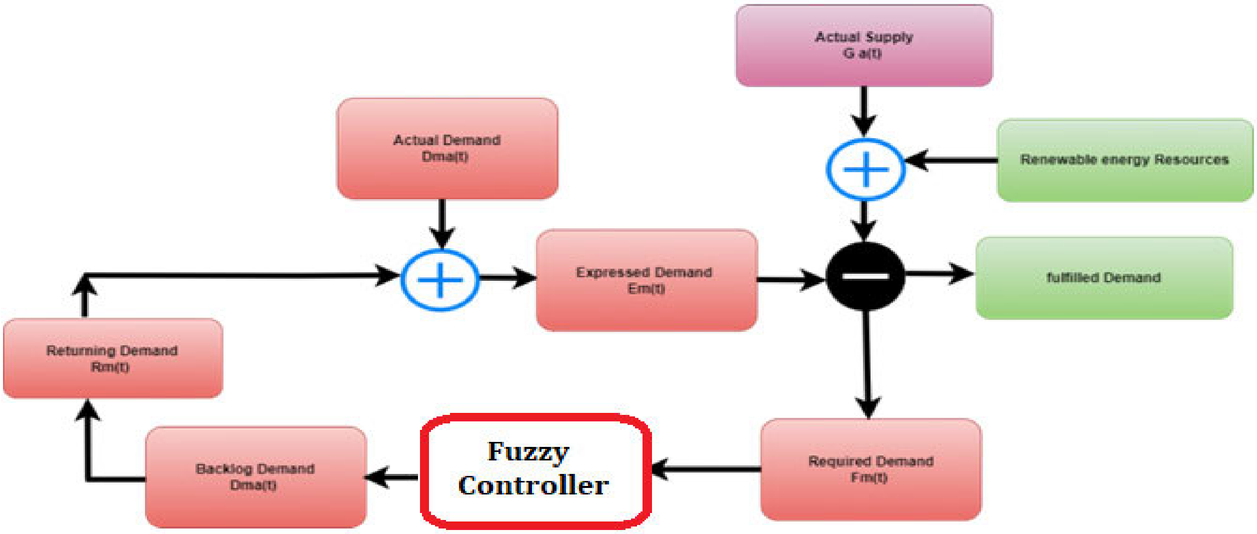

FIGURE 7. Fuzzy incorporation in the closed loop control system's block diagram.

reliability while still being able to govern the flow of electricity. Fig. 5 displays PV features for each of the aforementioned voltage and power controls, as well as a modified droop control.

C. PROTECTION SYSTEM

Protections for DC power systems are continuously being developed. Furthermore, because VSCs are susceptible to DC faults, using them in offshore grids provides a problem. This is because they have built-in antiparallel diodes. Undoubtedly, the main barriers to use of DC grids is the protection system [129].Due to the greater difficult protection system needs than AC, a separate protection scheme must be established for DC grids. Since Transmission system lines have very low series impedances and can't properly control the rise time of the fault conditions, the response must be quicker. Since the DC voltage lowers on all of the transmission lines, not just the one with the problem, in MT-DC systems, the security requires a high selectivity. Low series impedances in DC grids prevent them from controlling the rise time of the DC current during voltage collapse. There are over-currents of same values present inside the MT-DC system, making it challenging to determine which protection unit needs to be activated if the fault is near to any of the converters. Methods for locating faults should ideally be based on local observations [130].Therefore, the safety system should be able to detect and separate only the defective DC line. However, AC system-specific detection techniques might not be appropriate for DC grids. High-voltage DC breakers are the focus of the majority of research in DC protection. Due to the strict criteria, developing DC breakers has been quite difficult. The breaker has to be capable of immediately interrupt the flow of current, produce a zero-crossing, release a lot of power, and survive the system's voltage response after the breakdown. Resonant-based, solid-state-based, and the newly released hybrid DC breaker are the three different types of DC breakers [131], [132], [133], [134], [135].The hybrid breaker outperforms the other two in terms of performance.

D. CABLES

Currently, there are three primary kinds of DC cables on the market: extruded insulation cables (XLPE), mass-impregnated cables (MI), and self-contained fluid filled cables (SCFF). The most appealing option is the extruded wires that use cross-linked polyethylene as an insulator. XPLE cables do not require an oily duct system, are lightweight, and have a reduced banding radius. Up to ±320 kV and 900 MW, XPLE cables are offered [136]. XPLE cables are typically employed for HVDC powered by VSC. It is suggested that XPLE cables up to ±400 kV and 1500 MW be used in the Cigre model. In the warmer months of 2014, a newly developed HVDC transmission system using XLPE cables that could operate at up to 525kV and 2600MW of power level was introduced [137].Meanwhile, the North Sea Offshore System may include HVDC base on LCC that cannot be connected with XPLE cables in the future. Therefore, SCFF cables as well as MI cables need to be taken into account. Commercial SCFF cables are offered up to 600 kV [138]. There are MI cables that can handle 1000 MW and 500 kV.

E. DC TRANSFORMERS

The offshore DC system is anticipated to develop naturally over time, much like the AC grid. DC converters must be built in order to accommodate various DC voltages operating on the offshore grid. The designs of DC-DC converters can be functionally divided into two categories: non-isolated and isolated, with the isolated design being the most significant for an HVDC system [139], [140].

DC-DC Control systems for high voltage applications are not widely available as standard devices on the market. Several models have been described in the literature with power ratings ranging from tens of kW to a few MW and an AC bandwidth in the kHz range utilizing a variety of designs [139], [141], [142], [143], [144], [145].

F. OFFSHORE PLATFORMS

Offshore platforms are needed to accommodate offshore HVDC adapters and related equipment. On to an offshore platform, HVDC equipment is rarely used. For example, Borwin Alpha, the world's largest inaugural HVDC station placed on an offshore platform, and Troll-A, a gas and drilling platform. The offshore wind sector is setting the bar for construction, set-up, and upkeep. The offshore wind sector is predicted to create the required solutions for upcoming offshore platforms for the North Sea offshore system.

G. OFFSHORE ENERGY STORAGE

Despite being a significant boost to the Northern European grid, balance energy from central Norway cannot meet all of the demand. The North Sea offshore system may benefit greatly from options for offshore storage. Onshore energy storage and air compressor projects have historically had lengthy lead times because of slow public acceptance and/or drawn-out regulatory procedures (e.g. environmental impact studies). On these topics, offshore services are anticipated to perform better than their onshore counterparts. The offshore system in the North Sea will consist of a massive system with linked devices wind farms linked to various zones. Clearly large-scale storage must be the emphasis of such a system. The value of the system will, however, set a temporal limit on the amount of storage. While hydroelectric projects typically offer storage for shorter time periods, hydro power may give up to seasonal storage. Huge energy storage requires technology that can deliver high power for an extended period of time at a reasonable cost. Compressed air energy storage (CAES) and hydroelectric storage are the two technologies that are now available that are adequate [146]. The average system capabilities and storage capacities are a magnitude of less than those of the above stated storage systems with much higher capital costs [147], even if some developing battery techniques may offer power balance functions as well. The enormous amount of energy that must be stored in order to convert inefficient discontinuous wind resources into a continuously available power source is the most significant necessity for offshore power storage. CAES systems might be installed offshore and their storage reservoirs could be subsurface formations, subaquatic tanks, or even exhausted oil reservoirs. Similar to how the oil sector does it now, the turbine house might be built over sea level and connected to the subsea well by a riser system. The position of the turbine housing at water level would simplify repair. According to one source, CAES may already be cost-competitive with hydro storage [147].Encouraging CAES information is that a Canadian business is already operating the first underwater CAES prototype south of Toronto since the summer of 2014. Additionally, a contract to deliver the marketed product to the Aruba grid operator already exists. As a result, CAES is currently the most developed offshore storage technique. There are several ideas for locating offshore pumped hydro storage. The energy island, an offshore pumped storage facility in shallow waters, was a proposal that DNV GL published in 2007.SubHydro as well as MIT has both created proposals for the placement of sizable tanks with turbines for pumped storage on the ocean floor [148], [149]. The turbines generate power by allowing water into the reservoirs, and power storing by pushing water out, whether or not the tanks are vented. Current PHS typically outperforms CAES solutions with a round-trip performance of above 80%. However, in order to evaluate these principles, larger models are required. More study on offshore storage is desperately needed, especially at the system level. The best grid arrangement for the North Sea grid has been the subject of recent studies. These analyses, however, did not consider the appropriate installation of offshore storage technologies. Because of this, the location, size, control method, and capacity requirements of storage are still unknown. The implementation of offshore storage technologies can be seen as competing with onshore storage options or adaptable production capacities in future situations. Therefore, installation will only take place if offshore storage offers a better return on investment than the alternatives. Offshoring frequently entails higher costs, but if the demand for storage increases in the future, incentives or regulations can favor offshore storage alternatives. For instance, a shortage of viable onshore locations may compel ventures offshore.

XI. EUROPEAN MODELS AND SIMULATION SETUP

The complete structure of the pan-European power network is the basis for the structure of the European electricity market that is discussed in this article. The transmission model is based on an earlier idea presented in [150] and [151], which has since been verified, enlarged, and upgraded to incorporate more accurate depictions of the Nordic nations, Ireland, and the UK. The five subsections that represent this section are

(i) European transmission network model,
(ii) European market model,
(iii) market clearing assumption,
(iv) projection of the market dispatch on the transmission model and
(v) The case studies.

A. EUROPEAN TRANSMISSION NETWORK MODEL

The network simulation from [151] provides a framework for the transmission model provided in this study. Originally, the model included more than 27000 transmission assets (AC, DC wires and 2-3 winding transformers)and over 21000 buses (at three voltage phases: 132-150, 220, and 380-400 kV).To correspond for the grid upgrades anticipated by

2030, a selection of grid reinforcement initiatives and new electrical transmission from the e-Highway2050 Initiative [152],the Projects of Common Interest (PCI) and the 2020 Ten-Year Network Development Project (TYNDP) by [153] were added. The result obtained was simplified to just include the 220 and 380/400 kV levels in [150] to increase the functionality of the database. In order to account for the forecasts for 2030 stated by [154] in their 2022 TYNDP, the actual generator and load data have been modified. The appropriate transmission substation's load and RES supply at the distribution system have been combined and modified according to forecasts for 2030. From [155], the grid system of the Nordic nations was derived from Sweden, Denmark, Finland and Norway. The grid now included the new transmission system and grid reinforcements stated in [153]. As a result of data of coal based projects in Denmark [156] and Finland [157] as well as the closure of nuclear power reactors in Sweden [158], source data has also been adjusted in accordance with [154]. Based on the 2022 TYNDP, load demand and RES coverage have been modified [154]. Public access was accessible to the transmission system data for the United Kingdom and Ireland [159], [160]. The Irish Distribution Statement gives specific information on the distribution, production, and utilization changes anticipated for 2027.Data on generators for the UK has been adapted in accordance with the UK Energy Policy [162] and obtained from [161]. Usage and RES penetration were also modified for Ireland and the UK depending on the TYNDP for 2022 [154]. We do feasibility analysis for substantial wind energy facilities in the North Sea region using this model, which incorporates power islands in the North Sea.

B. EUROPEAN ELECTRICITY MARKET MODEL

A zoned cost system was used for energy in Europe; regardless of their precise locations, customers and suppliers inside the similar rate region, or bidding region, get the similar cost of energy. A country's location was typically used to identify a bidding zone. To represent intro-network restrictions, states can be subdivided into further bidding zones, as in the cases of Denmark, Italy, Norway, Sweden, and the United Kingdom. In order to achieve a suitable model of the European power market, all the nodes relating to one bidding zone have been combined into a single node, which symbolizes the zone. Norway was already separated into the Northern, Middle, and Southern (NO-N, NOM, NO-S), where NO-S correlates to NO1, NO2, and NO5, NO-M to NO3, and NO-N to NO4. This division follows the methodology used by [154]. Instead, the Single Energy Market is a combination of Northern Ireland and Ireland [163]. North Sea Power Islands were taken into account as a new offshore bidding region when they were incorporated into the model. Additionally, similar inter connectors within bidding zones incorporated the transmission network into the market model. These lines' capabilities were determined using reliability and security standards, and TSOs frequently cut back on existing transmission capacity to maintain a specific Transmission Reliability Margin (TRM).The anticipated capabilities for exchange markets in 2030 were extrapolated from [154], which bases predictions for the year on new transmission projects. Currently, implicit and explicit transmission capacity auctioning were the two approaches used by European TSOs to couple various market zones [164]. Transmission power and electricity were traded independently in two distinct markets with explicit auctions. Contrarily, with implicit auctions, various market regions were implicitly coupled, and the energy exchanges were what cause the flows on the inter-connectors. Although explicit auctioning was the most straightforward way for managing transmission capability on interconnections, it may lead to wasteful use of transmission capacity, which was why TSOs were gradually switching to implicit auctioning [165]. In this model, they took into account that all states were connected by a single market clear mechanism with implicit auctioning in order to account for this development.

C. MARKET-CLEARING ASSUMPTIONS

For the day market clearance, the market approach that was described in above section was adopted. The models did not take into account ancillary services, intraday trading, or electricity market regulation. Economic dispatch considering transmission grid restrictions was how the day-ahead market clearing challenge was put forth. The goal was to increase social welfare, which was defined as the total of consumer and producer surplus. The transmission model's load was thought to be inelastic, and the big value of loss load (VOLL) was set at 3000 EUR/MWh. With such a linear utility function that varies with the overall inelastic demand, or the gradient of the line joining 3000 EUR/MWh to 0 EUR/MWh in a band equivalent to 10% of the quantity demanded, an extra 20% of demand was deemed sensitive to the clearing price. According to [166], linear coefficients were used to represent generating cost functions. These coefficients were scaled up to take into account the most recent estimates of CO_2related costs from the TYNDP for 2022 [154]. (The Joint Research Centre (JRC)'s coefficients have put the price of CO_2 at 70 euros per ton [167]. They took into account a market having perfectly competitive market, in which every generator acts honestly and makes bids that accurately represented their marginal production costs. They did not take into account government subsidies, thus RES can compete in market bidding at no marginal cost. Only the highest production or demand capabilities of the industry participants were incorporated as restrictions in the formulation. The model did not take into account any technical restrictions like ramping restrictions, minimal durations for being online and offline, or starting and shut-down costs. PTDF uses a linear load flow model to calculate exchanges within bidding zones. The model does not take transmission losses into account. Every moment in a window of time that corresponds to one year in each simulation results in the market being cleared. Demand, wind, and solar profile data was found in [168]. When year-round water availability restrictions were taken into account for pumped storage hydropower plants in Continental Europe, it was found that these plants operate often during peak times.

D. PROJECTION OF THE MARKET DISPATCH ON THE GRID MODEL

The dispatching of generators, RES, and loads was predicted on the mode after the market has been cleared to ensure its feasibility. It is possible to think of this forecast as market-based re-dispatching, when plants were up- and down-regulated to address internal congestion's. However, as no reserves were obtained prior to the scheduled market clearance, this was more of a viability check than a market survey. These units can be changed to handle with congestion's. Units were redistributed using the merit order contour, and the cost of redistribution were assumed to be equal to the absolute values of difference between the day-ahead price and the marginal expenses of generators. When necessary, wind restriction and load shedding were also taken into account.

E. DEFINITION OF CASE-STUDIES

Four separate research findings have been produced with an emphasis on various criteria, such as the length of the island, the operational transmission capacity, and the linked states, in order to evaluate the influence of North Sea Energy Islands on the European power market. Five nations surrounding the North Sea were included in these cases: Denmark, Germany, the Netherlands, Belgium, and the United Kingdom. All of the simulations were described and run for a year-long period of time.

F. REFERENCE CASE: NO HUB

The model was then run without any of the NESH for comparison's sake. The instance in question was referred as ''No Hub.'' In the results and discussion, mostly results were presented as the difference with this case.

G. 10 GW AND 20 GW ISLANDS

The hub's dimensions were determined by the installed wind generation. 10 GW and 20 GW were two different sizes that were simulated. In the 10 GW scenario, one island was constructed in the North Sea, and six HVDC cables connect it to Belgium, Denmark, the Netherlands, Germany, and Denmark (DK1).Each connection has a 1700 MW conversion efficiency, with two links each in the Netherlands and Germany. The second island in the 20 GW scenario is identical to the first, with 10 GW of installed wind capacity, and six HVDC links with 1700 MW of transfer capacity. However, the connecting sites to the onshore systems have been adjusted.

H. MORE TRANSMISSION CAPACITY FOR EXCHANGES

This research study (''Exchanges'') examined the effects of increasing this transmission capacity for permitting additional exchanges through the hub because the building of the hub necessitates a specific amount of capacity. The only difference between this instance and the ''10 GW'' case was that the maximum transmission capacity was now 15 GW (instead of 10 GW). Denmark, Germany, and Belgium each have a 2.5 GW transfer capacity from the hub, and the Germany and Netherlands have a 5 GW transfer capacity (for each country).

I. CONNECTION TO THE UK

This research study (''UK'') intends to examine how the equilibrium of the NSEH-connected states might change in the event of a new interconnection, in this example to the UK. Similar to the prior instance, just one island is powered by 10 GW of wind energy. Five countries now share the 10 GW of transmission capacity. While Denmark, the UK and Belgium each have 1.45 GW of transmission capacity, Netherlands and Germany each have 2.9 GW.

XII. PROPOSED METHODOLOGY

We have modeled an eighteen bus network comprising of two clusters which represents two countries in the MATLAB Simulink environment. Three different cases have been developed to provide optimal control strategies for short term load forecasting in super smart grids. The proposed model is shown in Fig. 6.

XIII. MATHEMATICAL MODELING

In order to overcome the issues with power flow control management reliability in SSGs, stochastic modeling incorporating the fuzzy controller is suggested, based on how often a fault occurs. Figure 7. Shows a block diagram of a closed-loop controller design model for SSG modelling. The block diagram illustrates when problems occur, the generation and load profiles are vulnerable to change. The problems happen because the RERS are infrequent in nature. Utilizing the fuzzy based control network, the backlogged demand is managed.

In the event of multiple-interval failures, the desired demand can be written as backlog demand, together incorporating fuzzy for protection of system against voltage transients. The RER is at risk of overloading as a result of the faults, and the fuzzy controller will act as an equipment to control the movement of energy. It can be concluded that generation, demand, and supply all affect the power system.

Through various interval symmetric or asymmetric faults in RIPGs, the resilience of the power system is evaluated in order to locate the important nodes at earliest. This is accomplished by locating the Sm sensitivity matrix represented by Eq. 1b. This technique allows for the stability margins of a power system that departs from its typical boundary conditions due to the occurrence of several interval symmetrical or asymmetrical faults.

A. CRITICAL NODE ASSESSMENT IN SSGs POWER INFRASTRUCTURE

1) VULNERABILITY ASSESSMENT

Evaluation of the nodes that significantly affect the stability of a particular generator is suggested using Eq. 1a.

$$IMP_{inj} \geq \frac{-IMP_{th} \sin \varphi_{inj}}{\sin \varphi_{th}} \tag{1a}$$

When asymmetrical faults develop, the rotor angle will vary if the condition in Eq. 1 is not satisfied.

$$Sm_{inj} = \frac{\partial \frac{Zm_{th}}{\sin \varphi_{th}}}{\partial Y_{m,m}} \frac{\partial K_{th_k}}{\partial Y_{m,m}} \tag{1b}$$

K= Generator
m= load nodes

Generators are represented by index K, while load nodes are represented by index m. It has been suggested to use such vulnerability analysis to find important nodes that affect the generator stability margins.

2) GRAPHICAL ANALYSIS USING PROPAGATION CONCEPT

The probabilistic model called closed loop control can be put in after the important nodes have been identified using a sensitivity matrix as described in Eq. 1b.

B. PROBABILISTIC MODELING TO ACHIEVE POWER FLOW CONTROL STABILITY IN SSGs

Optimal demand and response balance is to be found using a probabilistic model of spinning reserves.

Gm (t) = generation
Dm (t) = demand
rm (t) = reserve required
rm_o = how much reserve to be supplied
Fm (t) = frustrated demand
$Dm^a(t)$ = actual demand
$Gm^f\ (t)$ = Forecasted generation
λ m = delay caused due to system transients

In order to overcome failed outages in Cluster 1 by providing an optimal load flow across the various RERs of Two clusters, it is necessary to have a regulated load distribution between the generator and the demand condition indicated in eq. 1. Condition for system stability

$$Dm^a\ (t) = Dm^f\ (t) \tag{1}$$

To balance demand and supply we inject spinning reserves:

$$Gm^f\ (t) = Dm^f\ (t) + rm_o(2) \tag{2}$$

But system have randomness due to various issues

$$Dm^a\ (t)\ = Dm^f\ (t) + Rm_D\ (t)$$

$$Dm^a\ (t) = \left\{ \left[Dm^f\ (t) \times \frac{1}{n_1} \sum_{i_1=1}^{n_1} \left(\lambda m_{i_1} \right) \right] + Rm_D\ (t) \right\} \tag{2.1}$$

In a similar manner, there must have been a shift in $D^a\ (t)$ regarding the network's sensitivity matrix SK, thevinin impedance, and the generator's injecting impedance *as* formulated in above Eqs. 1 and 2.

$$Dm^a(t) = \left\{ \left[Dm^f\ (t) \times \frac{1}{n_1} \sum_{i_1=1}^{n_1} \left(\lambda m_{i_1} \right) \right] \times \left[IMPm_{inj} \times Sm_{inj} \right] + Rm_{D_i}\ (t) \right\}. \tag{3}$$

average delay cause due to tripping

$$Amd = \lambda m_1 \tag{4}$$

$$\mathrm{Am_d} = \frac{1}{\mathrm{n_1}} \sum_{\mathrm{i_1=i_2=1}}^{\mathrm{n_1}} \left(\lambda_{\mathrm{i_1}} \right) \tag{5}$$

$$\mathrm{Dm^a\ (t) = Dm^f\ (t) + Rm_D\ (t)} \tag{6}$$

$$\mathrm{Dm^a\ (t)} = \left\{ \left[\mathrm{Dm^f\ (t)} \times \frac{1}{\mathrm{n_1}} \sum_{\mathrm{i_1=1}}^{\mathrm{n_1}} \left(\lambda_{\mathrm{i_1}} \right) \right] + \mathrm{Rm_D\ (t)} \right\} \tag{7}$$

Formulating eq. 1 & 2 within equation. 7, results are represented as,

$$\mathrm{Dm^a(t)} = \left\{ \left[\mathrm{Dm^f\ (t)} \times \tfrac{1}{\mathrm{n_1}} \sum_{\mathrm{i_1=1}}^{\mathrm{n_1}} \left(\lambda m_{\mathrm{i_1}} \right) \right] \times \left[\mathrm{imp_{inj}} \times \mathrm{S_{inj}} \right] + \mathrm{Rm_{D_i}\ (t)} \right\}. \tag{8}$$

$Rm_D(t)$ = Indicates the variation at random between $Dm^a(t)$ and $Dm^f(t)$, and it may be determined using a probabilistic auto-correlation model.

$$Rm_D(t) = E\left[Dm^a(t) Dm^f(t) \right] \tag{9}$$

When, $Dm^a(t) \quad \rightarrow \quad Dm^f(t)$, the random divergence $Rm_D(t) \rightarrow 0$, that attain a simultaneous stability.

$$Gm^f\ (t) = Gm^f\ (t) = Dm^{\mathrm{f}}(t) \tag{10}$$

The actual supply $Gm^a\ (t)$is regarded as being synchronized with the prior supply Gm(t-1) and as well as the addition of some randomness $Rm^G\ (t)$ for describing generation output graph in actual time, as shown in eq. 11.

$$Fm^a\ (t) = Gm\ (t-1) + Gm^f\ (t) + Rm^G\ (t)\,, \tag{11}$$

While Gm(t-1) stands for the input parameters that, restore the closed loop energy system network immediately to the prior time slot in so that power flow balancing between consumption and response patterns.

In order to offer an optimal $Gm^a\ (t)$, Gm (t-1) is adjusted utilizing the fuzzy integrated smart transmission network, as illustrated in Fig. 7.

By incorporating and describing in terms of risk score and relay-based probability - based modelling, it could be re-expressed in a more extended way, and it may be rephrased as follows in a more generic way:

$$Gm^a(t) = \sum\nolimits_{l=1}^{n} \left\{ \left[G_1(t-1) \times \frac{1}{n_1} \sum\nolimits_{i_1=1}^{n_1} \left(\lambda_{i_1} \right) \right] + \left[G_l^f(t) \times \frac{1}{n_1} \sum\nolimits_{i_1=1}^{n_1} \left(\lambda_{i_1} \right) \right] \times \left[IMP_{inj} \times\ S_{inj} \right] + R_{G_i}(t) \right\} \tag{12}$$

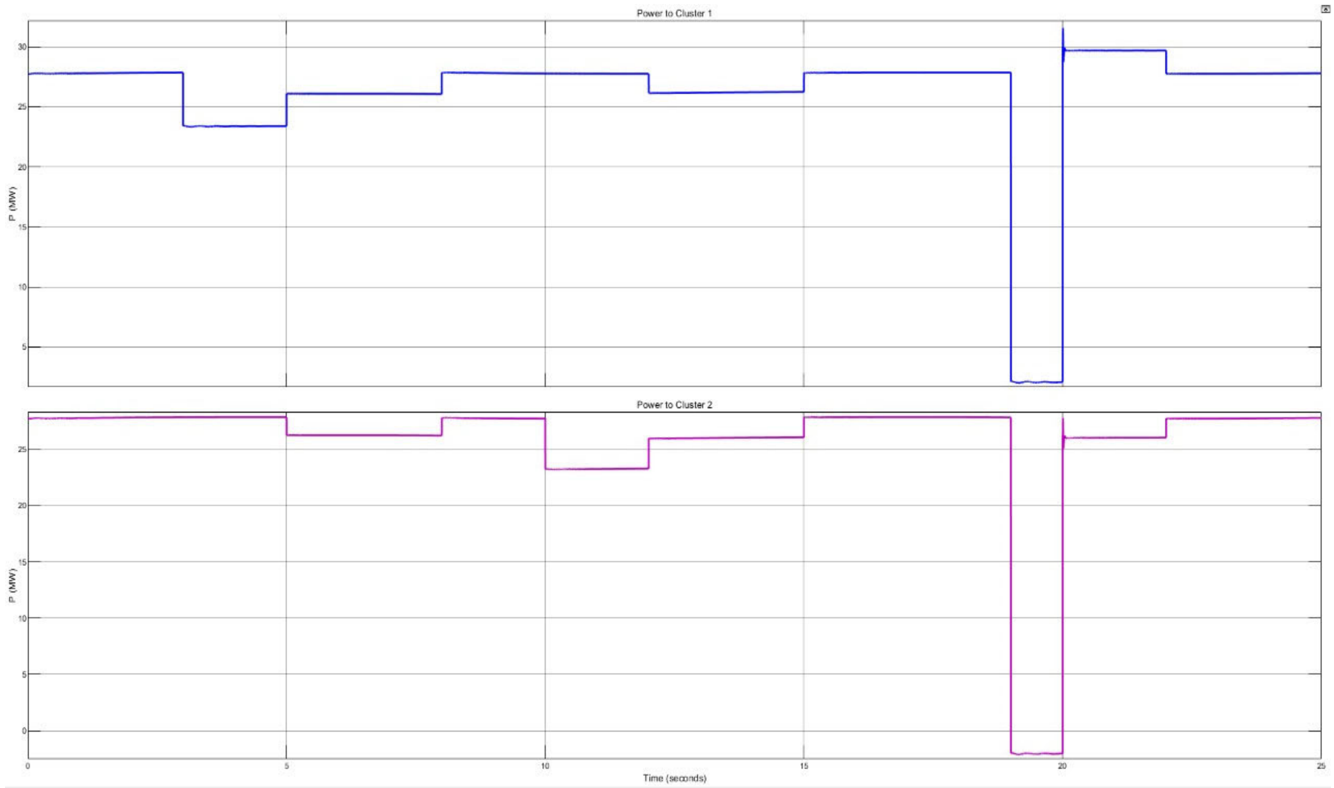

FIGURE 8. **Load power profile of cluster1 and cluster2.**

where, the probabilistic model of an auto correlation may also be used to determine $Rm_G(t)$ the arbitrary variation between $Gm^a(t)$ and $Gm^f(t)$ and a probabilistic model of a regression analysis may be used to determine it as well.

$$Rm_G(t) = E\left[G^a(t)G^f(t)\right] \tag{13}$$

When $Gm^a(t) \rightarrow Gm^f(t)$, the random divergence $Rm_G(t) \rightarrow 0$, that attains a balanced power between Gf (t) and Df (t) gives stability in numerous linked RIPGs.

The control factor Gm (t-1) ought be calibrated in the best possible manner to bring stability power between Gmf(t) and Dmf(t) in order to totally minimize an RG(t), that is, $Rm_G(t) \rightarrow 0$.

The frustrated request F(t), that may be written as, represents the active power shortfall resulting from a three phase malfunction.

$$F(t) = E^a(t) - G^a(t) \tag{14}$$

To establish the best distribution flow between response and load, F (t) must consistently be satisfied at a certain time period..

When the F(t) establishes then

$$E^a(t) > G^a(t) \tag{15}$$

By adding Ad (average delay) to equation 14, the expression may be rewritten as

$$F(t) = \left[\left(E_1^a(t) - G_1^a(t)\right) \times \frac{1}{n_1}\sum\nolimits_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \tag{16}$$

Eq. 16 may be rewritten as by taking its explicit configuration as well as representing it in form of Eqs. 1 and 2.

$$F(t) = \sum\nolimits_{i=1}^{n}\left\{\begin{array}{l}\left[\left(E_l^a(t) - G_i^a(t)\right) \times \frac{1}{n_1}\sum\nolimits_{l_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \\ \times\left[IMP_{inj_i} \times S_{inj_i}\right]\end{array}\right\} \tag{17}$$

The network will get feedback from F(t) in terms of backlogged or restoring request B(t). It will, however, be accompanied by a little closed loop delay. As can be seen from (17), the formula for the backlogged request B(t) shall be expressed in form of F(t), together with the multiplication of a corresponding closed loop delay 1.

$$B(t) = \sum\nolimits_{t_1=1}^{n_1}\left(\frac{1}{\lambda_{e_1}}\right) \times \left(E^a(t) - G^a(t)\right) \tag{18}$$

Further formulating equation

Backlogged demand = B(t), where F(t) and some close loop corresponding delay are multiplied.

$$B(t) = \sum\nolimits_{c_1=1}^{n_1}\left(\frac{1}{\lambda_{c_1}}\right) \times \sum\nolimits_{i=1}^{n}\left\{\left[\left(\frac{E_l^a(t) - G_1^a(t)}{n}\right) \times \frac{1}{n_1}\sum\nolimits_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \times \left[IMP_{inj_i} \times S_{inj_i}\right]\right\} \tag{19}$$

The reserve r (t) is expresses as

$$r(t) = G^a(t) - E^a(t) \tag{20}$$

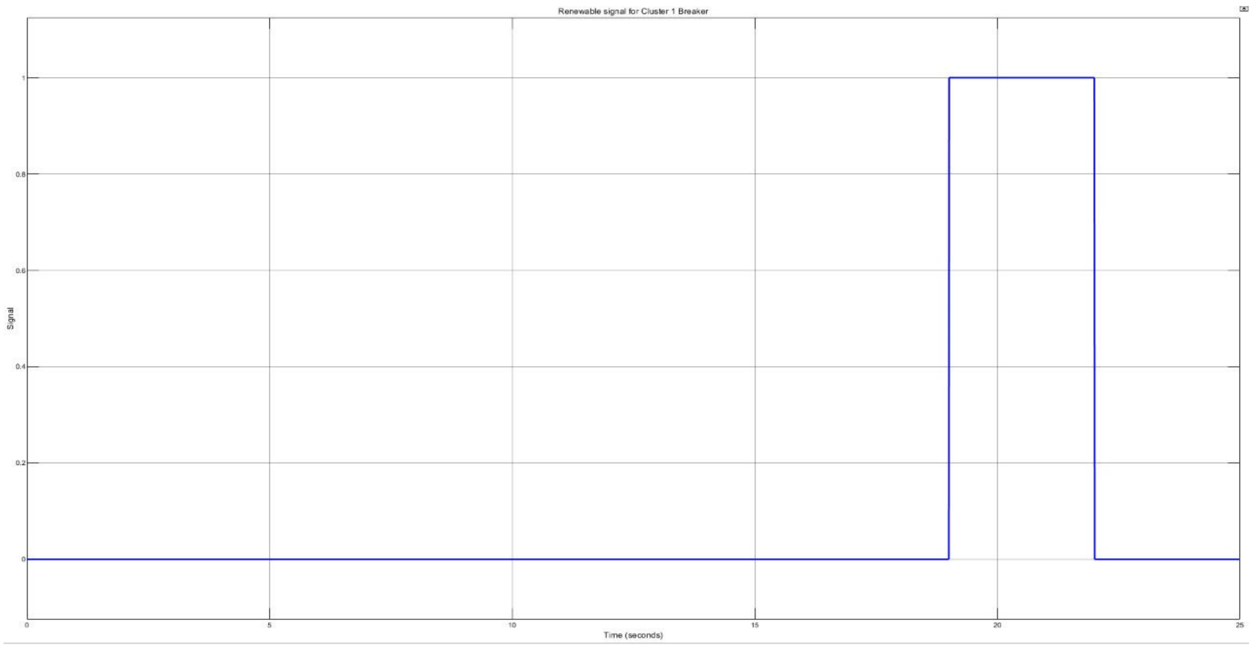

FIGURE 9. **Load profile of wind station.**

When the conditions below are met, many linked RIPGs should be in the reserve state.

$$G^a(t) > E^a(t) \tag{21}$$

Further it can be formulated by incorporating system delay.

$$r(t) = \sum_{l=1}^{n} \left\{ \begin{array}{l} \left[\left(G_l^a(t) - E_l^a(t) \right) \times \frac{1}{n_l} \sum_{i_1=1}^{n_1} \left(\lambda_{l_1} \right) \right] \\ \times \left[IMP_{inj_i} \times S_{inj_i} \right] \end{array} \right\} \tag{22}$$

The rule for the conservation of r (t) requirement threshold would be, if

$$r_0 < r(t) \tag{23}$$

The Ga(t) must then be increased via the fuzzy controller combined smart transmission circuit. Consequently, the F(t) will be decreased and ro and r(t) shall be as near as possible to each other. This procedure may be carried out by bonding to the ramp-up limiting route; alternatively, if

$$r_0 > r(t) \tag{24}$$

Then, to get ro and r(t) as near to one another as feasible, we must reduce the Ga(t). This may be accomplished by reducing limitations gradually. If ramping restrictions exist,

$$r_0 \leq G(t) - G(t-1) \leq r(t) \tag{25}$$

From eq. 11 $G(t) - G(t-1)$ is expressed as:

$$r_0 \leq G^f(t) + R_G(t) \leq r(t) \tag{26}$$

The major issue here is maintaining continuous balance of B(t), in any circumstance. This may be achieved by reducing RG(t) via an integrated smart transmission network powered by fuzzy controller. To do this, synchronizing the r_0 with r(t) parameter is necessary, by ramping up and down the restrictions from (23) and (24)

Thus, by reducing RG(t), (26) may be written as

$$r_0 \leq G^f(t) \leq r(t) \tag{27}$$

Hence it is concluded from equation (6), Gf(t) and Df(t) may be brought into synchronization as:

$$r_0 \leq Df(t) \leq r(t) \tag{28}$$

It is clear that the power flow achieves balance between request and response.

XIV. SIMULATION RESULTS

For simulation model, two clusters and wind power stations are considered. The clusters are electric source of energy with constant power of 27 MW; while clusters also generate extra power to supply power to each other in case of some kind of faults in anyone cluster. The power against time load profile of two clusters is depicted in Fig. 8. The simulation model is depicted in Fig. 6.

Case 1:

For the time 0 < t < 3s, cluster 1 is generating 27 MW power, but after 3s, cluster1 faces a fault and its power drops to become 25 MW. During this time interval, cluster1 needs extra power from some external source to meet the demand of consumers. During the time of fault, the cluster 2 takes some time to start and begins to provide its some extra power to cluster1for the time interval of 5 < t < 8 s. During this time, the power of cluster2 drops but cluster1 enhances. This phenomena is depicted in Fig. 8 above image.

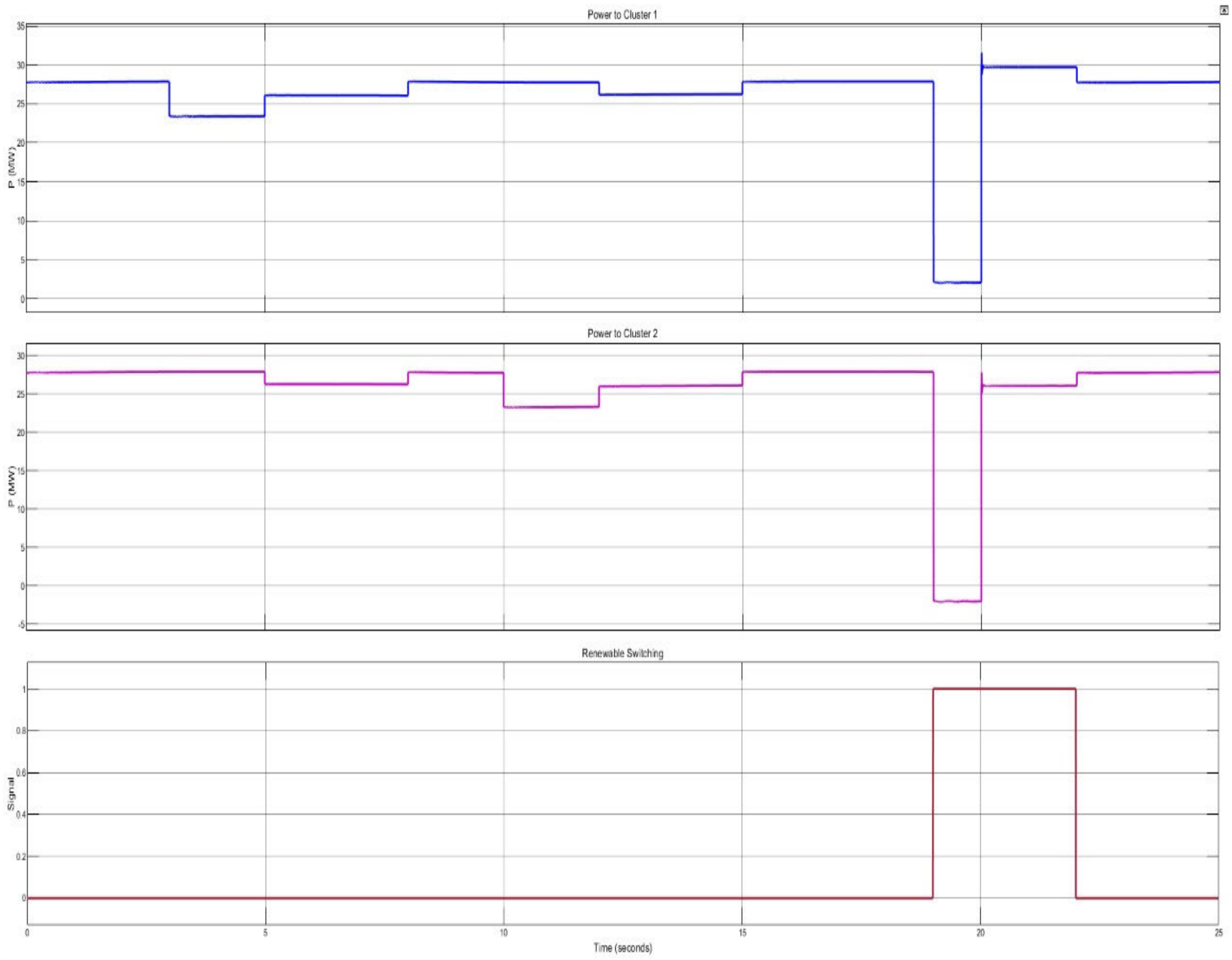

FIGURE 10. **Load profile of clusters and renewable wind station.**

Case 2:

During the time interval 8 < t < 10 s, fault of cluster 1 is removed and it starts to operate at its maximum capacity. So, for this time, there is no exchange of power between the two clusters and they are operating at their maximum capacity. For the time interval of 10 < t < 12 s, cluster 2 faces a fault and its power drops to 23 MW. During this time interval, cluster 2 needs extra power from some external source to meet the demand of consumers.. During the time of fault, the cluster1 takes some time to start and begins to provide its some extra power to cluster 1 for the time interval of 12 < t < 15 s. During this time interval, the power of cluster 1 drops but cluster 2 gains. For time duration 15 < t <19 s, there is no fault in both clusters and they are working at their maximum capacity. This phenomena is depicted in Fig. 8 below image.

Case 3:

For the time interval of 19 < t <20 s, both clusters face fault and their load power drops to zero. So at this time there is a need of some external source to supply power to fulfill the needs of consumers. The power profile of renewable wind power station is shown in figure 7. The wind power station works as an external source of energy during the time of fault in both clusters simultaneously. The figure shows clearly that wind station is not operating up to 19 s as its load is zero. But when the both clusters face a fault, then wind station starts to operate and generates power. The generated power of wind station starts to supply to clusters for 19 < t < 20 s. Then both clusters gain power from wind and operate at their full capacity. This phenomena is depicted in Figs. 9 and 10.

Through this SSGs generic model, the network operators can easily provide load flow balancing between different SAARC and European countries.

The simultaneously simulation results of clusters and renewable wind station are shown in Fig. 10. The load profile clearly depicts that the recommended system is capable to remove the irregularities, fluctuations in flow of power and can make the flow smooth, linear and regular between multiple countries of SAARC and European continents.

XV. CONCLUSION

The present research work discourse the problem of irregular flow of supply in a problematic network consisting of two countries. The proposed model is also developed to increase the balance of the network. The proposed model significantly improved the regular flow of supply in super smart grid. The overview of the results of simulations is that when a fault occurs in cluster1, the dropout of its power is compensated by the cluster2. Similarly, the dropout in power of cluster2 during a fault in its operation is compensated by the cluster1. However, whenever both clusters suffer a fault in their operation, then renewable wind system provides energy to the clusters in order to sure the regular flow of supply. The simulation outputs clearly depicts that the recommended model works significantly.

In the next section, we will discuss about the countries moving towards 100% renewable energy resources and shifting their smart grids power infrastructure into futuristic SSGs.

XVI. 100% RENEWABLE ENERGY SYSTEMS'S ANALYSES FOR DIFFERENT COUNTRIES

Srensen [169], citing Denmark as a report, published the first analysis of a 100% sustainable energy system in the prominent journal Science in 1975. Surprisingly, Science has since only published single article examining 100% RE scenarios. The second article on 100% renewable energy was written by [170] in 1976. It was focused on the United States and was titled the soft energy path with the prophetic subheading the road not taken [169], who was the first researcher to cite it [171], may have served as an inspiration for Lovins. Instead of conducting a quantitative analytic research, like [169] did, [170] concentrated more on the structure, relevance, and crucial elements. Both utilized the current methodology of vision-driven energy system transition study [172]. Reference [173] made another significant contribution to the research community in 1996 when he published the first worldwide educational study of a 100% RE process for the objective year 2050. A paper on 100% RE for the goal year 2100 was released by the Greenpeace International Stockholm Environment Institute in 1993 [174]. Despite the fact that this report was intended to guide the IPCC toward 100% RE, it required another 25 years for it to be recognized [174]. After another 13 years, the second worldwide 100% RE system investigation was reported by [175] in 2009 and was developed with 2030 as the target year. In 2011, more specifics of that investigation were released [176], [177].

The cost of RE has dramatically decreased [178], especially for wind and solar PV, making 100% RE economically viable and an intriguing path to further study. Biomass, biofuels, and biogas were all included in the [169] and [170] publications; although [179] specifically stated that they were ''considering only air pollutants free technologies greenhouse gases during their entire lifecycle.'' [175]. The most widely recognized paper in the subject, [176], has aided in breaking down boundaries and belief systems in a variety of areas on large scale and has sparked a movement toward 100% RE. The previously noted limitations have been overcome by more recent research by [179], [180], [181], [182], [183], and [184], which has also produced grid assessments of 20 or 24 illustrative areas comprising the countries as well as more detailed power system data for nearly all of the world's countries. The first investigation into transportation that is entirely made of renewable resources was released in 2005 [185]. It looked explored the effects of switching all American on-road automobiles to hydrogen fuel cells driven by wind electrolysis on air pollution and the environment.

Unfortunately, [169] never got appreciation from the scientific community at that time despite being one of the earliest pioneers in the subject and developing the first worldwide 100% RE system analysis for the middle of the 20th century as well as other methodological advancements. His early contributions are acknowledged in a few reviews and related works [186], [187], [188], [189]. With his dissertation from 2005 [190] explaining the very first 100% RE multi-node computation in hourly resolving using historical seasonal facts for an examined super-grid containing billion individuals across Europe, Asia, the Middle East, North Africa, and Western Eurasia, while [190] made a significant methodological advancement. A comparable study that took a worldwide view was released in 2004 [191], but it seemed to get less attention. The Desertec Plan of such years was reinforced by the groundbreaking study of [190], which was detailed in greater depth by [189], [192], and [193]. In this regard, the German Aerospace Center (DLR) began initial work in 2005 on the design of the REMix cost-optimizing power structure, which can be geographically and temporally solved. As opposed to the then-current models, REMix deliberately concentrated on the development and application of parametric RE (VRE) automation [194].

This approach produced fresh understandings of the relationship between VRE and present plants, the associated framework needs, and the scientific and financial viability of the needed load regulating in the system [195]. [196] calculated the very first prime combination of stellar PV and wind energy for a 100% RE system for the instance of Europe in 2010 and came to the conclusion that 45% stellar PV and 55% air energy would be the best combination. Greiner and colleagues examined the effects of considering various wind and stellar pairings and inhomogeneity amongst some of the European countries using a simplified methodology called seasonal-driven framework [197], [198], and they assessed the effects of increasing transmission links [199] and storing [200], [201]. They began studying 100% RE systems in 2004 [202] and helped to significantly expand the field with the development of the freeware power system analysis software Energy PLAN [203], [204], which has been tailored for 100% RE structural simulations in timely resolution, overnight analyses and sector coupling. This group is responsible for some of the most widely read works in the area, which helped spread the idea of 100% RE to several scientific teams worldwide. They also assisted in expanding the focus past the power industry by beginning to incorporate heat and transportation into their model, which permitted discoveries that led to the notion of the smart energy system [205], [206], [207], [208], [209]. This made it possible to conduct in-depth research on the transition of separate and coupled areas within the same company [210], as well as teams for the heat sector [211], [212], [213], seawater desalination, and the transport sector [214], [215], [216]. The transfer of electric energy to chemical propellant, or power-to-X, was another essential building element for the area because earlier studies relied heavily on bioenergy (biomass, biofuels, and biogas), frequently helped by unsustainable energy sources, or oversimplified hydrogen economic considerations. Reference [217] who detailed a coherent present day sector pairing outlook and the connection between a 100% renewable system based on electricity and renewable fuels, specifically e-methane, in 2009, delivered this intellectual breakthrough. This requires combining the well-known hydrogen-based CO_2 reduction processes [218], [219], [220], a sustainable CO_2 sourcing method [221] from biomass, a point source, or the atmosphere, and renewable electricity. From 2010 power-to-X for transportation has been included in the results in the analyses from the [222], and [223], whereas previously the major possibilities were biofuels [224]. This theoretical breakthrough, also known as power-to-gas, opened the door for the more comprehensive power-to X concept [225], seasonal storage past hydrogen, ideas based on non-bioenergy for the chemical sector [226], [227], and drop-in remedies for lengthy aviation with e-kerosene jet fuel [228], as well as for marine transportation [229], [230], such as e-ammonia [231], [232], and e-methanol [233]. This framework made it possible to investigate a cross-sectional complete electrification both straight, or indirectly, depending on the circumstances.

The five essential components of a completely sustainable and scalable power network for chemical mixture employing hydrogen, Fischer-Tropsch based e-methanol, e-ammonia, e-fuels, and e-methane were not integrated for another 12 years [234]. Sterner conceptualized the idea of exceeding the constraints of hydrogen by using CO_2-to-X formation in power network analysis [235], [236]. Typically, CO_2-to-X is referred to as carbon capture and utilization (CCU) [237], [238], [239], [240], with CO_2 coming from biomass, or fossil fuels or direct air capture [227] and utilized for materials [241], hydrocarbons [242], and chemicals [227]. There have been over 100 scholarly assessments of 100% RE systems that use CCUs powered by renewable electricity. CCU is a key component of a 0% CO_2 emission and 100% RE system and is fundamentally distinct from CCS [242], [243]. However, by the end of 2021, it is unknown whether any of the IPCC's integrated assessment models (IAMs), which comprise a worldwide depiction of economy, land, energy, and climate, will be able to incorporate these five essential components of a sustainable energy-industry system. The inability of IAMs to build 100% RE routes may be explained by the absence of these fundamental components. Greenpeace and the DLR made a significant contribution to widespread social awareness with a number of reports and articles [244], [245] outlining the advantages of a 100% RE system. The idea of 100% RE was given access for the very first time to a large stakeholder base outside of scientific community across professions, which increased awareness amongst policymakers. Additionally, these studies provided a comprehensive explanation of 100% RE system alternatives as a whole transition pathway with progressive time stages. Although Greenpeace has ceased its operations, the modeling framework has been further refined [246], [247], and the long-term primary author [247] has maintained in an academic capacity. The DLR is also comprehensively examining 100% RE system evaluations with its optimization technique REMix [194], [195], [248] in additional to these research endeavors. In order to encourage openness and transparency in the modeling of the energy system, the Open Energy Modeling Initiative [249] was established in 2014 [250]. Inside this network, many power system models (ESM) [251] share information and best practices. The simulation framework the instances for the European power system (PyPSA-Eur) [241] and Python for Power System Analysis (PyPSA) [252], [253], and sector-coupled system (PyPSA-Eur-Sec) [212], [254], [255], [256] integrate strong modeling tools with entirely open research in various. Such as open license that expanded to the information, design and analysis of results. [254] and colleagues continue to add to the PyPSA framework, and an increasing number of research teams are using PyPSA for their investigations. According to [257], PyPSA is presently the most complex models for short-term energy system assessments and has since been expanded for long-term pathways. With the LUT Power System Transition Model (LUT-PSTM), [258] set a new benchmark for worldwide transition analyses toward 100% RE in research conducted between 2017 and 2021. Modeling was done for a comprehensive energy-industry system as well as the world's 145 distinct locations at completely hourly precision with multi-node optimization. With a total of around 120 techniques spanning all sectors and industries, this structure approach also provides thorough power-to-X sector coupling [234], [235]. A coupled heat and power sector transition [258], a power industry transition [259], a power industry transition [260], and an energy sector overnight scenario [261] were already included in earlier versions. The LUT-PSTM ties to cost optimized photovoltaic hybrid energy system's initial hourly universal 0.45 0.45 mapping [262]. It also identified novel impacts that had not previously been seen, such as a battery-PtX impact and a new structure to lessen the effects of the monsoon in India [263]. It also provided insights for hitherto ignored places in the Global South. According to [257], the LUT-PSTM is presently regarded as one of the most sophisticated design for long-term power system transition assessments. With the aid of the LUT-PSTM, the actual potential of solar PV was made clear: it quickly became the dominant primary electricity generation methods for the worldwide energy-industry-CDR system [242], [264]. This kind of completes the circle because [169] already demonstrated extremely high PV percentage of approximately 70% in the overall power source in the middle of the 1990s [173], and subsequent modeling teams have verified these results [265], [266]. Incorporating more technologies, connecting energy systems, expanding research areas with better spatial and temporal precision, and incorporating the transmission grid are all made possible by the advancing models [267], [268]. It will be important to link energy system simulations with more in-depth power network calculations for every synchronously run program in order to show the feasibility of operating the power and energy networks with prospective solar and wind driven supplies [269], [270]. However, there is another viewpoint on the history of 100% RE scenarios. The pioneer's initial stage typically involved convincing national stake holders that renewable energy sources will have the capability to replace fossil fuels, especially nuclear power and coal power plants with their larger utilization rates. The case of Germany is briefly described here. In the first publicly funded research from the 1980s, nuclear and fossil fuel dominance was projected through the year 2030, with renewable energy sources accounting for no more than 30% of primary energy demand [271]. Progressive scenarios for Germany up until roughly 2000 identified RE as a potential primary power generating source through 2050. Even with the decision to phase out nuclear energy in 2000, these shares barely rose above 60–65% [272]. The German Ministry of the Environment then funded a number of so-called ''lead studies'' with up to 80% RE shares in the power sector, which, among other things, paved the way for the German government's 2010 energy concept [273]. Although the general aim of 80–95 percent reduction in GHG emissions by 2050 is indicated there, up until well after 2015, the specific objectives and accompanying research have mostly focused on a minimum 80% reduction in GHG emissions [274].

Despite the fact that a first national route with 100% renewable energy by 2060 has been released in 2012 [275], further scenarios with 100% RE or very close to 100% RE [276] followed [275], these analyses have not yet had a substantial impact on the political discussion. The price of change and its economic consequences were topics of heated dispute in the public discourse at the time. The consequences of the signed Paris Agreement were not more openly discussed in the community or elevated to the top of the political agenda until increased political pressure, particularly that from the Fridays for Future act and endorsed by Scientists for Future [277], [278]. Since then, a number of fresh studies, including [215], [279], [280], [281], [282], [283], [284], have dealt specifically with the creation of 100 percent RE scheme for Germany, building on prior studies that laid the foundation [188], [276], [285], [286].

XVII. GLOBAL 100% ANALYSIS OF RENEWABLE ENERGY SYSTEMS

The analysis of the worldwide 100% RE system is presented in part A and B below is the main topic of this part. However, just 8% of all research on 100% RE are worldwide, 18% are continental and regional evaluations, and 74% are analyses of national or sub-national 100% RE systems. As of the beginning of July 2021 [287], there are 550 recognized items that make up Figure 11. United States (45 articles), Australia (30 articles), Germany (35 articles), Denmark (39 articles), China (17 articles), Italy (10 articles), Sweden (13 articles), Finland (13 articles), Japan (13 articles), Portugal (13 articles), Croatia (11 articles), Spain (11 articles), United Kingdom (14 articles), and Greece are the nations that have been the subject of the most research (10 articles). These 14 OECD members, plus China, account for 63% of all national and sub-national trade with 100% RE system analyses are common.

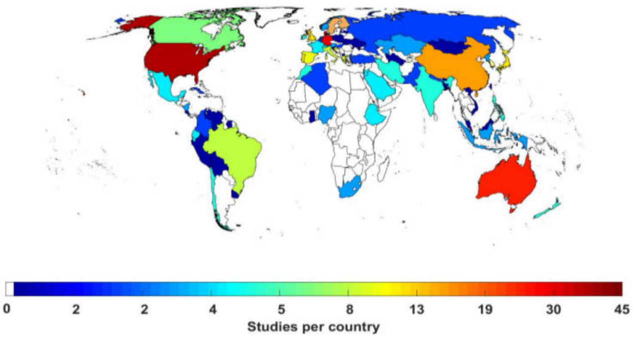

FIGURE 11. 100% RE system analyses per country, (Figure original resource from C. Breyer; [372]).

Approximately 5 billion people live in countries that are not yet particularly for Africa, the Middle East, and Central Southeast Asia, South Asia, and Asia. This will be the best importance of achieving a climate and sustainability goals development goals to fill this knowledge gap [186], such as energy Transition plans and policies are often established on a national level. Fortunately, 100% RE systems are likely to be available soon given that these nations frequently receive substantial amounts of exhibit less seasonal variations and receive large amounts of solar energy. Insights into the global 100% RE system are provided below presentation and discussion of studies.

A. 100% RENEWABLE ENERGY SYSTEM STUDIES SO FAR GLOBALLY

Various research groups have released global 100% RE system analyses. We only take into account studies that were published in peer-reviewed publications. The studies cover 145 geographic entities in all, covering the entire world. In order to highlight regional distinctions where appropriate and develop findings that apply to the entire world, global analysis sometimes uses various geographic entities. Different research groups employ different models and methodologies, however they all agreed that a global 100% RE system is feasible by the middle of the century. According to modeling and optimization, model types are fundamentally differentiated [288]. A computer simulation is a depiction of a system that is used to visualize and simulate the system's behavior under a certain set of circumstances. In an optimization modeling technique, an objective function is minimized or maximized while taking restrictions into account. The whole power supply for the heat, power, and transport sectors is often included in the research findings, with commercial energy needs generally getting involved as a part of other areas. Furthermore, there is a glaring deficiency and research problem since practically nowhere is a thorough explanation of the industry sector present, i.e., distinct key sectors like cement, steel, iron and steel, etc. As a result, the global 100% RE research did not model a complete defossilization of the industry sector's demand for non-energy feed stocks. The industry sector is discussed in depth in [265], although the authors acknowledge that the model utilized, TIMES, was unable to fully apply power-to-X capability for the industries, necessitating the continued usage of fossil hydrocarbon inputs. The chemical industrial sector is still entirely dependent on fossil fuels, according to [247] and [266].

However, research of a defossilized chemical sector, or one that gradually eliminates fossil feedstock, suggests considerable proportions of CCU for synthetic hydrocarbon fuel sources to industry, especially for e-methanol [226], [227], [289]. The most recent version of the LUT-ESTM includes all of the capabilities of a system that uses only renewable energy sources [235], but it has yet to be implemented globally. The most recent version of PyPSA-Eur- Sec also provides a thorough modeling of the connection between the energy and industrial sectors, which includes industrial feedstock [256]. Given specific limitations, such as climate targets, societal choices, the availability of energy supplies, and the need for energy systems, a generation of new of power system models has made it possible to analyses energy system transformation possibilities in detail. Modern energy system models exhibit exceptional performance in terms of technological, geographic, and temporal resolution, as well as sector coupling. To maintain the clarity of techniques and data assumptions, minimum standards of model documentation are crucial [257], [290].The top models, according to [257], are capable of modeling complete changes at hourly resolution, with sector linkage, connected multi-regions, and an extensive range of technologically advanced power parts of the system.

The most proven open source tool for power transition assessments for Europe is PyPSA [255], however it is not currently accessible globally [291]. PyPSA is among the attractive open source tools. The LUT-ESTM model is ''global-local,'' which means that it may be used to analyses the transition of the energy system at many sizes, including global, regional, and local [235], [260]. At the moment, it can analyze a globe with 145 separately modeled areas. 72 areas are added to the Mesap/PlaNet (DLR-EM) modeling by [247] along with more in-depth nation versions [292], [293], [294]. As the majority of global models divide the world into 12–24 areas, this restricts their ability to examine crucial features. References [179], [181], and [184] carried out annual-average 100% RE assessments for 139, 143, or 145 nations and then divided those nations into 20 or 24 globe regions for grid analyses with a temporal resolution of 30 seconds across a number of years. Since many countries are now interconnected and integrating them saves money compared to separating them, countries were aggregated for grid analysis [183]. A average global contribution of VRE of about 90% and 80% of power generation and primary power supply, respectively, can be achieved by combining least-cost solar PV electricity with low-cost batteries, reduced electrolyzes, CO_2 direct air capture (DAC) innovation, and hydrogen-based synthesis routes, as demonstrated by [179], and [235], though without H_2-to-X options. In comparison to [179], [235], [265], [266], and [295] achieve VRE shares in 50–60% of the total primary energy demand (TPED). This is primarily because the latter models have greater supposed bioenergy accessibility and lower levels of energy functionality.

B. 100% RENEWABLE ENERGY BASED GLOBAL SCENARIOS CONSIDERING SOLAR PV AND WIND INTEGRATIONS

One point to consider when examining conceptual variances in such research is the importance of wind and solar power, which may be the largest difference among worldwide 100% RE system evaluations. The discussion that follows focuses on wind and solar power as the dominant sources of power and energy overall in the research under consideration (Figure 12), as more than 80% of all energy is found to come from these two fundamental sources in 75% of all research. The following discussion of bioenergy and highly concentrated solar thermal energy (CSP) does not aim to minimize the significant value of the various RE sources.

Depending upon local circumstances, each individual RE source has the potential to be highly important regionally. Based on the percentages of wind and solar PV power they project as a part of the world's total power generation, all known worldwide 100% RE network models that were described in peer-reviewed studies and included data on the generation of electricity were evaluated. There were a total of 17 studies found; only the first, by [173], dates back to the 1990s; all other studies were released after 2008. The global survey by [176] is the most referenced study in the subject of 100% RE research. Figures 7 and 8 shows the findings for the generation of energy from wind and solar power in absolute terms as well as their relative contributions to the generation of electricity and TPED. The majority of assessments outline an energy transition for overall energy needs from the present through 2050. All the other models' analyses have a lack of hourly resolution; hourly modeling has become increasingly common among complex models and is a component of the techniques employed by [179] and [235]. Only three researches predict more than 50,000 TWh/yr of solar Photovoltaic electricity, and 25% of all studies are showing less than 20,000 TWh/yr. Reference [265]

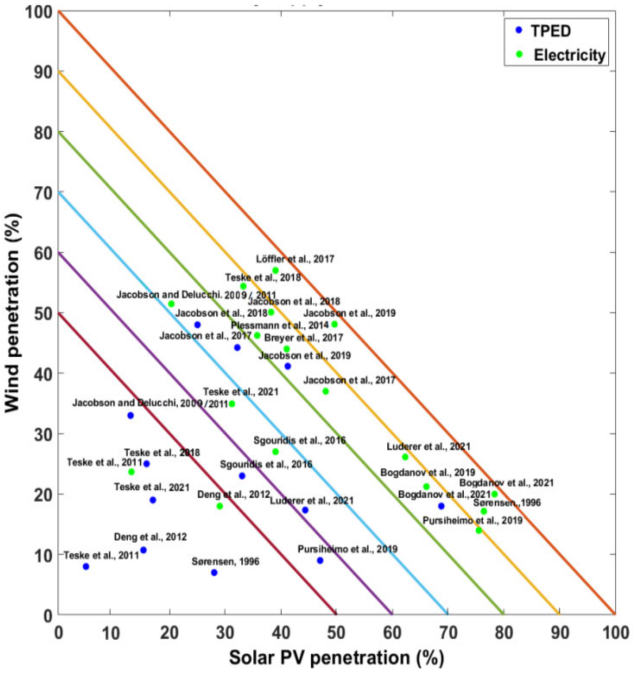

FIGURE 12. **Impact of wind and solar electricity in global energy market (Figure original resource from C. Breyer; [372]).**

reach at approximately 93,000 TWh/yr and [235] reach at 104,000 TWh/yr by 2050. These two studies have the greatest proportions of PV. As described by [235], [265], and [296] relevant capex for only one monitoring PV are also used. The only research that take into account solar PV tracking—which increases electricity yields and lowers power generation costs and is a prominent trend in current utility-scale PV energy plants are [179], [182], [183], [184], [235], [260], [297], and [298]. Furthermore, even in [235], the used PV capex value does not take into account the most recent cost trends, which suggest that utility-scale PV will have roughly 30% lower capex in 2050, or 164 e/kWp, according to projections made by [299]. However, [266] and [299] have linked their solar Photovoltaic capex prediction. In updated scenarios, modeling using a techno-economic optimization technique will also most likely result in larger PV production share, higher PV power supply, as well as further decreases in anticipated energy system costs. Three researches between 2011 and 2018 observed that the values of more than 40,000 TWh/yr [176], [181], [295], but after 2018, all research stayed below 40,000 TWh/yr, reflecting the noted increase in solar PV electricity contribution. Current solar PV costs enable cost-optimized analyses to establish consensus estimates of 14–26% wind shares in the supply of power (Figure 7).

Interestingly, just three research obtained value higher than 40%: [266] in 2021 with 42%, [265] in 2019 with 44%, and [235] in 2021 with 69%. [173] had predicted a TPED share of 28% for photovoltaic Panels in 1996. The greater sector connectivity in [258] and the fossil hydrocarbon power generation for industrial needs in [265], and [266] are the primary differences between the two earlier and later studies. Furthermore, the power-to-X applications and sector coupling may be impacted by the reduced temporal resolution of TIMES employed by [265] and REMIND-MAgPIE by [266]. There are a variety of reasons for the low supply participation of PV and the often larger supply participation of wind in other circumstances. Reasons for larger or lower proportions of the primary RE technologies are discussed in the section that follows.

First, excessively high solar Photovoltaic cost estimations automatically prevent increased PV supply percentages from being included in cost-optimizing modeling. The majority of the scenarios generated during the early half of the 2010s, when solar PV capex projections were often still very high, had this as a significant issue. With the exception of [235], [265], and [266], there had been a failure to forecast the sharp reduction in PV cost that occurred in the middle to late 2010s. The relative percentages of wind and solar power can also be affected by relative cost disparities, though this seems to be a smaller problem with wind expenditure. In contrast, as solar PV advantages more from cheap batteries than wind power does, financial considerations for cells have a significant influence. The findings with the greatest solar PV share take into account the costs of corresponding systems development or low-cost batteries. Secondly, certain scenarios—such as in [300]—assume reasonably high bioenergy contributions. Given that the amount of available arable land is decreasing [301], ecosystems are now under tremendous stress [302], there is a need for more food production [303], and continuing impacts of climate change are threatening even present food supply [304], [305], [306], high bioenergy use could be seriously at odds with sustainability principles. Reference [307] come to the conclusion that the supply of bioenergy cannot exceed 100 EJ/yr (about 27,800 TWh/yr). So, in certain models, unrealistically high and potentially unsustainable bioenergy production estimates prevent indirectly electrification chances that solar PV would otherwise be able to fill in the absence of bioenergy. While adhering to the 100 EJ/yr limit [245], [247], [266] have a sizeable bioenergy share. Furthermore, contrary to what we predicted in the [175], [176], [177], [179], [180], [181], and [189] study, scenarios with no bioenergy source do not led to the lowest private cost choices, as was subsequently shown in a review of model situations having and omitting bioenergy [308], [309]. Reference [179] do social cost assessments and discover that yearly personal and societal expenses are usually significantly lower than that in normal commercial situations, despite the fact that they do not uncover the least-cost alternatives. Limitations and optimization for the utilization of materials like metals and land-use are part of cost optimization techniques, in contrast to the limited concentration on prices without account for indirect costs. Usually, restrictions are applied to such considerations. Particularly for energy supplies like fossil fuels that are not utilized in 100% RE systems, a model motivated by supplements that are approximated for the determined scenario time frame and the advancement that take place inside this time frame, e.g. between 2020 and 2050, relies on particular price predictions is subject to significant limitations. Moreover, estimating technology costs over years entails uncertainty. Thirdly, some situations, despite the potential for greater prices, promote resource variation above price optimization for concerns of societal and political resilience as well as more general concerns about supply security. This technique is more frequently used in simulation studies [288], where it is possible to define particular percentage for all of the techniques present in the system. Results are evaluated for consistent power generation and costs within imposed limitations after the model situation has been performed. As substantial proportions of CSP plants are assumed, resource diversification is highly highlighted in the various [246] scenarios as well as the [179] scenarios. Technically practical and enabling greater technological diversity, CSP in linkage with thermal energy storage (TES) has a higher system cost than solar photovoltaics. Future studies may need to revise their results due to full-year optimization of CSP-TES in comparison to PV-battery model using the most recent price forecasts. However, advantages include a large capacity ratio of above 90%, reduced emissions, and supply process heat for water desalination and industry, and also the option of hybridization for supplemental usage of biofuels may be desirable in the case of linked CSP-TES systems. Applying dated photovoltaic and battery backup cost estimates as in [310], yields findings about the TES-related value of CSP-TES that call for additional research using the most recent cost assumptions. Although they can have a significant impact locally on energy systems, CSP-related issues are frequently ignored by cost-optimizing models. Fourth, as shown in [311], erroneous assumptions about renewable energy resources can also result in reduced PV supply proportions. Given that their PV capex is equal to [265] 's and [235]'s, this instance is highly intriguing, but the importance of PV appears to have been grossly overestimated as a result of artificially constrained solar PV potential. From 2035 onward, this restriction severely restricts the growth of PV capacity and consequently drives up the number of wind capacity installations. In virtually every alternative system for the years beyond 2035 the rate of solar PV cost digression is higher, and solar PV electricity finally becomes more affordable than wind electricity. As a result, wind power is losing market value against photovoltaic. Fifth, many scenarios have insufficient power-to-X pathways, inadequate sector coupling, and overly high prices anticipated for the two main techniques that provide flexibility: batteries and electrolyzes. In order to satisfy the entire main energy demand, low-cost batteries, electrolyzers, and proven power-to-X channels significantly boost the VRE share. Solar PV benefits more from low-cost electrolyzers than wind generation because low-cost energy is best matched with relatively inflexible energy consumption groups through the intermediaries of fuel cells and electrolyzer-based power-to-X routes. More study on globe 100% RE system scenarios is required, including power system simulations with resource sufficiency, to further evaluate a societally optimal balance of techniques and resources. Sixth, as shown in Figure 13, the absolute participation of the two most significant VRE technologies varies and their aggregate significantly varies between studies, excluding the percentages of solar PV and wind power. Three key elements from the relevant studies drive this. The overall demand for VRE generation is significantly impacted by many assumptions about how the demand for energy services will rise and, consequently, how much energy will be needed. Assumptions about the growth of energy efficiency, which vary among studies, highlight this even more. The demand for VRE generation is directly impacted by the expected bioenergy consumption because the degree of power-to-X is correlated with the supply portion of bioenergy. If strong sustainability restrictions for bio energy are put in place or if the supply of bio energy is even restricted, the need for VRE generation increase dramatically. Energy need for the transportation and heating sectors is examined by [213] and [216] who draw attention to structural discrepancies between some of the studies utilized for Figure 13 and studies striving for lower RE shares. Higher renewable power stocks in the northern latitudes, higher hydro power needs to share in areas with outstanding hydroelectric power, similar for geothermal power, and greater bio energy stocks in areas with outstanding bio energy accessibility are documented as resource-driven distinctions in technology shares [179], [180], [181], [235], [246], [247], [260].

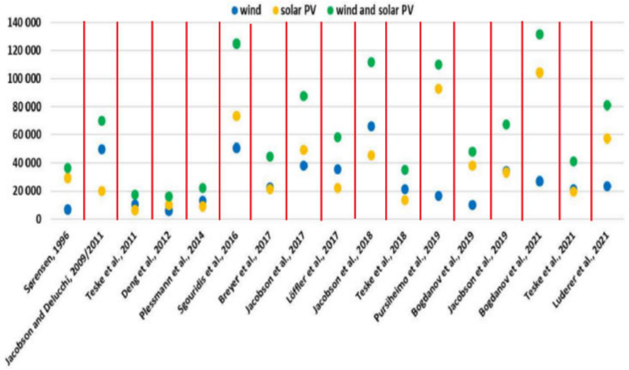

FIGURE 13. Wind and solar based electricity generation till 2050 (Figure original resource from C. Breyer; [372]).

These distinctions are typically related to poor population densities. According to estimates, the overall environmental hydro power potential will be 3290 TWh at prices of 100 USD/MWh or less [312], which would represent a potential increase of about 75% in comparison to the hydro power output of 4350 TWh in 2020 [313]. Since the information, year of the environmental hydro power resource assessment, more than 400 Twh of extra hydroelectric power had been produced. The existing environmental hydropower capacity can be viewed as relatively restricted and not much scalable given the tremendous growth in demand for energy production. Additionally, based on wind energy and particularly solar PV, the production of hydropower carries a far larger risk of having a detrimental impact on the climate [314]. Last but not least, there are two strong arguments that are at odds with one another; full cost optimization, which favor's higher pv-battery shares, and more resource variety, which favor's firm increases of wind and CSP or encourages higher shares of geothermal and ocean energy, both of which increase system energy costs. Energy system evaluations are finding more and more evidence of the PV-battery-electrolyzer nexus's significant system influence globally [169], [235], and even more locally, such as in China [315], [316], India [317], and Africa [318], [319]. Based on cost developments, material requirements, and regional acceptability, battery storage and boosted hydro energy saving may interact [320], [321], as the potential for pumped hydro energy storage may be far more than most studies have assumed so far [322]. Since the costs and operational profiles of battery and pumped hydro energy storage are fairly similar, no change in cost of the system or design may be anticipated. Higher proportions of pump hydro energy storage and lesser amounts of battery storage may both be feasible, though. Model inter comparisons, like those done for Energy PLAN and the LUT-ESTM [320], may be able to advance research on 100% RE systems significantly. Model comparisons could identify hidden flaws and raise the bar for standards while also examining the issues already mentioned. Researchers will be able to better understand the financial effects of specific scenario restrictions and alternatives by comparing the costs of various transition paths developed using various input assumptions, constraints, or technology cost digression assumptions inside the similar pattern. Any operational power network concerns, long-term resource sufficiency issues, socio-technical, environment, and general political and economic factors should all be taken into account in a more thorough review of the local outcomes produced by global models.. These evaluations should compare the results of national research directly with the shown paths' viability. In recent years, a growing number of spin-offs of 100% RE processes have come to light, including lower levels of air pollution [169], [323], a significant decrease in energy-induced water stress [324], a significant rise in energy system employment [169], [325], increase in energy protection [326], initial forecast of material demands [327], and stabilization and advancement in net power [295], [328]. These evaluations should compare the results of national research directly with the shown paths' viability. In recent years, a growing number of co-benefits of 100% RE systems have come to light, including lower levels of air pollution [169], [323], a significant decrease in energy-induced water stress [324], a significant rise in energy system employment [169], [325], higher levels of energy security [326], material requirements estimation [327], and net energy improvement [295], [328]. The stark imbalance of 100% RE research for Europe, and Australia and a serious lack of such research for the Global South, as earlier noted out by Hansen et al., can also be addressed by high geologically global 100% RE system analysis. [186]. Additionally, more openness in scientific publications is required since journals should priorities first-of-their-kind investigations while frequently publishing the marginal advancements of nations with extensive research. Such an inequality calls for critical thought.

XVIII. STABILITY ANALYSIS STUDIES SO FAR CONSIDERING RENWABLE ENERGY SYSTEMS

It appears that a large portion of the literature's opposition to 100% RE systems originates from the underlying presumption that a solar and wind-based energy system is impractical due to the variability of these sources of energy. Critics of 100% renewable energy systems frequently compare solar and wind power to ''firm'' energy sources such nuclear power and fossil fuels, which typically come equipped with their own reserve (CCS). This has been the main argument put forth in several of the comments that have already been cited, including those by [329], [330], [331], [332], [333], [334]. Although it is true that maintaining the integrity of a system with changeable inputs is more difficult, a variety of approaches can be used that are frequently overlooked or underused in critical research increasing the capacity of wind and solar power; improving interlinkages [183], [199], [254], [263], [335], [336]; addressing demand [337], [338], e.g., smart electric cars charging using postponed charging or supplying extra energy to the power grid via car, [339], [340], [341]; storage [200], [262], [322], [342], [343], [344], [345], such as static batteries; and sector. The majority of the cutting-edge creation of 100% RE situations is done by properly utilizing all three tactics to reduce unpredictability. 100% RE systems becoming more and more feasible with each iteration of the research and each technological advancement in these fields. Even erstwhile detractors had to admit that the addition of e-fuels via PtX enables 100% RE at prices comparable to fossil fuels. These sceptics no longer assert that 100% RE would be impractical or excessively expensive, but they still question whether it is the most cost-effective option. Numerous mitigating strategies exist for variability, particularly in the near term, and power system analyses are increasingly include these in their 100% RE predictions. However, because the emphasis in energy-balancing research is on usage balancing on an hourly time scale, stability of power systems is frequently neglected. Inverters are used to link solar and wind PV power stations to the grid, rendering them distinct from traditional, simultaneously linked power plants. Network operators have studied the difficulties in holding the dependability and balance of energy networks controlled by non-synchronous resources for production in increasing depth [269], [346], [347], [348] due to the expanding significance of energy systems. The management of 100% transformer system operations is the subject of ongoing study [349]. Up to now, few small islands or a portion of a wider synchronous system have operated entirely on wind and solar power [350]. As these situations grow more common, close to 100% VRE functioning should be authorized since VRE will occasionally account for 100% of consumption (despite though their part is still somewhat lower on average). Today, excess wind energy and solar PV that is not otherwise useful is restricted, preventing non-synchronous sources from ever exceeding a specific proportion. For instance, that this so non-synchronous system adoption in the Ireland synchronous system was initially set at 50%, then increased to 60%, and is presently at 75% [351]. This allows for a wind contribution of 40% without significant curtailment; however, in order to meet a greater renewable objective with a significant contribution from wind, the penetration of non-synchronous systems will need to be raised to 90%. 100% inverter-based resources (IBRs) provide the flexibility and control to design how the equipment reacts to changing grid conditions. They can independently control actual and reactive power. Grid-forming inverters, a new generation of inverters that have shown the ability to support consistent network operation when no generators are online [352], [353].

The potential for overcoming the impending issues is demonstrated by this promising technological advancement and evolving power system modeling tools [354], [355], [356]. In some ways, it might be possible to make IBRs act even more supportively than synchronous machines. The magnitude of the shifts, however, necessitates a basic rethinking of energy systems, including the identification of necessary system services. One issue is that different inverter models and producers do not use heterogeneous control systems, which affects how IBRs respond to grid situations. Such algorithms can also connect locally and systemically with other power system components, such as high-voltage direct existing transmission connections, on both a local and a system-wide level. This poses stability issues and significantly exacerbates the examination of IBRs in the energy system [347], [349]. Considering this scenario, more research is required to determine the viability and determine the financial impact of grid-supporting resources.

XIX. RESEARCH TOWARDS REDUCING CO_2 EMISSIONS CONSIDERING 100% RENEWABLE ENERGY SYSTEMS

Study on 100% RE systems has not yet certainly taken carbon dioxide removal alternatives into account. Natural climatic solutions (NCS) were thoroughly included by [247], but other CDR possibilities, such as bioenergy carbon capture and storage (BECCS) and direct air collected carbon and storage (DACCS) [357], were not included in their system [357]. Among some of the models employed for 100% RE systems study up to this point, only the LUT-ESTM has offered insights on DACCS [242], [358], while excluding the most crucial NCS. Solar PV [242], CSP [359], and geothermal power [360], among others, have all been studied in relation to DACCS.

There is research that predicts CDR demand from DACCS to be in the range of 20–30 $GtCO_2$/yr for ambitious climate targets in the second part of this century [264], [361]. In addition to more NCS, or natural- and land-based options, such as soil carbon sequestration, ecosystem restoration, afforestation and reforestation, blue carbon and sea grass, and bio char, there are also other promising CDR technologies available besides DACCS and BECCS [362]. However, accurate models that link these CDR systems to 100% RE models are exceedingly uncommon. As a result of 100% RE system scenarios, all research groups on 100% RE systems concentrate on true-zero CO_2 emission power system solutions, but they not yet include innovations and routes that could permit net-negative CO_2 emissions. In order to advance towards to the energy transition, [363] showed that it is presently more lucrative to concentrate on increasing the supply of RE than on carbon capture, but that in the long run, active regulation of the atmospheric CO_2 levels may become necessary. Surprisingly, [266] described the first scenario developed using a IAMs system that satisfies the minimum requirement of a 95% RE share by 2050 and encompasses the complete energy system. This filled a study vacuum in the power and at atmospheric study that [186] and [335] had previously filled. Highly resolved power system models that can incorporate a wider range of CDR alternatives and provide transition situations that follow all fossil fuels-based industry feedstock flows may be the next significant technological step in 100% RE research. This should take into account the complete spectrum of energy-industry-CDR choices and take into account non-energy feedstock use, such as the requirement for fossil hydrocarbons in today's chemical industry. The need to depict 1.5°C climate target scenarios that adhere to the most recent findings in climate system science is growing. These findings suggest that due to incorrectly taken into account adverse climate feedback mechanisms [364], the previously anticipated remaining carbon budgets [373] must be revised to lower values.

Latest studies on science suggest that environmental factors [366] may already be operational at the current level of temperature. This includes dynamics in many Earth systems which irreversible at temperatures of 1.0 to 1.5°C above the pre-industrial global mean surface air temperature. These are the increasing thawing of permafrost [367], the melting of the Greenland ice sheet [368], the instability of the Western Antarctic Ice Shield [369], and the die-off of coral reefs [365]. This would imply that far more ambitious climate targets must be the goal in order to achieve a higher level of climate security. These temperature targets for climate security may be as low as 1.0°C [370], [371], [372] and between 280 and 350 ppm of atmospheric CO_2, which is lower than the 420 ppm CO_2 concentration attained in 2021. Therefore, complex power system models should be updated in order to expand the analysis's scope beyond power systems with zero emissions. It will be necessary to model industrial-energy CDR net-negative emissions systems based on a 100%

renewable energy supply to create schemes of a world with lower atmospheric carbon dioxide levels than today.

REFERENCES

[1] M. Azeroual, A. El Makrini, H. El Moussaoui, and H. El Markhi, "Renewable energy potential and available capacity for wind and solar power in Morocco towards 2030," *J. Eng. Sci. Technol. Rev.*, vol. 11, no. 1, pp. 189–198, Feb. 2018.

[2] M. Azeroual, T. Lamhamdi, H. El Moussaoui, and H. El Markhi, "Simulation tools for a smart grid and energy management for microgrid with wind power using multi-agent system," *Wind Eng.*, vol. 44, no. 6, pp. 661–672, Dec. 2020.

[3] R. Bayindir, I. Colak, G. Fulli, and K. Demirtas, "Smart grid technologies and applications," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 499–516, Dec. 2016.

[4] T. S. Ustun, "The importance of microgrids & renewable energy in meeting energy needs of the Brazilian Amazon," in *Proc. IEEE Int. Conf. Power Energy (PECon)*, Nov. 2016, pp. 1–6.

[5] S. Jinlei, P. Lei, L. Ruihang, M. Qian, T. Chuanyu, and W. Tianru, "Economic operation optimization for 2nd use batteries in battery energy storage systems," *IEEE Access*, vol. 7, pp. 41852–41859, 2019.

[6] A. H. Hubble and T. S. Ustun, "Scaling renewable energy based microgrids in underserved communities: Latin America, south Asia, and sub-saharan Africa," in *Proc. IEEE PES PowerAfrica*, Jun. 2016, pp. 8–134.

[7] J. Ashfaq, S. Hussain, and Ustun, "Design and performance analysis of a stand-alone PV system with hybrid energy storage for rural India," *Electronics*, vol. 8, no. 9, p. 952, Aug. 2019.

[8] S. Singh, P. Chauhan, M. A. Aftab, I. Ali, S. M. S. Hussain, and T. S. Ustun, "Cost optimization of a stand-alone hybrid energy system with fuel cell and PV," *Energies*, vol. 13, no. 5, p. 1295, Mar. 2020.

[9] F. Nadeem, M. A. Aftab, S. M. S. Hussain, I. Ali, P. K. Tiwari, A. K. Goswami, and T. S. Ustun, "Virtual power plant management in smart grids with XMPP based IEC 61850 communication," *Energies*, vol. 12, no. 12, p. 2398, Jun. 2019.

[10] D. Anderson, C. Zhao, C. Hauser, V. Venkatasubramanian, D. Bakken, and A. Bose, "Intelligent design' real-time simulation for smart grid control and communications design," *IEEE Power Energy Mag.*, vol. 10, no. 1, pp. 49–57, Feb. 2011.

[11] E. Weingartner, H. vom Lehn, and K. Wehrle, "A performance comparison of recent network simulators," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2009, pp. 1–5.

[12] X. Dong, H. Lin, R. Tan, R. K. Iyer, and Z. Kalbarczyk, "Software-defined networking for smart grid resilience: Opportunities and challenges," in *Proc. 1st ACM Workshop Cyber-Phys. Syst. Secur.*, Apr. 2015, pp. 61–68.

[13] D. Niyigena, C. Habineza, and T. Selim Ustun, "Computer-based smart energy management system for rural health centers," in *Proc. 3rd Int. Renew. Sustain. Energy Conf. (IRSEC)*, Dec. 2015, pp. 1–5.

[14] H. Kikusato, T. S. Ustun, M. Suzuki, S. Sugahara, J. Hashimoto, K. Otani, K. Shirakawa, R. Yabuki, K. Watanabe, and T. Shimizu, "Microgrid controller testing using power hardware-in-the-loop," *Energies*, vol. 13, no. 8, p. 2044, Apr. 2020.

[15] T. Selim Ustun and S. M. Suhail Hussain, "IEC 61850 modeling of UPFC and XMPP communication for power management in microgrids," *IEEE Access*, vol. 8, pp. 141696–141704, 2020.

[16] A. Latif, S. M. S. Hussain, D. C. Das, and T. S. Ustun, "Double stage controller optimization for load frequency stabilization in hybrid wind-ocean wave energy based maritime microgrid system," *Appl. Energy*, vol. 282, Jan. 2021, Art. no. 116171.

[17] M. Monemi Bidgoli, H. Karimi, S. Jadid, and A. Anvari-Moghaddam, "Stochastic electrical and thermal energy management of energy hubs integrated with demand response programs and renewable energy: A prioritized multi-objective framework," *Electr. Power Syst. Res.*, vol. 196, Jul. 2021, Art. no. 107183.

[18] X. Sun, Y. Chen, J. Liu, and S. Huang, "A co-simulation platform for smart grid considering interaction between information and power systems," in *Proc. ISGT*, Washington, DC, USA, Feb. 2014, pp. 1–6.

[19] Alankrita, A. Pati, N. Adhikary, S. K. Mishra, B. Appasani, and T. S. Ustun, "Fuzzy logic based energy management for grid connected hybrid PV system," *Energy Rep.*, vol. 8, pp. 751–758, Nov. 2022.

[20] K. H. Youssef and F. M. Abouelenin, "Analysis of simultaneous unbalanced short circuit and open conductor faults in power systems with untransposed lines and six-phase sections," *Alexandria Eng. J.*, vol. 55, no. 1, pp. 369–377, Mar. 2016.

[21] M. Novak, R. Kravec, M. Kanalik, Z. Conka, and M. Kolcun, "UPFC influence to transient stability of power system," in *Proc. ELEKTRO*, Rajecke Teplice, Slovakia, May 2014, pp. 343–346.

[22] Y. Liu, K. Sun, R. Yao, and B. Wang, "Power system time domain simulation using a differential transformation method," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 3739–3748, Sep. 2019.

[23] S. Jafarzadeh, I. Genc, and A. Nehorai, "Real-time transient stability prediction and coherency identification in power systems using Koopman mode analysis," *Electric Power Syst. Res.*, vol. 201, Dec. 2021, Art. no. 107565.

[24] L. Wang, H.-W. Li, and C.-T. Wu, "Stability analysis of an integrated offshore wind and seashore wave farm fed to a power grid using a unified power flow controller," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2211–2221, Aug. 2013.

[25] T. B. Nguyen, "Dynamic security assessment of power systems using trajectory sensitivity approach," Ph.D. Dissertation, Dept. Elect. Eng., Univ. Illinois, Champaign, IL, USA, 2002.

[26] J. Rodriguez, J.-S. Lai, and F. Zheng Peng, "Multilevel inverters: A survey of topologies, controls, and applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 724–738, Aug. 2002.

[27] I. Papic, "Mathematical analysis of FACTS devices based on a voltage source converter: Part II: Steady state operational characteristics," *Electr. Power Syst. Res.*, vol. 56, no. 2, pp. 149–157, 2000.

[28] S. Kannan, S. Jayaram, and M. M. A. Salama, "Real and reactive power coordination for a unified power flow controller," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1454–1461, Aug. 2004.

[29] A. Nabavi-Niaki and M. R. Iravani, "Steady-state and dynamic models of unified power flow controller (UPFC) for power system studies," *IEEE Trans. Power Syst.*, vol. 11, no. 4, pp. 1937–1943, Nov. 1996.

[30] A. El Saeed, M. Tantawi, and K. Youssef, "Power quality phenomena in academic building," in *Proc. IEEE Porto Power Tech.*, Porto, Portugal, Sep. 2001, pp. 10–13.

[31] M. H. J. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions* (Power Engineering Series). Piscataway, NJ, USA: Wiley-IEEE, 2000.

[32] C. Dou, J. Yang, Z. Bo, Y. Bi, T. Gui, and X. Li, "Decentralized coordinated robust controller design for multimachine power system based on multi-agent system," in *Proc. 11th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, Birmingham, U.K., 2012, pp. 23–26.

[33] M. Tariq and M. Adnan, "Stabilizing super smart grids using V2G: A probabilistic analysis," in *Proc. IEEE 89th Veh. Technol. Conf. (VTC-Spring)*, Kuala Lumpur, Malaysia, May 2019, pp. 1–5.

[34] M. Tariq, M. Adnan, G. Srivastava, and H. Vincent Poor, "Instability detection and prevention in smart grids under asymmetric faults," *IEEE Trans. Ind. Appl.*, vol. 56, no. 4, pp. 4510–4520, Aug. 2020.

[35] T. Huang and J. Wang, "A practical method of transient stability analysis of stochastic power systems based on EEAC," *Int. J. Electr. Power Energy Syst.*, vol. 107, pp. 167–176, May 2019.

[36] M. Li, A. Pal, A. G. Phadke, and J. S. Thorp, "Transient stability prediction based on apparent impedance trajectory recorded by PMUs," *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 498–504, Jan. 2014.

[37] E. Farantatos, R. Huang, G. J. Cokkinides, and A. P. Meliopoulos, "A predictive generator out-of-step protection and transient stability monitoring scheme enabled by a distributed dynamic state estimator," *IEEE Trans. Power Del.*, vol. 31, no. 4, pp. 1826–1835, Aug. 2016.

[38] N. Ahmad, Y. Ghadi, M. Adnan, and M. Ali, "Load forecasting techniques for power system: Research challenges and survey," *IEEE Access*, vol. 10, pp. 71054–71090, 2022.

[39] M. Tariq and M. Adnan, "Load flow balancing and transient stability analysis in super smart girds using V2G," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Washington, DC, USA, Feb. 2018, pp. 19–22.

[40] M. Adnan, M. Ali, A. Basalamah, and M. Tariq "Preventing cascading failure through fuzzy co-operative control mechanism using V2G," *IEEE Access*, vol. 7, pp. 142607–142622, 2019.

[41] M. Liaqat, M. Gufran Khan, M. Rayyan Fazal, Y. Ghadi, and M. Adnan, "Multi-criteria storage selection model for grid-connected photovoltaics systems," *IEEE Access*, vol. 9, pp. 115506–115522, 2021.

[42] M. Liaqat, Y. Ghadi, and M. Adnan, "Multi-objective optimal power sharing model for futuristic SAARC super smart grids," *IEEE Access*, vol. 10, pp. 328–351, 2022.

[43] M. Adnan, M. Ali, and M. Tariq, "A probabilistic approach for power network stability in smart grids," in *Proc. 15th Int. Conf. Emerg. Technol. (ICET)*, Peshawar, Pakistan, Dec. 2019, pp. 8138–8143.

[44] M. H. Shahbaz and A. A. Amin, "A review of classical and modern control techniques utilized in modern microgrids," *Recent Adv. Electr. Electron. Eng.*, vol. 14, no. 4, pp. 459–472, Jun. 2021.

[45] R. Ebrahimpour, E. K. Abharian, A. A. M. Birjandi, and S. ZeinolabedinMoussavi, "Transient stability assessment of a power system with a UPFC by mixture of experts," *Int. J. Comput. Electr. Eng.*, vol. 2, no. 4, pp. 643–648, 2010.

[46] P. Kundur and O. Malik, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.

[47] H. R. Pota and Y. Dong, "Recent development in direct assessment of transient stability limit," in *Proc. Electr. Energy Conf.*, Jan. 1990, pp. 134–138. Accessed: Aug. 30, 2022. [Online]. Available: https://search.informit.org/doi/10.3316/INFORMIT.608906274959883

[48] M. Ayar, S. Obuz, R. D. Trevizan, A. S. Bretas, and H. A. Latchman, "A distributed control approach for enhancing smart grid transient stability and resilience," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 3035–3044, Nov. 2017.

[49] J. Vijayan. (2010). *Stuxnet Renews Power Grid Security Concerns*. Computerworld. Accessed: Aug. 30, 2022. [Online]. Available: https://www.computerworld.com/article/2519574/stuxnet-renews-power-grid-security-concerns.html

[50] R. M. Lee, M. J. Assante, and T. Conway, "Analysis of the cyber-attack on the Ukrainian power grid," in *Proc. SANS Ind. Control. Syst.*, vol. 388, 2016, pp. 1–29.

[51] *Advancement of SynchroPhasor Technology in Projects Funded by the American*, Office Electr. Del. Energy Rel., Washington, DC, USA, 2016.

[52] A. Karimi and A. Feliachi, "Decentralized adaptive backstepping control of electric power systems," *Electr. Power Syst. Res.*, vol. 78, no. 3, pp. 484–493, Mar. 2008.

[53] N. A. Hidayatullah, Z. J. Paracha, and A. Kalam, "Impact of distributed generation on smart grid transient stability," *Smart Grid Renew. Energy*, vol. 2, no. 2, pp. 99–109, 2011.

[54] A. Rajabi-Ghahnavieh, M. Fotuhi-Firuzabad, M. Shahidehpour, and R. Feuillet, "UPFC for enhancing power system reliability," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2881–2890, Oct. 2010.

[55] R. Mihalic, P. Zunko, and D. Povh, "Improvement of transient stability using unified power flow controller," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 485–492, Jan. 1996.

[56] M. R. Qader, "Design and simulation of a different innovation controller-based UPFC (unified power flow controller) for the enhancement of power quality," *Energy*, vol. 89, pp. 576–592, Sep. 2015.

[57] J. Aghaei, M. Zarei, M. Asban, S. Ghavidel, A. Heidari, and V. G. Agelidis, "Determining potential stability enhancements of flexible AC transmission system devices using corrected transient energy function," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 2, pp. 470–476, Feb. 2016.

[58] D. Sullivan and D. Mader, "Fundamentals and characteristics of dynamic reactive power control," in *Proc. IEEE PESWebinar*, Dec. 2018, pp. 1–8, Accessed: Sep. 25, 2022. [Online]. Available: https://resourcecenter.ieee-pes.org/education/webinars/PESVIDWEBGPS0016.html

[59] *IEEE Approved Draft Guide for the Functional Specifications for Transmission Static Synchronous Compensator (STATCOM) Systems*. Piscataway, NJ, USA: IEEE, 2018.

[60] *IEEE Guide for the Functional Specification of Transmission Static Var Compensators*. Piscataway, NJ, USA: IEEE, 2011.

[61] E. Lannoye, D. Flynn, and M. O'Malley, "Transmission, variable generation, and power system flexibility," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 57–66, Jan. 2015.

[62] S. S. Refaat, H. Abu-Rub, A. P. Sanfilippo, and A. Mohamed, "Impact of grid-tied large-scale photovoltaic system on dynamic voltage stability of electric power grids," *IET Renew. Power Gener.*, vol. 12, no. 2, pp. 157–164, Feb. 2018.

[63] L. Cong and Y. Wang, "Co-ordinated control of generator excitation and STATCOM for rotor angle stability and voltage regulation enhancement of power systems," *IEE Proc. Gener. Transm. Distrib.*, vol. 149, pp. 659–666, Nov. 2002.

[64] A. Esparza, J. Segundo, C. Nuñez, N. Visairo, E. Barocio, and H. García, "Transient stability enhancement using a wide-area controlled SVC: An HIL validation approach," *Energies*, vol. 11, no. 7, p. 1639, Jun. 2018.

[65] A. Kanchanaharuthai, V. Chankong, and K. A. Loparo, "Transient stability and voltage regulation in multimachine power systems vis-à-vis STATCOM and battery energy storage," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2404–2416, Sep. 2015.

[66] M. Adnan, A. Israr, N. Khan, and M. Irfan, "A generic scenario of a load flow study in SAARC countries super grid using high voltage alternating current (HVAC) and high voltage direct current (HVDC)," *Int. J. Sci. Eng. Res.*, vol. 7, pp. 210–223, Jan. 2016.

[67] A. Movahedi, A. H. Niasar, and G. B. Gharehpetian, "Designing SSSC, TCSC, and STATCOM controllers using AVURPSO, GSA, and GA for transient stability improvement of a multi-machine power system with PV and wind farms," *Int. J. Electr. Power Energy Syst.*, vol. 106, pp. 455–466, Mar. 2019.

[68] V. Vittal, E. Z. Zhou, C. Hwang, and A.-A. Fouad, "Derivation of stability limits using analytical sensitivity of the transient energy margin," *IEEE Trans. Power Syst.*, vol. 4, no. 4, pp. 1363–1372, Nov. 1989.

[69] K. N. Shubhanga and A. M. Kulkarni, "Application of structure preserving energy margin sensitivity to determine the effectiveness of shunt and series FACTS devices," *IEEE Trans. Power Syst.*, vol. 17, no. 3, pp. 730–738, Aug. 2002.

[70] K. R. Padiyar and A. Lakshmi Devi, "Control and simulation of static condenser," in *Proc. IEEE Appl. Power Electron. Conf. Exposit. (ASPEC)*, Orlando, FL, USA, Feb. 1994, pp. 13–17.

[71] K. Padiyar and K. U. Rao, "Discrete control of TCSC for stability improvement in power systems," in *Proc. Int. Conf. Control Appl.*, Albany, NY, USA, Sep. 1995, pp. 28–29.

[72] A. Tamim, "Assessment of solar energy potential and development in Afghanistan," in *Proc. ES Web Conf.*, vol. 239, 2021, Art. no. 00012.

[73] S. Sabella, "Complex modeling and analysis of the energy systems in Afghanistan with OSeMOSYS," M.S. thesis, KTH Roy. Inst. Technol., Sweden Aalto Univ., Finland, Europe, 2021.

[74] M. H. Patmal and H. Shiran, "Public awareness and their attitudes toward adopting renewable energy technologies in Afghanistan," *Int. J. Innov. Res. Sci. Stud.*, vol. 4, no. 2, pp. 82–91, Mar. 2021.

[75] M. Jahangiri, A. Haghani, A. Mostafaeipour, A. Khosravi, and H. A. Raeisi, "Assessment of solar-wind power plants in Afghanistan: A review," *Renew. Sustain. Energy Rev.*, vol. 99, pp. 169–190, Jan. 2019.

[76] M. Amin and D. Bernell, "Power sector reform in Afghanistan: Barriers to achieving universal access to electricity," *Energy Policy*, vol. 123, pp. 72–82, Dec. 2018.

[77] G. A. Ludin, M. A. Amin, A. Aminzay, and T. Senjyu, "Theoretical potential and utilization of renewable energy in Afghanistan," *AIMS Energy*, vol. 5, no. 1, pp. 1–19, 2016.

[78] S. Ahady, N. Dev, and A. Mandal, "An overview of the opportunities and challenges in sustaining the energy industry in Afghanistan," in *Proc. ES Web Conf.*, vol. 173, 2020, p. 03006.

[79] F. Aminjonov, "Afghanistan's energy security," in *Proc. Tracing Central Asian Countries' Contribution*, Dec. 2016, pp. 1–30.

[80] R. Rostami, S. M. Khoshnava, H. Lamit, D. Streimikiene, and A. Mardani, "An overview of Afghanistan's trends toward renewable and sustainable energies," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 1440–1464, Sep. 2017.

[81] A. Mostafaeipour, S. J. H. Dehshiri, and S. S. H. Dehshiri, "Ranking locations for producing hydrogen using geothermal energy in Afghanistan," *Int. J. Hydrogen Energy*, vol. 45, no. 32, pp. 15924–15940, Jun. 2020.

[82] O. Odilovich and E. Najibullah, "How to reduce poverty in Afghanistan," *Academic J. Digit. Econ. Stability*, pp. 577–581, Aug. 2021.

[83] S. Ahmadzai and A. McKinna, "Afghanistan electrical energy and trans-boundary water systems analyses: Challenges and opportunities," *Energy Rep.*, vol. 4, pp. 435–469, Nov. 2018.

[84] M. A. Haque. *Bangladesh Power Sector-An Appraisal From a Multi-Dimensional Perspective (Part-1)*. Accessed: Oct. 4, 2021. [Online]. Available: https://www.eblsecurities.com/AM_Resources/AM_ResearchReports/SectorReport/Bangladesh%20power%20sector-An%20appraisal%20from%20a%20multi-dimensional%20perspective%20(Part1)_%20September%202020.pdf

[85] S. E. Sharif, "Bangladesh power sector review for 2020," in *Proc. Ministry Power, Energy Mineral Resour.*, Bangladesh, 2020, pp. 1–11, doi: 10.13140/RG.2.2.33692.51845.

[86] M. N. Uddin, M. A. Rahman, M. Mofijur, J. Taweekun, K. Techato, and M. G. Rasul, "Renewable energy in bangladesh: Status and prospects," *Energy Proc.*, vol. 160, pp. 655–661, Feb. 2019.

[87] A. Z. MdSohag, P. Kumari, R. Agrawal, S. Gupta, and A. Jamwal, "Renewable energy in Bangladesh: Current status and future potentials," in *Proc. Int. Conf. Mech. Energy Technol. (ICMET)*, S. Yadav, D. B. Singh, P. K. Arora, and H. Kumar, Eds. Singapore: Springer, 2020, pp. 353–363, doi: 10.1007/978-981-15-2647-3_32.

[88] S. Alam. *Solar Power can Meet Full Electricity Needs in Bangladesh!*. The Financial Express. Accessed: Oct. 4, 2021. [Online]. Available: https://thefinancialexpress.com.bd/views/solar-power-can-meet-fullelectricity-needs-in-bangladesh-1600876819

[89] M. Rahman. *Do we Have Over Capacity for Power Generation?*. Accessed: Oct. 4, 2021. [Online]. Available: https://thefinancialexpress.com.bd/views/views/do-we-have-over-capacity-forpower-generation-1593791785

[90] N. Tenzin and R. P. Saini, "Wind and solar resource potential assessment in Bhutan," *Int. J. Eng. Adv. Technol.*, vol. 8, no. 3, pp. 391–395, 2019.

[91] K. Lhazom and P. Thanarak, "Power sector prospects and policies of rural electrification in Bhutan," *Naresuan Univ.*, vol. 14, no. 2, pp. 21–37, 2019.

[92] P. Laha and B. Chakraborty, "Low carbon electricity system for India in 2030 based on multi-objective multi-criteria assessment," *Renew. Sustain. Energy Rev.*, vol. 135, Jan. 2021, Art. no. 110356.

[93] L. S. Tiewsoh, J. Jirásek, and M. Sivek, "Electricity generation in India: Present state, future outlook and policy implications," *Energies*, vol. 12, no. 7, p. 1361, Apr. 2019.

[94] A. Sawhney, "Striving towards a circular economy: Climate policy and renewable energy in India," *Clean Technol. Environ. Policy*, vol. 23, no. 2, pp. 491–499, Mar. 2021.

[95] B. R. Singh and O. Singh, "Future scope of solar energy in India," *SAMRIDDHI, A J. Phys. Sci., Eng. Technol.*, vol. 8, no. 1, pp. 20–25, Jun. 2016.

[96] S. S. Raghuwanshi and R. Arya, "Renewable energy potential in India and future agenda of research," *Int. J. Sustain. Eng.*, vol. 12, no. 5, pp. 291–302, Sep. 2019.

[97] W. Van Sark, E. H. Lysen, D. Cocard, P. Beutin, G. F. Merlo, B. Mohanty, J. Vandenakker, A. R. Idris, A. Firag, A. Waheed, and A. Shaheed, "The first PV-diesel hybrid system in the Maldives installed at Mandhoo Island," in *Proc. 21st Eur. Photovoltaic Sol. Energy Conf.*, 2006, pp. 4–8.

[98] I. Ali, G. Shafiullah, and T. Urmee, "A preliminary feasibility of roof-mounted solar PV systems in the Maldives," *Renew. Sustain. Energy Rev.*, vol. 83, pp. 18–32, Mar. 2018.

[99] M. Kamran, M. R. Fazal, and M. Mudassar, "Towards empowerment of the renewable energy sector in Pakistan for sustainable energy evolution: SWOT analysis," *Renew. Energy*, vol. 146, pp. 543–558, Feb. 2020.

[100] M. Irfan, Z.-Y. Zhao, M. K. Panjwani, F. H. Mangi, H. Li, A. Jan, M. Ahmad, and A. Rehman, "Assessing the energy dynamics of pakistan: Prospects of biomass energy," *Energy Rep.*, vol. 6, pp. 80–93, Nov. 2020.

[101] S. Kanwa, B. Khan, and M. Qasim Rauf, "Infrastructure of sustainable energy development in Pakistan: A review," *J. Modern Power Syst. Clean Energy*, vol. 8, no. 2, pp. 206–218, 2020.

[102] A. Battaglini, J. Lilliestam, C. Bals, and A. Haas, "The supersmart grid," in *European Climate Forum*. Potsdam, Germany: Potsdam Institute for Climate Impact Research, Jun. 2008.

[103] Institute of Technical Thermodynamics, Section Systems Analysis and Technology Assessment, GAC DLR. (2006). *Trans-Mediterranean Interconnection for Concentrating Solar Power*. 2006. [Online]. Available: http://www.dlr.de/tt/trans-csp

[104] *Clean Power From Deserts*, DESERTEC, The Club of Rome, Hamburg, Germany, 2007.

[105] Z. Moravej, M. Pazoki, and M. Khederzadeh, "New pattern-recognition method for fault analysis in transmission line with UPFC," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1231–1242, Jun. 2015.

[106] M. A. Pai, *Transient Stability of Power System*. Norwell, MA, USA: Kluwer Academic, 2000.

[107] R. Salim, M. Oleskovicz, and R. Ramos, "Power quality of distributed generation systems as affected by electromechanical oscillations—Definitions and possible solutions," *IET Gener. Transm. Distrib.* vol. 5, no. 11, pp. 1114–1123, 2011.

[108] M. Adnan, M. G. Khan, A. A. Amin, M. R. Fazal, W.-S. Tan, and M. Ali, "Cascading failures assessment in renewable integrated power grids under multiple faults contingencies," *IEEE Access*, vol. 9, pp. 82272–82287, 2021.

[109] E. Solvang, J. Charmasson, J. Sauterleute, A. Harby, Å. Killingtveit, and H. Egeland, "Norwegian hydropower for large-scale electricity balancing needs," SINTEF Energy Research, Trondheim, Norway, Tech. Rep. TR A7227, 2014.

[110] E. Grøv, A. Bruland, B. Nilsen, K. Panthi, and M. Lu, "Developing future 20 000 MW hydro electric power in Norway," HydroBalance, CEDREN, SINTEF, Trondheim, Norway, Tech. Rep. SBF2011A0021, 2011.

[111] *Special Report: World Energy Investment Outlook*, Int. Energy Agency (IEA), Paris, France, 2014.

[112] R. Doherty and M. O'Malley, "A new approach to quantify reserve demand in systems with significant installed wind capacity," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 587–595, May 2005.

[113] B. Mauch, J. Apt, P. M. S. Carvalho, and P. Jaramillo, "What day-ahead reserves are needed in electric grids with high levels of wind power?" *Environ. Res. Lett.*, vol. 8, no. 3, Sep. 2013, Art. no. 034013.

[114] N. Flourentzou, V. G. Agelidis, and G. D. Demetriades, "VSC-based HVDC power transmission systems: An overview," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 592–602, Mar. 2009.

[115] N. B. Negra, J. Todorovic, and T. Ackermann, "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms," *Electr. Power Syst. Res.*, vol. 76, no. 11, pp. 916–927, 2006.

[116] P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati, "HVDC connection of offshore wind farms to the transmission system," *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 37–43, Mar. 2007.

[117] T. K. Vrana and O. B. Fosso, "Technical aspects of the north sea super grid," in *Power System Analyses: Modelling and Solving Techniques*, Cigre Electra, 2011, p. 13.

[118] M. Barnes and A. Beddard, "Voltage source converter HVDC links—The state of the art and issues going forward," *Energy Procedia*, vol. 24, pp. 108–122, 2012.

[119] B. Andersen, L. Xu, P. J. Horton, and P. Cartwright, "Topologies for VSC transmission," *Power Eng. J.*, vol. 16, no. 3, pp. 298–304, Jul. 2002.

[120] U. N. Gnanarathna, A. M. Gole, and R. P. Jayasinghe, "Efficient modeling of modular multilevel HVDC converters (MMC) on electromagnetic transient simulation programs," *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 316–324, Jan. 2011.

[121] M. P. Bahrman, "Overview of HVDC transmission," in *Proc. IEEE PES Power Syst. Conf. Expo.* IEEE, 2006, pp. 18–23.

[122] J. Arrillaga, *High Voltage Direct Current Transmission*, 2nd ed. New York, NY, USA: Institution of Electrical Engineers, 1998.

[123] J. Beerten and R. Belmans, "Modeling and control of multi-terminal VSC HVDC systems," *Energy Proc.*, vol. 24, pp. 123–130, Jan. 2012.

[124] T. M. Haileselassie and K. Uhlen, "Precise control of power flow in multiterminal VSC-HVDCs using DC voltage droop control," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–9.

[125] *Offshore Transmission Technology Report*, ENTSO-E, Brussels, Belgium, 2012.

[126] E. Prieto-Araujo, F. D. Bianchi, A. Junyent-Ferre, and O. Gomis-Bellmunt, "Methodology for droop control dynamic analysis of multiterminal VSC-HVDC grids for offshore wind farms," *IEEE Trans. Power Delivery*, vol. 26, no. 4, pp. 2476–2485, May 2011.

[127] R. T. Pinto, S. F. Rodrigues, P. Bauer, and J. Pierik, "Comparison of direct voltage control methods of multi-terminal DC (MTDC) networks through modular dynamic models," in *Proc. 14th Eur. Conf. Power Electron. Appl.*, 2011, pp. 1–10.

[128] R. E. Torres-Olguin, A. R. Årdal, H. Støylen, A. G. Endegnanew, and K. Ljøkelsøy, "Experimental verification of a voltage droop control for grid integration of offshore wind farms using multi-terminal HVDC," *Energy Proc.*, vol. 53, pp. 104–113, 2014.

[129] D. Van Hertem, M. Ghandhari, and M. Delimar, "Technical limitations towards a SuperGrid—A European prospective," in *Proc. IEEE Int. Energy Conf.*, Dec. 2010, pp. 302–309.

[130] K. DeKerf, K. Srivastava, M. Reza, D. Bekaert, S. Cole, D. Van Hertem, and R. Belmans, "Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems," *IET Gener. Transm. Distrib.*, vol. 5, no. 4, pp. 496–503, Apr. 2011.

[131] M. Walter and C. Franck, "Influence of arc chamber parameters on passive resonance circuit of HVDC circuit breakers," in *Proc. CIGRE Bologna Symp.*, 2011, pp. 1–7.

[132] D. Schmitt, Y. Wang, T. Weyh, and R. Marquardt, ''DC-side fault current management in extended multiterminal-HVDC-grids,'' in *Proc. Int. Multi-Conf. Syst., Sygnals Devices*, Mar. 2012, pp. 1–5.

[133] D. Andersson and A. Henriksson, ''Passive and active DC breakers in the three Gorges-Changzhou HVDC project,'' in *Proc. Int. Conf. Power Syst.*, Wuhan, China, 2001, p. 391.

[134] M. Callavik. (Jan. 28, 2012). *ABB Achieves Another Milestone in Electrical Engineering*. [Online]. Available: http://www.abb-conversations.com/2012/11/abb-achieves-another-milestone-in-electrical-engineering/

[135] M. Callavik. (Nov. 9, 2012). *The Hybrid HVDC Breaker*. [Online]. Available: http://www.abbconversations.com/2012/11/abb-achieves-another-milestone-in-electrical-engineering

[136] S. Cole, ''Steady-state and dynamic modelling of VSC HVDC systems for power system simulation,'' Katholieke Universoteit Leuven, Leuven, Belgium, Tech. Rep. D/2010/7515/78, 2010.

[137] P. Leupp. *HVDC Power Technology a Key Enabler for Evolving Trends*. [Online]. Available: http://www02.abb.com/global/abbzh/abbzh250.nsf/0/c812bd1cb1826afdc1257950002f63d4/$file/HVDCpower-technology_Peter-Leupp.pdf

[138] PRYSMIAN. (Oct. 2023). *Submarine Energy Systems*. [Online]. Available: http://www.prysmian.com/attach/pdf/energy/Leaflet_Submarine_A4.pdf

[139] R. L. Steigerwald, R. W. De Doncker, and M. H. Kheraluwala, ''A comparison of high-power DC–DC soft-switched converter topologies,'' *IEEE Trans. Ind. Appl.*, vol. 32, no. 5, pp. 1139–1145, Sep./Oct. 1996.

[140] A. Hagar, ''A new family of transformerless modular DC–DC converters for high power applications,'' Univ. Toronto, Toronto, ON, USA, Tech. Rep., 2011. [Online]. Available: https://hdl.handle.net/1807/29738

[141] L. Yang, T. Zhao, J. Wang, and A. Q. Huang, ''Design and analysis of a 270 kW five-level DC/DC converter for solid state transformer using 10 kV SiC power devices,'' in *Proc. IEEE Power Electron. Specialists Conf.*, Dec. 2007, pp. 245–251.

[142] G. Ortiz, J. Biela, D. Bortis, and J. W. Kolar, ''1 megawatt, 20 kHz, isolated, bidirectional 12 kV to 1.2 kV DC–DC converter for renewable energy applications,'' in *Proc. Int. Power Electron. Conf. (ECCE ASIA)*, Jun. 2010, pp. 3212–3219.

[143] S. Meier, T. Kjellqvist, S. Norrga, and H.-P. Nee, ''Design considerations for medium-frequency power transformers in offshore wind farms,'' in *Proc. 13th Eur. Conf. Power Electron. Appl.*, 2009, pp. 1–12.

[144] C. Meyer, *Key Components for Future Offshore DC Grids*. Herzogenrath, Germany: Shaker Verlag, 2007.

[145] C. Barker, C. Davidson, and R. Whitehouse, ''Requirements of DC–DC Converters to facilitate large DC Grids,'' in *Proc. CIGRE Symp.*, 2012.

[146] P. Vennemann, K. Heinz Gruber, J. U. Haaheim, A. Kunsch, H. P. Sistenich, and H. R. Thöni, ''Pumped storage plants—Status and perspectives,'' *VGB PowerTech*, vol. 91, no. 4, pp. 32–38, 2011.

[147] S. Succar and R. H. Williams, ''Compressed air energy storage: Theory, resources, and applications for wind power,'' *Princeton Environ. Inst. Rep.*, vol. 8, pp. 1–81, Apr. 2008.

[148] O. C. Spro, ''Value-added of offshore energy storage for deep-sea wind farms,'' in *Proc. EERA Deepwind*, Trondheim, Norway, 2014, p. 1.

[149] G. E. Fennell, ''System design and manufacturability of concrete spheres for undersea pumped hydro energy or hydrocarbon storage,'' Master of Science, Dept. Mech. Eng., Massachusetts Inst. Technol., Cambridge, MA, USA, 2011.

[150] L. Halilbasic and F. Thams, ''Technical and economical scaling rules for the implementation of demo results,'' Best Paths Project, DTU, Europe, Tech. Rep. 612748, Sep. 2018.

[151] D. Rivas and S. Borroy, ''Definition and building of best paths scenario,'' Best Paths Project, CIRCE, Europe, Tech. Rep. 612748, Nov. 2018.

[152] e-Highway2050 Project, ''Europe's future secure and sustainable electricity infrastructure,'' SINTEF Energy Res./Energisystemer, Europe, Tech. Rep., Nov. 2015.

[153] *Vision on Market Design and System Operation Towards 2030*, ENTSO-E, Brussels, Belgium, Aug. 2020.

[154] *TYNDP 2022—Draft Scenario Report*, ENTSO-E, Brussels, Belgium, Oct. 2021.

[155] A. Tosatto and S. Chatzivasileiadis, ''HVDC loss factors in the Nordic power market,'' *Electr. Power Syst. Res.*, vol. 190, Jan. 2021, Art. no. 106710, doi: 10.1016/j.epsr.2020.106710.

[156] *Danish Climate Agreement for Energy and Industry 2020*, Danish Ministry of Energy, Denmark, Jun. 2020.

[157] *Government Report on the National Energy and Climate Strategy for 2030*, Finnish Ministry Econ. Affairs Employment, Finland, Europe, Dec. 2017.

[158] *Sweden's Integrated National Energy and Climate Plan*, Swedish Ministry Environ. Energy, Sweden, Europe, Jan. 2019.

[159] *Electricity Ten Year Statement*, National Grid ESO, Warwick, WMD, USA, Nov. 2019.

[160] *All-Island Ten Year Transmission System Statement*, EirGrid and SONI, Europe, Jul. 2018.

[161] *Transparency Platform*, ENTSO-E, Brussels, Belgium, 2015. [Online]. Available: https://transparency.entsoe.eu/

[162] *Energy Policy: An Overview*, U.K. Parliament, London, U.K., Dec. 2020.

[163] Single Electricity Market Operator. (2007). *The Integrated Single Electricity Market is a new wholesale market for Ireland and Northern Ireland*. Accessed: Jan. 12, 2022. [Online]. Available: https://www.sem-o.com/

[164] Nord Pool Group. (2014). *Explicit and Implicit Capacity Auction*. [Online]. Available: https://www.nordpoolgroup.com/4a8398/globalassets/download-center/pcr/how-does-it-work_explicit-and-implicit-capacity-auction.pdf

[165] EPEX Spot. (2014). *European Market Coupling*. [Online]. Available: https://www.ep exspot.com/en/marketcoupling

[166] T. V. Jensen and P. Pinson, ''RE-Europe, a large-scale dataset for modeling a highly renewable European electricity system,'' *Sci. Data*, vol. 4, Nov. 2017, Art. no. 170175, doi: 10.1038/sdata.2017.175.

[167] *Covenant of Mayors for Climate and Energy: Default Emission Factors for Local Emission Inventories*, Joint Res. Centre (JRC), European, Feb. 2017.

[168] ENTSO-E. (2016). *Statistics and Data*. [Online]. Available: https://www.entsoe.eu/publications/statistics-and-data/

[169] B. Sørensen, ''Energy and resources,'' *Energy*, vol. 189, no. 4199, pp. 255–260, 1975.

[170] A. B. Lovins, *The Most Important Issue We've Ever Published*, vol. 6, no. 20. New York, NY, USA: New York Times, 1977.

[171] A. B. Lovins, ''Long-term constraints on human activity,'' *Environ. Conservation*, vol. 3, no. 1, pp. 3–14, 1976, doi: 10.1017/S0376892900017641.

[172] S. Sgouridis, C. Kimmich, J. Solé, M. Cerný, M.-H. Ehlers, and C. Kerschner, ''Visions before models: The ethos of energy modeling in an era of transition,'' *Energy Res. Social Sci.*, vol. 88, Jun. 2022, Art. no. 102497, doi: 10.1016/j.erss.2022.102497.

[173] B. Sørensen, ''Scenarios for greenhouse warming mitigation,'' *Energy Convers. Manage.*, vol. 37, nos. 6–8, pp. 693–698, Jun. 1996.

[174] *Towards a Fossil Free Energy Future*, [SEI] Stockholm Environ. Inst., Amsterdam, The Netherlands, 1993. [Online]. Available: http://www.energycommunity.org/documents/greenpeacereport.pdf

[175] M. Z. Jacobson and M. A. Delucchi, ''A path to sustainable energy by 2030,'' *Sci. Amer.*, vol. 301, no. 5, pp. 58–65, Nov. 2009, doi: 10.1038/scientificamerican1109-58.

[176] M. Z. Jacobson and M. A. Delucchi, ''Providing all global energy with wind, water, and solar power, part I: Technologies, energy resources, quantities and areas of infrastructure, and materials,'' *Energy Policy*, vol. 39, no. 3, pp. 1154–1169, Mar. 2011, doi: 10.1016/j.enpol.2010.11.040.

[177] M. A. Delucchi and M. Z. Jacobson, ''Providing all global energy with wind, water, and solar power, part II: Reliability, system and transmission costs, and policies,'' *Energy Policy*, vol. 39, no. 3, pp. 1170–1190, Mar. 2011, doi: 10.1016/j.enpol.2010.11.045.

[178] M. L. A. Junginger, *Technological Learning in the Transition to a Low-Carbon Energy System*. New York, NY, USA: Academic, 2019.

[179] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, S. J. Coughlin, C. A. Hay, I. P. Manogaran, Y. Shu, and A.-K. von Krauland, ''Impacts of green new deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries,'' *One Earth*, vol. 1, no. 4, pp. 449–463, Dec. 2019, doi: 10.1016/j.oneear.2019.12.003.

[180] M. Z. Jacobson, M. A. Delucchi, Z. A. Bauer, S. C. Goodman, W. E. Chapman, M. A. Cameron, C. Bozonnat, L. Chobadi, and H. A. Clonts, ''100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world,'' *Joule*, vol. 1, no. 1, pp. 108–121, Sep. 2017, doi: 10.1016/j.joule.2017.07.005.

[181] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, and B. V. Mathiesen, ''Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes,'' *Renew. Energy*, vol. 123, pp. 236–248, Aug. 2018, doi: 10.1016/j.renene.2018.02.009.

[182] M. Z. Jacobson, ''On the correlation between building heat demand and wind energy supply and how it helps to avoid blackouts,'' *Smart Energy*, vol. 1, Feb. 2021, Art. no. 100009, doi: 10.1016/j.segy.2021.100009.

[183] M. Z. Jacobson, ''The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected,'' *Renew. Energy*, vol. 179, pp. 1065–1075, Dec. 2021, doi: 10.1016/j.renene.2021.07.115.

[184] M. Z. Jacobson, A.-K. von Krauland, S. J. Coughlin, E. Dukas, A. J. H. Nelson, F. C. Palmer, and K. R. Rasmussen, ''Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries,'' *Energy Environ. Sci.*, vol. 15, no. 8, pp. 3343–3359, Aug. 2022, doi: 10.1039/d2ee00722c.

[185] M. Z. Jacobson, W. G. Colella, and D. M. Golden, ''Atmospheric science: Cleaning the air and improving health with hydrogen fuel-cell vehicles,'' *Science*, vol. 308, no. 5730, pp. 1901–1905, Jun. 2005, doi: 10.1126/science.1109157.

[186] K. Hansen, C. Breyer, and H. Lund, ''Status and perspectives on 100% renewable energy systems,'' *Energy*, vol. 175, pp. 471–480, May 2019, doi: 10.1016/j.energy.2019.03.092.

[187] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, ''The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system,'' *Energy Convers. Manage.*, vol. 201, Dec. 2019, Art. no. 111977, doi: 10.1016/j.enconman.2019.111977.

[188] O. H. Hohmeyer and S. Bohm, ''Trends toward 100% renewable electricity supply in Germany and Europe: A paradigm shift in energy policies,'' *WIREs Energy Environ.*, vol. 4, no. 1, pp. 74–97, Jan. 2015, doi: 10.1002/wene.128.

[189] C. Breyer, D. Bogdanov, A. Aghahosseini, A. Gulagi, and M. Fasihi, ''On the techno-economic benefits of a global energy interconnection,'' *Econ. Energy Environ. Policy*, vol. 9, no. 1, pp. 83–102, Jan. 2020, doi: 10.5547/2160-5890.9.1.cbre.

[190] G. Czisch, *Szenarien Zur Zukünftigen Stromversorgung Kostenoptimierte Variationen zur Versorgung Europas Und Seiner Nachbarn MIT Strom Aus Erneuerbaren Energien*. Kassel, Germany: Kassel University, 2005.

[191] M. Biberacher, *Modelling and Optimisation of Future Energy Systems Using Spatial and Temporal Methods*. Minneapolis, MN, USA: Augsburg University, 2004.

[192] F. Trieb and H. Müller-Steinhagen, ''Europe–middle east–north Africa cooperation for sustainable electricity and water,'' *Sustainability Sci.*, vol. 2, no. 2, pp. 205–219, Sep. 2007, doi: 10.1007/s11625-007-0025-x.

[193] F. Trieb, C. Schillings, T. Pregger, and M. O'Sullivan, ''Solar electricity imports from the middle east and north Africa to Europe,'' *Energy Policy*, vol. 42, pp. 341–353, Mar. 2012, doi: 10.1016/j.enpol.2011.11.091.

[194] Y. Scholz, *Renewable Energy Based Electricity Supply at Low Costs Development of the REMix Model and Application for Europe*. Stuttgart, Germany: Stuttgart University, 2012.

[195] H. C. Gils, Y. Scholz, T. Pregger, D. Luca de Tena, and D. Heide, ''Integrated modelling of variable renewable energy-based power supply in Europe,'' *Energy*, vol. 123, pp. 173–188, Mar. 2017, doi: 10.1016/j.energy.2017.01.115.

[196] D. Heide, L. von Bremen, M. Greiner, C. Hoffmann, M. Speckmann, and S. Bofinger, ''Seasonal optimal mix of wind and solar power in a future, highly renewable Europe,'' *Renew. Energy*, vol. 35, no. 11, pp. 2483–2489, Nov. 2010, doi: 10.1016/j.renene.2010.03.012.

[197] E. H. Eriksen, L. J. Schwenk-Nebbe, B. Tranberg, T. Brown, and M. Greiner, ''Optimal heterogeneity in a simplified highly renewable European electricity system,'' *Energy*, vol. 133, pp. 913–928, Aug. 2017, doi: 10.1016/j.energy.2017.05.170.

[198] R. A. Rodriguez, S. Becker, and M. Greiner, ''Cost-optimal design of a simplified, highly renewable pan-European electricity system,'' *Energy*, vol. 83, pp. 658–668, Apr. 2015, doi: 10.1016/j.energy.2015.02.066.

[199] R. A. Rodríguez, S. Becker, G. B. Andresen, D. Heide, and M. Greiner, ''Transmission needs across a fully renewable European power system,'' *Renew. Energy*, vol. 63, pp. 467–476, Mar. 2014, doi: 10.1016/j.renene.2013.10.005.

[200] M. G. Rasmussen, G. B. Andresen, and M. Greiner, ''Storage and balancing synergies in a fully or highly renewable pan-European power system,'' *Energy Policy*, vol. 51, pp. 642–651, Dec. 2012, doi: 10.1016/j.enpol.2012.09.009.

[201] T. V. Jensen and M. Greiner, ''Emergence of a phase transition for the required amount of storage in highly renewable electricity systems,'' *Eur. Phys. J. Special Topics*, vol. 223, no. 12, pp. 2475–2481, Oct. 2014, doi: 10.1140/epjst/e2014-02216-9.

[202] H. Lund, ''Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply,'' *Renew. Energy*, vol. 31, no. 4, pp. 503–515, Apr. 2006, doi: 10.1016/j.renene.2005.04.008.

[203] H. Lund. *EnergyPLAN: Advanced Energy System Analysis Computer Model*. Accessed: Nov. 18, 2021. [Online]. Available: https://www.energyplan.eu

[204] H. Lund, J. Z. Thellufsen, P. A. Østergaard, P. Sorknæs, I. R. Skov, and B. V. Mathiesen, ''EnergyPLAN–advanced analysis of smart energy systems,'' *Smart Energy*, vol. 1, Feb. 2021, Art. no. 100007, doi: 10.1016/j.segy.2021.100007.

[205] B. V. Mathiesen, H. Lund, and K. Karlsson, ''100% renewable energy systems, climate mitigation and economic growth,'' *Appl. Energy*, vol. 88, no. 2, pp. 488–501, Feb. 2011, doi: 10.1016/j.apenergy.2010.03.001.

[206] H. Lund and B. V. Mathiesen, ''Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050,'' *Energy*, vol. 34, no. 5, pp. 524–531, May 2009, doi: 10.1016/j.energy.2008.04.003.

[207] D. Connolly, H. Lund, and B. V. Mathiesen, ''Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European union,'' *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1634–1653, Jul. 2016, doi: 10.1016/j.rser.2016.02.025.

[208] H. Lund, A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, and D. Connolly, ''From electricity smart grids to smart energy systems—A market operation based approach and understanding,'' *Energy*, vol. 42, no. 1, pp. 96–102, Jun. 2012, doi: 10.1016/j.energy.2012.04.003.

[209] H. Lund, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, ''Smart energy and smart energy systems,'' *Energy*, vol. 137, pp. 556–565, Oct. 2017, doi: 10.1016/j.energy.2017.05.123.

[210] B. V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnøe, K. Sperling, and F. K. Hvelplund, ''Smart energy systems for coherent 100% renewable energy and transport solutions,'' *Appl. Energy*, vol. 145, pp. 139–154, May 2015, doi: 10.1016/j.apenergy.2015.01.075.

[211] J. Ikäheimo, J. Kiviluoma, R. Weiss, and H. Holttinen, ''Power-to-ammonia in future north European 100% renewable power and heat system,'' *Int. J. Hydrogen Energy*, vol. 43, no. 36, pp. 17295–17308, Sep. 2018, doi: 10.1016/j.ijhydene.2018.06.121.

[212] K. Zhu, M. Victoria, T. Brown, G. B. Andresen, and M. Greiner, ''Impact of CO_2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe,'' *Appl. Energy*, vol. 236, pp. 622–634, Feb. 2019, doi: 10.1016/j.apenergy.2018.12.016.

[213] D. Keiner, L. D. S. N. S. Barbosa, D. Bogdanov, A. Aghahosseini, A. Gulagi, S. Oyewo, M. Child, S. Khalili, and C. Breyer, ''Global-local heat demand development for the energy transition time frame up to 2050,'' *Energies*, vol. 14, no. 13, p. 3814, Jun. 2021, doi: 10.3390/en14133814.

[214] A. Nadolny, C. Cheng, B. Lu, A. Blakers, and M. Stocks, ''Fully electrified land transport in 100% renewable electricity networks dominated by variable generation,'' *Renew. Energy*, vol. 182, pp. 562–577, Jan. 2022, doi: 10.1016/j.renene.2021.10.039.

[215] M. Robinius, A. Otto, K. Syranidis, D. S. Ryberg, P. Heuser, L. Welder, T. Grube, P. Markewitz, V. Tietze, and D. Stolten, ''Linking the power and transport sectors—Part 2: Modelling a sector coupling scenario for Germany,'' *Energies*, vol. 10, no. 7, p. 957, Jul. 2017, doi: 10.3390/en10070957.

[216] S. Khalili, E. Rantanen, D. Bogdanov, and C. Breyer, ''Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world,'' *Energies*, vol. 12, no. 20, p. 3870, Oct. 2019, doi: 10.3390/en12203870.

[217] M. Sterner, *Bioenergy and Renewable Power Methane in Integrated 100% Renewabe Energy Systems*. Kassel, Germany: Kassel University, 2009.

[218] K. Ohkawa, K. Hashimoto, A. Fujishima, Y. Noguchi, and S. Nakayama, "Electrochemical reduction of carbon dioxide on hydrogenstoring materials: Part 1. The effect of hydrogen absorption on the electrochemical behavior on palladium electrodes," *J. Electroanal. Chem.*, vol. 345, nos. 1–2, pp. 445–456, 1993, doi: 10.1016/0022-0728(93)80495-4.

[219] A. Bandi, M. Specht, T. Weimer, and K. Schaber, "CO_2 recycling for hydrogen storage and transportation—Electrochemical CO_2 removal and fixation," *Energy Convers. Manage.*, vol. 36, nos. 6–9, pp. 899–902, 1995, doi: 10.1016/0196-8904(95)00148-7.

[220] M. Specht, F. Staiss, A. Bandi, and T. Weimer, "Comparison of the renewable transportation fuels, liquid hydrogen and methanol, with gasoline—Energetic and economic aspects," *Int. J. Hydrogen Energy*, vol. 23, no. 5, pp. 387–396, 1998, doi: 10.1016/s0360-3199(97)00077-3.

[221] M. Fasihi, O. Efimova, and C. Breyer, "Techno-economic assessment of CO_2 direct air capture plants," *J. Cleaner Prod.*, vol. 224, pp. 957–980, Jul. 2019, doi: 10.1016/j.jclepro.2019.03.086.

[222] D. Connolly, B. V. Mathiesen, and I. Ridjan, "A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system," *Energy*, vol. 73, pp. 110–125, Aug. 2014, doi: 10.1016/j.energy.2014.05.104.

[223] M. S. Kany, B. V. Mathiesen, I. R. Skov, A. D. Korberg, J. Z. Thellufsen, H. Lund, P. Sorknæs, and M. Chang, "Energy efficient decarbonisation strategy for the Danish transport sector by 2045," *Smart Energy*, vol. 5, Feb. 2022, Art. no. 100063, doi: 10.1016/j.segy.2022.100063.

[224] B. V. Mathiesen and H. P. Lund Nørgaard, "Integrated transport and renewable energy systems," *Utilities Policy*, vol. 16, no. 2, pp. 107–116, Jun. 2008, doi: 10.1016/j.jup.2007.11.007.

[225] M. Sterner and M. Specht, "Power-to-gas and power-to-X—The history and results of developing a new storage concept," *Energies*, vol. 14, no. 20, p. 6594, Oct. 2021, doi: 10.3390/en14206594.

[226] P. Gabrielli, M. Gazzani, and M. Mazzotti, "The role of carbon capture and utilization, carbon capture and storage, and biomass to enable a net-zero-CO_2 emissions chemical industry," *Ind. Eng. Chem. Res.*, vol. 59, no. 15, pp. 7033–7045, Apr. 2020, doi: 10.1021/acs.iecr.9b06579.

[227] Á. Galán-Martín, V. Tulus, I. Díaz, C. Pozo, J. Pérez-Ramírez, and G. Guillén-Gosálbez, "Sustainability footprints of a renewable carbon transition for the petrochemical sector within planetary boundaries," *One Earth*, vol. 4, no. 4, pp. 565–583, Apr. 2021, doi: 10.1016/j.oneear.2021.04.001.

[228] V. Becattini, P. Gabrielli, and M. Mazzotti, "Role of carbon capture, storage, and utilization to enable a net-zero-CO_2-emissions aviation sector," *Ind. Eng. Chem. Res.*, vol. 60, no. 18, pp. 6848–6862, May 2021, doi: 10.1021/acs.iecr.0c05392.

[229] S. Horvath, M. Fasihi, and C. Breyer, "Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040," *Energy Convers. Manage.*, vol. 164, pp. 230–241, May 2018, doi: 10.1016/j.enconman.2018.02.098.

[230] B. Stolz, M. Held, G. Georges, and K. Boulouchos, "Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe," *Nature Energy*, vol. 7, no. 2, pp. 203–212, Jan. 2022, doi: 10.1038/s41560-021-00957-9.

[231] M. Fasihi, R. Weiss, J. Savolainen, and C. Breyer, "Global potential of green ammonia based on hybrid PV-wind power plants," *Appl. Energy*, vol. 294, Jul. 2021, Art. no. 116170, doi: 10.1016/j.apenergy.2020.116170.

[232] O. Osman, S. Sgouridis, and A. Sleptchenko, "Scaling the production of renewable ammonia: A techno-economic optimization applied in regions with high insolation," *J. Cleaner Prod.*, vol. 271, Oct. 2020, Art. no. 121627, doi: 10.1016/j.jclepro.2020.121627.

[233] F. Lonis, V. Tola, and G. Cau, "Assessment of integrated energy systems for the production and use of renewable methanol by water electrolysis and CO_2 hydrogenation," *Fuel*, vol. 285, Feb. 2021, Art. no. 119160, doi: 10.1016/j.fuel.2020.119160.

[234] D. Bogdanov, A. Gulagi, M. Fasihi, and C. Breyer, "Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination," *Appl. Energy*, vol. 283, Feb. 2021, Art. no. 116273, doi: 10.1016/j.apenergy.2020.116273.

[235] D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A. S. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. D. S. N. S. Barbosa, M. Fasihi, S. Khalili, T. Traber, and C. Breyer, "Low-cost renewable electricity as the key driver of the global energy transition towards sustainability," *Energy*, vol. 227, Jul. 2021, Art. no. 120467, doi: 10.1016/j.energy.2021.120467.

[236] T. Galimova, M. Ram, D. Bogdanov, M. Fasihi, S. Khalili, A. Gulagi, H. Karjunen, T. N. O. Mensah, and C. Breyer, "Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals," *J. Cleaner Prod.*, vol. 373, Nov. 2022, Art. no. 133920.

[237] C. Hepburn, E. Adlen, J. Beddington, E. A. Carter, S. Fuss, N. M. Dowell, J. C. Minx, P. Smith, and C. K. Williams, "The technological and economic prospects for CO_2 utilization and removal," *Nature*, vol. 575, no. 7781, pp. 87–97, Nov. 2019, doi: 10.1038/s41586-019-1681-6.

[238] C. Sapart, "CCU as a solution to mitigate climate change: State of the art and perspectives," in *Proc. 16th Int. Conf. Greenhouse Gas Control Technol. (GHGT)*, 2022, p. 4286792.

[239] R. J. Detz and B. van der Zwaan, "Transitioning towards negative CO_2 emissions," *Energy Policy*, vol. 133, Oct. 2019, Art. no. 110938, doi: 10.1016/j.enpol.2019.110938.

[240] L. Desport and S. Selosse, "An overview of CO_2 capture and utilization in energy models," *Resour., Conservation Recycling*, vol. 180, May 2022, Art. no. 106150, doi: 10.1016/j.resconrec.2021.106150.

[241] H. Ostovari, A. Sternberg, and A. Bardow, "Rock 'n' use of CO_2: Carbon footprint of carbon capture and utilization by mineralization," *Sustain. Energy Fuels*, vol. 4, no. 5, pp. 4482–4496, Aug. 2020, doi: 10.1039/D0SE00190B.

[242] C. Breyer, M. Fasihi, C. Bajamundi, and F. Creutzig, "Direct air capture of CO_2: A key technology for ambitious climate change mitigation," *Joule*, vol. 3, no. 9, pp. 2053–2057, Sep. 2019, doi: 10.1016/j.joule.2019.08.010.

[243] T. Bruhn, H. Naims, and B. Olfe-Kräutlein, "Separating the debate on CO_2 utilisation from carbon capture and storage," *Environ. Sci. Policy*, vol. 60, pp. 38–43, Jun. 2016, doi: 10.1016/j.envsci.2016.03.001.

[244] *Energy [R]evolution—A Sustainable World Energy Outlook*, Greenpeace Int., Eur. Renew. Energy Council (EREC), Amsterdam, The Netherlands, 2010, doi: 10.1136/bmj.h4754.

[245] S. Teske, T. Pregger, S. Simon, and T. Naegler, "High renewable energy penetration scenarios and their implications for urban energy and transport systems," *Current Opinion Environ. Sustainability*, vol. 30, pp. 89–102, Feb. 2018, doi: 10.1016/j.cosust.2018.04.007.

[246] S. Teske, *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios With Non-Energy GHG Pathways for +1.5°C and +2°C*. Cham, Switzerland: Springer, 2019.

[247] S. Teske, T. Pregger, S. Simon, T. Naegler, J. Pagenkopf, Ö. Deniz, B. van den Adel, K. Dooley, and M. Meinshausen, "It is still possible to achieve the Paris climate agreement: Regional, sectoral, and land-use pathways," *Energies*, vol. 14, no. 8, p. 2103, Apr. 2021, doi: 10.3390/en14082103.

[248] H. C. Gils and S. Simon, "Carbon neutral archipelago–100% renewable energy supply for the Canary islands," *Appl. Energy*, vol. 188, pp. 342–355, Feb. 2017, doi: 10.1016/j.apenergy.2016.12.023.

[249] Openmod. *Open Energy Modelling Initiative*. Accessed: Feb. 15, 2022. [Online]. Available: https://openmod-initiative.org

[250] S. Pfenninger et al., "Opening the black box of energy modelling: Strategies and lessons learned," *Energy Strategy Rev.*, vol. 19, pp. 63–71, Jan. 2018, doi: 10.1016/j.esr.2017.12.002.

[251] Openmod. *Energypedia*. Accessed: Feb. 15, 2022. [Online]. Available: https://wiki.openmod-initiative.org/wiki/Open_Models

[252] T. Brown, J. Hörsch, and D. Schlachtberger, "PyPSA: Python for power system analysis," *J. Open Res. Softw.*, vol. 6, no. 1, p. 4, Jan. 2018, doi: 10.5334/jors.188.

[253] J. Hörsch, F. Hofmann, D. Schlachtberger, and T. Brown, "PyPSA-eur: An open optimisation model of the European transmission system," *Energy Strategy Rev.*, vol. 22, pp. 207–215, Nov. 2018, doi: 10.1016/j.esr.2018.08.012.

[254] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system," *Energy*, vol. 160, pp. 720–739, Oct. 2018, doi: 10.1016/j.energy.2018.06.222.

[255] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, ''Early decarbonisation of the European energy system pays off,'' *Nature Commun.*, vol. 11, no. 1, p. 6223, Dec. 2020, doi: 10.1038/s41467-020-20015-4.

[256] M. Victoria, E. Zeyen, and T. Brown, ''Speed of technological transformations required in Europe to achieve different climate goals,'' *Joule*, vol. 6, no. 5, pp. 1066–1086, May 2022, doi: 10.1016/j.joule.2022.04.016.

[257] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, ''Classification and challenges of bottom-up energy system models—A review,'' *Renew. Sustain. Energy Rev.*, vol. 129, Sep. 2020, Art. no. 109917, doi: 10.1016/j.rser.2020.109917.

[258] D. Bogdanov, A. Toktarova, and C. Breyer, ''Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan,'' *Appl. Energy*, vol. 253, Nov. 2019, Art. no. 113606, doi: 10.1016/j.apenergy.2019.113606.

[259] U. Caldera, D. Bogdanov, S. Afanasyeva, and C. Breyer, ''Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia,'' *Water*, vol. 10, no. 1, p. 3, Dec. 2017, doi: 10.3390/w10010003.

[260] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. de Souza Noel Simas Barbosa, and C. Breyer, ''Radical transformation pathway towards sustainable electricity via evolutionary steps,'' *Nature Commun.*, vol. 10, no. 1, p. 1077, Mar. 2019, doi: 10.1038/s41467-019-08855-1.

[261] D. Bogdanov and C. Breyer, ''North-east Asian super grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options,'' *Energy Convers. Manage.*, vol. 112, pp. 176–190, Mar. 2016, doi: 10.1016/j.enconman.2016.01.019.

[262] G. Pleßmann, M. Erdmann, M. Hlusiak, and C. Breyer, ''Global energy storage demand for a 100% renewable electricity supply,'' *Energy Proc.*, vol. 46, pp. 22–31, Jan. 2014, doi: 10.1016/j.egypro.2014.01.154.

[263] A. Gulagi, M. Ram, and C. Breyer, ''Solar-wind complementarity with optimal storage and transmission in mitigating the monsoon effect in achieving a fully sustainable electricity system for India,'' in *Proc. 1st Int. Conf. Large-Scale Grid Integr. Renew. Energy India*, 2017, pp. 1–6. [Online]. Available: https://www.researchgate.net/publication/319516069

[264] C. Breyer, D. Bogdanov, S. Khalili, and D. Keiner, ''Solar photovoltaics in 100% renewable energy systems,'' in *Encyclopedia of Sustainability Science and Technology*. New York, NY, USA: Springer, doi: 10.1007/978-1-4939-2493-6_1071-1.

[265] E. Pursiheimo, H. Holttinen, and T. Koljonen, ''Inter-sectoral effects of high renewable energy share in global energy system,'' *Renew. Energy*, vol. 136, pp. 1119–1129, Jun. 2019, doi: 10.1016/j.renene.2018.09.082.

[266] G. Luderer, S. Madeddu, L. Merfort, F. Ueckerdt, M. Pehl, R. Pietzcker, M. Rottoli, F. Schreyer, N. Bauer, L. Baumstark, C. Bertram, A. Dirnaichner, F. Humpenöder, A. Levesque, A. Popp, R. Rodrigues, J. Strefler, and E. Kriegler, ''Impact of declining renewable energy costs on electrification in low-emission scenarios,'' *Nature Energy*, vol. 7, no. 1, pp. 32–42, Jan. 2022, doi: 10.1038/s41560-021-00937-z.

[267] N. Helistö, J. Kiviluoma, H. Holttinen, J. D. Lara, and B. Hodge, ''Including operational aspects in the planning of power systems with large amounts of variable generation: A review of modeling approaches,'' *WIREs Energy Environ.*, vol. 8, no. 5, pp. 1–34, Sep. 2019, doi: 10.1002/wene.341.

[268] *Transmission Planning for 100% Clean Electricity*, [ESIG] Energy Systems Integration Group, Reston, VA, USA, Accessed: Mar. 11, 2022. [Online]. Available: https://www.esig.energy/transmission-planning-for 100-clean-electricity

[269] J. Taouba, M. Uros, and G. Dominic. (2018). *Deliverable 3.3: New Options for Existing System Services and Needs for New System Services*. [Online]. Available: https://www.h2020-migrate.eu/_Resources/Persistent/5c5beff0d5bef78799253aae9b19f50a9cb6eb9f/D3.2Localcontrolandsimulationtoolsforlargetransmissionsystems.pdf

[270] H. Holttinen, J. Kiviluoma, D. Flynn, J. C. Smith, A. Orths, P. B. Eriksen, N. Cutululis, L. Soder, M. Korpas, A. Estanqueiro, J. MacDowell, A. Tuohy, T. K. Vrana, and M. O'Malley, ''System impact studies for near 100% renewable energy systems dominated by inverter based variable generation,'' *IEEE Trans. Power Syst.*, vol. 37, no. 4, pp. 3249–3258, Jul. 2022, doi: 10.1109/tpwrs.2020.3034924.

[271] C.-J. Winter and J. Nitsch, *Hydrogen as an Energy Carrier: Technologies, Systems, Economy*. Berlin, Germany: Springer, 1988.

[272] M. N. J. Fischedick, O. Langniß, *Nach Dem Ausstieg: Zukunftskurs Erneuerbare Energien*. Stuttgart: Hirzel, 2000.

[273] *Energiekonzept Für Eine Umweltschonende, Zuverlässige und Bezahlbare Energieversorgung*, Ministries of Economic Affairs and Environment for the Federal Government, Berlin, Germany, 2010.

[274] T. Pregger, J. Nitsch, and T. Naegler, ''Long-term scenarios and strategies for the deployment of renewable energies in Germany,'' *Energy Policy*, vol. 59, pp. 350–360, Aug. 2013, doi: 10.1016/j.enpol.2013.03.049.

[275] J. Nitsch. (2012). *Long-Term Scenarios and Strategies for the Deployment of Renewable Energies in Germany in View of European and Global Developments Summary of the Final Report*. Berlin, Germany. [Online]. Available: https://elib.dlr.de/76044/

[276] A. Palzer and H.-M. Henning, ''A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part II: Results,'' *Renew. Sustain. Energy Rev.*, vol. 30, pp. 1019–1034, Feb. 2014, doi: 10.1016/j.rser.2013.11.032.

[277] G. Hagedorn, ''The concerns of the young protesters are justified: A statement by scientists for future concerning the protests for more climate protection,'' *GAIA Ecolog. Perspect. Sci. Soc.*, vol. 28, no. 2, pp. 79–87, Jan. 2019, doi: 10.14512/gaia.28.2.3.

[278] C. Gerhards, ''Klimaverträgliche Energieversorgung Für deutschland 16 Orientierungspunkte,'' *Germany Diskussionsbeiträge der Scientists Future*, vol. 7, p. 55, Apr. 2021, doi: 10.5281/zenodo.4409334.

[279] *Resource-Eficient Pathways Towards Greenhouse-Gas-Neutrality RESCUE Summary Report*, [UBA] German Environ. Agency, Berlin, Germany, 2019. [Online]. Available: https://www.umweltbundesamt.de/en/rescue

[280] G. Luderer, C. Kost, and D. Sörgel, *Deutschland Auf Dem Weg Zur Klimaneutralität 2045 Szenarien und Pfade im Modellvergleich (Ariadne-Report)*. Potsdam, Germany: PIK, 2021, doi: 10.48485/pik.2021.006.

[281] S. Simon, M. Xiao, C. Harpprecht, S. Sasanpour, H. Gardian, and T. Pregger, ''A pathway for the German energy sector compatible with a 1.5 °C carbon budget,'' *Sustainability*, vol. 14, no. 2, p. 1025, Jan. 2022, doi: 10.3390/su14021025.

[282] K. Hansen, B. V. Mathiesen, and I. R. Skov, ''Full energy system transition towards 100% renewable energy in Germany in 2050,'' *Renew. Sustain. Energy Rev.*, vol. 102, pp. 1–13, Mar. 2019, doi: 10.1016/j.rser.2018.11.038.

[283] H. K. Bartholdsen, ''Pathways for Germany's low-carbon energy transformation towards 2050,'' *Energies*, vol. 14, no. 15, p. 2988, 2019, doi: 10.3390/en12152988.

[284] T. Traber, F. S. Hegner, and H.-J. Fell, ''An economically viable 100% renewable energy system for all energy sectors of Germany in 2030,'' *Energies*, vol. 14, no. 17, p. 5230, Aug. 2021, doi: 10.3390/en14175230.

[285] C. Breyer, *Vergleich Und Optimierung Von Zentral Und Dezentral Orientierten Ausbaupfaden Zu Einer Stromversorgung Aus Erneuerbaren Energien in Deutschland*. Berlin, Germany: Reiner Lemoine Institute, 2013, Accessed: Mar. 11, 2022. [Online]. Available: https://reiner-lemoine-institut.de/wpcontent/publications/0_Vergleich_und_Optimierung _zentral_unddezentral_071_100EE/Breyer2013.pdf

[286] S. Weitemeyer, D. Kleinhans, T. Vogt, and C. Agert, ''Integration of renewable energy sources in future power systems: The role of storage,'' *Renew. Energy*, vol. 75, pp. 14–20, Mar. 2015, doi: 10.1016/j.renene.2014.09.028.

[287] S. Khalili and C. Breyer, ''Review on 100% renewable energy system analyses—A bibliometric perspective,'' *IEEE Access*, vol. 10, pp. 125792–125834, 2022.

[288] H. Lund, F. Arler, P. Østergaard, F. Hvelplund, D. Connolly, B. Mathiesen, and P. Karnøe, ''Simulation versus optimisation: Theoretical positions in energy system modelling,'' *Energies*, vol. 10, no. 7, p. 840, Jun. 2017, doi: 10.3390/en10070840.

[289] A. Kätelhön, R. Meys, S. Deutz, S. Suh, and A. Bardow, ''Climate change mitigation potential of carbon capture and utilization in the chemical industry,'' *Proc. Nat. Acad. Sci. USA*, vol. 116, no. 23, pp. 11187–11194, Jun. 2019, doi: 10.1073/pnas.1821029116.

[290] K.-K. Cao, F. Cebulla, J. J. Gómez Vilchez, B. Mousavi, and S. Prehofer, ''Raising awareness in model-based energy scenario studies—A transparency checklist,'' *Energy, Sustainability Soc.*, vol. 6, no. 1, pp. 1–20, Dec. 2016, doi: 10.1186/s13705-016-0090-z.

[291] F. D. M. Parzan and L. Franken. (2022). *Global Socio-Economic and Environmental Data for PyPSA-Earth: An Open Optimisation Model of the Earth Energy System*. Accessed: Feb. 19, 2022. [Online]. Available: https://zenodo.org/record/5895010#.YhFIb-hBxPY

[292] S. Teske, T. Morris, and K. Nagrath, "100% Renewable energy for tanzania-access to renewable and affordable energy for all within one generation. Report prepared by ISF for bread for the world," Inst. Sustainable Futures, Univ. Technol. Sydney, Ultimo, NSW, Australia, Tech. Rep. 70569, 2017.

[293] S. Teske, T. Morris, and K. Nagrath, *100% Renewable Energy for Bangladesh-Access to Renewable Energy for all Within One generation. Report Prepared by ISF for Coastal Development Partnership (CDP) Bangladesh; Bread for the World*. Hamburg, Germany: World Future Council, 2019.

[294] S. Teske, T. Morris, and K. Nagrath, "100% renewable energy for Costa Rica. Report prepared by ISF for the world future council/Germany and the one earth foundation," Inst. Sustain. Futures, Univ. Technol. Sydney, Ultimo, NSW, Australia, Tech. Rep. 70569, 2020.

[295] S. Sgouridis, D. Csala, and U. Bardi, "The sower's way: Quantifying the narrowing net-energy pathways to a global energy transition," *Environ. Res. Lett.*, vol. 11, no. 9, Sep. 2016, Art. no. 094009, doi: 10.1088/1748-9326/11/9/094009.

[296] S. Afanasyeva, D. Bogdanov, and C. Breyer, "Relevance of PV with single-axis tracking for energy scenarios," *Sol. Energy*, vol. 173, pp. 173–191, Oct. 2018, doi: 10.1016/j.solener.2018.07.029.

[297] *International Technology Roadmap for Photovoltaic (ITRPV) Results 2021*, [ITRPV] International Technology Roadmap for Photovoltaic, Frankfurt, Germany, 2022. [Online]. Available: https://www.vdma.org/international-technology-roadmap-photovoltaic

[298] M. Z. Jacobson, A.-K. von Krauland, S. J. Coughlin, F. C. Palmer, and M. M. Smith, "Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage," *Renew. Energy*, vol. 184, pp. 430–442, Jan. 2022, doi: 10.1016/j.renene.2021.11.067.

[299] E. Vartiainen, G. Masson, C. Breyer, D. Moser, and E. R. Medina, "Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity," *Prog. Photovoltaics, Res. Appl.*, vol. 28, no. 6, pp. 439–453, Jun. 2020, doi: 10.1002/pip.3189.

[300] Y. Y. Deng, K. Blok, and K. van der Leun, "Transition to a fully sustainable global energy system," *Energy Strategy Rev.*, vol. 1, no. 2, pp. 109–121, Sep. 2012, doi: 10.1016/j.esr.2012.07.003.

[301] *Food and Agriculture Organization of the United Nations FAO-STAT Land Use*, FAOSTAT, Rome, Italy, 2021. [Online]. Available: https://www.fao.org/faostat/en/#home

[302] R. E. A. Almond, M. Grooten, and T. Petersen, *Living Planet Report 2020 Bending the Curve of Biodiversity Loss*. Gland, Switzerland: World Wildlife Fund, 2020.

[303] *World Population Prospects 2019*, United Nations Dept. Econ. Social Affairs, New York, NY, USA, 2019. [Online]. Available: https://population.un.org/wpp/

[304] A. Chaudhary, D. Gustafson, and A. Mathys, "Multi-indicator sustainability assessment of global food systems," *Nature Commun.*, vol. 9, no. 1, p. 848, Feb. 2018, doi: 10.1038/s41467-018-03308-7.

[305] M. Springmann et al., "Options for keeping the food system within environmental limits," *Nature*, vol. 562, no. 7728, pp. 519–525, Oct. 2018, doi: 10.1038/s41586-018-0594-0.

[306] K.-H. Erb, C. Lauk, T. Kastner, A. Mayer, M. C. Theurl, and H. Haberl, "Exploring the biophysical option space for feeding the world without deforestation," *Nature Commun.*, vol. 7, no. 1, Apr. 2016, doi: 10.1038/ncomms11382.

[307] F. Creutzig et al., "Bioenergy and climate change mitigation: An assessment," *GCB Bioenergy*, vol. 7, no. 5, pp. 916–944, Sep. 2015, doi: 10.1111/gcbb.12205.

[308] T. N. O. Mensah, A. S. Oyewo, and C. Breyer, "The role of biomass in sub-saharan Africa's fully renewable power sector—The case of Ghana," *Renew. Energy*, vol. 173, pp. 297–317, Aug. 2021, doi: 10.1016/j.renene.2021.03.098.

[309] T. N. O. Mensah, A. S. Oyewo, D. Bogdanov, A. Aghahosseini, and C. Breyer, "Pathway for a fully renewable power sector of Africa by 2050: Emphasising on flexible generation from biomass," *SSRN Electron. J.*, 2022.

[310] K. M. Kennedy, T. H. Ruggles, K. Rinaldi, J. A. Dowling, L. Duan, K. Caldeira, and N. S. Lewis, "The role of concentrated solar power with thermal energy storage in least-cost highly reliable electricity systems fully powered by variable renewable energy," *Adv. Appl. Energy*, vol. 6, Jun. 2022, Art. no. 100091, doi: 10.1016/j.adapen.2022.100091.

[311] K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert, and C. von Hirschhausen, "Designing a model for the global energy system—GENeSYS-MOD: An application of the open-source energy modeling system (OSeMOSYS)," *Energies*, vol. 10, no. 10, p. 1468, Sep. 2017, doi: 10.3390/en10101468.

[312] D. E. H. J. Gernaat, P. W. Bogaart, D. P. V. Vuuren, H. Biemans, and R. Niessink, "High-resolution assessment of global technical and economic hydropower potential," *Nature Energy*, vol. 2, no. 10, pp. 821–828, Sep. 2017, doi: 10.1038/s41560-017-0006-y.

[313] *World Energy Outlook 2021*, [IEA] Int. Energy Agency, Paris, France, 2021. [Online]. Available: hhttps://Www.iea.org/weo

[314] N. V. Emodi, T. Chaiechi, and A. B. M. R. A. Beg, "The impact of climate variability and change on the energy system: A systematic scoping review," *Sci. Total Environ.*, vol. 676, pp. 545–563, Aug. 2019, doi: 10.1016/j.scitotenv.2019.04.294.

[315] X. Lu, S. Chen, C. P. Nielsen, C. Zhang, J. Li, H. Xu, Y. Wu, S. Wang, F. Song, C. Wei, K. He, M. B. McElroy, and J. Hao, "Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system," *Proc. Nat. Acad. Sci. USA*, vol. 118, no. 42, Oct. 2021, doi: 10.1073/pnas.2103471118.

[316] C. Breyer, "Low-cost solar power enables a sustainable energy industry system," *Proc. Nat. Acad. Sci. USA*, vol. 118, no. 49, pp. 49–51, Dec. 2021, doi: 10.1073/pnas.2116940118.

[317] A. Gulagi, M. Ram, D. Bogdanov, S. Sarin, T. Mensah, and C. Breyer, "The role of renewables for rapid transitioning of the power sector across states in India," *Nature Commun.*, vol. 13, p. 5499, Sep. 2022.

[318] A. S. Oyewo, A. A. Solomon, D. Bogdanov, A. Aghahosseini, T. N. O. Mensah, M. Ram, and C. Breyer, "Just transition towards defossilised energy systems for developing economies: A case study of Ethiopia," *Renew. Energy*, vol. 176, pp. 346–365, Oct. 2021, doi: 10.1016/j.renene.2021.05.029.

[319] A. Oyewo, D. Bogdanov, A. Aghahosseini, T. Mensah, and C. Breyer, *Contextualizing the Scope, Scale, and Speed of Energy Pathways Toward Sustainable Development in Africa*. Cambridge, MA, USA: iScience, 2022.

[320] G. Lopez, A. Aghahosseini, M. Child, S. Khalili, M. Fasihi, D. Bogdanov, and C. Breyer, "Impacts of model structure, framework, and flexibility on perspectives of 100% renewable energy transition decision-making," *Renew. Sustain. Energy Rev.*, vol. 164, Aug. 2022, Art. no. 112452, doi: 10.1016/j.rser.2022.112452.

[321] J. C. Osorio-Aravena, A. Aghahosseini, D. Bogdanov, U. Caldera, N. Ghorbani, T. N. O. Mensah, S. Khalili, E. Muñoz-Cerón, and C. Breyer, "The impact of renewable energy and sector coupling on the pathway towards a sustainable energy system in Chile," *Renew. Sustain. Energy Rev.*, vol. 151, Nov. 2021, Art. no. 111557, doi: 10.1016/j.rser.2021.111557.

[322] M. Stocks, R. Stocks, B. Lu, C. Cheng, and A. Blakers, "Global atlas of closed-loop pumped hydro energy storage," *Joule*, vol. 5, no. 1, pp. 270–284, Jan. 2021, doi: 10.1016/j.joule.2020.11.015.

[323] T. Galimova, M. Ram, and C. Breyer, "Mitigation of air pollution and corresponding impacts during a global energy transition towards 100% renewable energy system by 2050," *Energy Rep.*, vol. 8, pp. 14124–14143, Nov. 2022.

[324] A. Lohrmann, J. Farfan, U. Caldera, C. Lohrmann, and C. Breyer, "Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery," *Nature Energy*, vol. 4, no. 12, pp. 1040–1048, Nov. 2019, doi: 10.1038/s41560-019-0501-4.

[325] M. Ram, J. C. Osorio-Aravena, A. Aghahosseini, D. Bogdanov, and C. Breyer, "Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050," *Energy*, vol. 238, Jan. 2022, Art. no. 121690, doi: 10.1016/j.energy.2021.121690.

[326] A. Azzuni and C. Breyer, "Global energy security index and its application on national level," *Energies*, vol. 13, no. 10, p. 2502, May 2020, doi: 10.3390/en13102502.

[327] T. Junne, N. Wulff, C. Breyer, and T. Naegler, "Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt," *Energy*, vol. 211, Nov. 2020, Art. no. 118532, doi: 10.1016/j.energy.2020.118532.

[328] E. White and G. J. Kramer, "The changing meaning of energy return on investment and the implications for the prospects of post-fossil civilization," *One Earth*, vol. 1, no. 4, pp. 416–422, Dec. 2019, doi: 10.1016/j.oneear.2019.11.010.

[329] C. T. M. Clack et al., "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 26, pp. 6722–6727, Jun. 2017, doi: 10.1073/pnas.1610381114.

[330] T. Trainer, "Some problems in storing renewable energy," *Energy Policy*, vol. 110, pp. 386–393, Nov. 2017, doi: 10.1016/j.enpol.2017.07.061.

[331] B. P. Heard, B. W. Brook, T. M. L. Wigley, and C. J. A. Bradshaw, "Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 1122–1133, Sep. 2017, doi: 10.1016/j.rser.2017.03.114.

[332] J. D. Jenkins, M. Luke, and S. Thernstrom, "Getting to zero carbon emissions in the electric power sector," *Joule*, vol. 2, no. 12, pp. 2498–2510, Dec. 2018, doi: 10.1016/j.joule.2018.11.013.

[333] M. R. Shaner, S. J. Davis, N. S. Lewis, and K. Caldeira, "Geophysical constraints on the reliability of solar and wind power in the United States," *Energy Environ. Sci.*, vol. 11, no. 4, pp. 914–925, 2018, doi: 10.1039/c7ee03029k.

[334] M. Yuan, F. Tong, L. Duan, J. A. Dowling, S. J. Davis, N. S. Lewis, and K. Caldeira, "Would firm generators facilitate or deter variable renewable energy in a carbon-free electricity system?" *Appl. Energy*, vol. 279, Dec. 2020, Art. no. 115789, doi: 10.1016/j.apenergy.2020.115789.

[335] M. Victoria, N. Haegel, I. M. Peters, R. Sinton, A. Jäger-Waldau, C. del Cañizo, C. Breyer, M. Stocks, A. Blakers, I. Kaizuka, K. Komoto, and A. Smets, "Solar photovoltaics is ready to power a sustainable future," *Joule*, vol. 5, no. 5, pp. 1041–1056, May 2021.

[336] M. Child, C. Kemfert, D. Bogdanov, and C. Breyer, "Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe," *Renew. Energy*, vol. 139, pp. 80–101, Aug. 2019, doi: 10.1016/j.renene.2019.02.077.

[337] H. C. Gils, "Economic potential for future demand response in Germany–modeling approach and case study," *Appl. Energy*, vol. 162, pp. 401–415, Jan. 2016, doi: 10.1016/j.apenergy.2015.10.083.

[338] B. K. Sovacool, M. L. Barnacle, A. Smith, and M. C. Brisbois, "Towards improved solar energy justice: Exploring the complex inequities of household adoption of photovoltaic panels," *Energy Policy*, vol. 164, May 2022, Art. no. 112868, doi: 10.1016/j.enpol.2022.112868.

[339] L. Juuso, N. Rami, and P. D. Lund, "Effectiveness of smart charging of electric vehicles under power limitations," *Arch. Thermodyn.*, vol. 33, no. 4, pp. 23–40, 2013, doi: 10.1002/er.3130.

[340] M. Child, A. Nordling, and C. Breyer, "The impacts of high V2G participation in a 100% renewable Åland energy system," *Energies*, vol. 11, no. 9, p. 2206, Aug. 2018, doi: 10.3390/en11092206.

[341] T. Boström, B. Babar, J. B. Hansen, and C. Good, "The pure PV-EV energy system – a conceptual study of a nationwide energy system based solely on photovoltaics and electric vehicles," *Smart Energy*, vol. 1, Feb. 2021, Art. no. 100001, doi: 10.1016/j.segy.2021.100001.

[342] H. Lund, P. A. Østergaard, D. Connolly, I. Ridjan, B. V. Mathiesen, J. Z. Thellufsen, and P. Sorknæs, "Energy storage and smart energy systems," *Int. J. Sustain. Energy Planning Manage.*, vol. 11, pp. 3–14, Oct. 2016, doi: 10.5278/ijsepm.2016.11.2.

[343] J. Haas, F. Cebulla, W. Nowak, C. Rahmann, and R. Palma-Behnke, "A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply," *Energy Convers. Manage.*, vol. 178, pp. 355–368, Dec. 2018, doi: 10.1016/j.enconman.2018.09.087.

[344] M. Sterner and I. Stadler, *Handbook of Energy Storage Demand, Technologies, Integration*. Berlin, Germany: Springer-Verlag, 2019.

[345] A. Gulagi, D. Bogdanov, and C. Breyer, "The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India," *J. Energy Storage*, vol. 17, pp. 525–539, Jun. 2018, doi: 10.1016/j.est.2017.11.012.

[346] H. Qazi. (2020). *Technical Shortfalls for Pan European Power System With High Levels of Renewable Generation*. Accessed: Feb. 19, 2022. [Online]. Available: https://eu-sysflex.com/documents/

[347] *High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters*, ENTSO-E, Brussels, Belgium, 2019. [Online]. Available: https://euagenda.eu/upload/publications/untitled-292051-ea.pdf

[348] [ESIG] Energy Systems Integration Group. (2019). *Toward 100% Renewable Energy Pathways: Key Research Needs*. Accessed: Mar. 8, 2022. https://www.esig.energy/resources/toward-100-renewable-energy-pathways-key-research-needs/

[349] *Inaugural Research Agenda*, Global PST Consortium, Los Angeles, CA, USA, 2021. [Online]. Available: https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf

[350] B. S. Hodge, H. Jain, C. Brancucci, G. Seo, M. Korpå, J. Kiviluoma, H. Holttinen, J. C. Smith, A. Orths, A. Estanqueiro, L. Söder, D. Flynn, T. K. Vrana, R. W. Kenyon, and B. Kroposki, "Addressing technical challenges in 100% variable inverter-based renewable energy power systems," *WIREs Energy Environ.*, vol. 9, no. 5, pp. 1–19, Sep. 2020, doi: 10.1002/wene.376.

[351] H. Holttinen, A. Groom, E. Kennedy, D. Woodfin, L. Barroso, A. Orths, K. Ogimoto, C. Wang, R. Moreno, K. Parks, and T. Ackermann, "Variable renewable energy integration: Status around the world," *IEEE Power Energy Mag.*, vol. 19, no. 6, pp. 86–96, Nov. 2021, doi: 10.1109/MPE.2021.3104156.

[352] X. Zhao and D. Flynn, "Stability enhancement strategies for a 100% grid-forming and grid-following converter-based Irish power system," *IET Renew. Power Gener.*, vol. 16, no. 1, pp. 125–138, Jan. 2022, doi: 10.1049/rpg2.12346.

[353] X. Zhao, P. G. Thakurta, and D. Flynn, "Grid-forming requirements based on stability assessment for 100% converter-based Irish power system," *IET Renew. Power Gener.*, vol. 16, no. 3, pp. 447–458, Feb. 2022, doi: 10.1049/rpg2.12340.

[354] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge, and B. Hannegan, "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 61–73, Mar. 2017.

[355] P. Denholm, D. J. Arent, S. F. Baldwin, D. E. Bilello, G. L. Brinkman, J. M. Cochran, W. J. Cole, B. Frew, V. Gevorgian, J. Heeter, B.-M.-S. Hodge, B. Kroposki, T. Mai, M. J. O'Malley, B. Palmintier, D. Steinberg, and Y. Zhang, "The challenges of achieving a 100% renewable electricity system in the United States," *Joule*, vol. 5, no. 6, pp. 1331–1352, Jun. 2021, doi: 10.1016/j.joule.2021.03.028.

[356] W. J. Cole, D. Greer, P. Denholm, A. W. Frazier, S. Machen, T. Mai, N. Vincent, and S. F. Baldwin, "Quantifying the challenge of reaching a 100% renewable energy power system for the United States," *Joule*, vol. 5, no. 7, pp. 1732–1748, Jul. 2021, doi: 10.1016/j.joule.2021.05.011.

[357] F. Creutzig, C. Breyer, J. Hilaire, J. Minx, G. P. Peters, and R. Socolow, "The mutual dependence of negative emission technologies and energy systems," *Energy Environ. Sci.*, vol. 12, no. 6, pp. 1805–1817, Jun. 2019, doi: 10.1039/c8ee03682a.

[358] C. Breyer, M. Fasihi, and A. Aghahosseini, "Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: A new type of energy system sector coupling," *Mitigation Adaptation Strategies for Global Change*, vol. 25, no. 1, pp. 43–65, Jan. 2020, doi: 10.1007/s11027-019-9847-y.

[359] F. M. Brethomé, N. J. Williams, C. A. Seipp, M. K. Kidder, and R. Custelcean, "Direct air capture of CO_2 via aqueous-phase absorption and crystalline-phase release using concentrated solar power," *Nature Energy*, vol. 3, no. 7, pp. 553–559, Jul. 2018, doi: 10.1038/s41560-018-0150-z.

[360] T. M. P. Ratouis, S. Ó. Snæbjörnsdóttir, M. J. Voigt, B. Sigfæsson, G. Gunnarsson, E. S. Aradóttir, and V. Hjörleifsdóttir, "Carbfix 2: A transport model of long-term CO_2 and H_2S injection into basaltic rocks at hellisheidi, SW-iceland," *Int. J. Greenhouse Gas Control*, vol. 114, Feb. 2022, Art. no. 103586, doi: 10.1016/j.ijggc.2022.103586.

[361] C. Chen and M. Tavoni, "Direct air capture of CO_2 and climate stabilization: A model based assessment," *Climatic Change*, vol. 118, no. 1, pp. 59–72, May 2013, doi: 10.1007/s10584-013-0714-7.

[362] B. K. Sovacool, "Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering," *Energy Strategy Rev.*, vol. 35, May 2021, Art. no. 100656, doi: 10.1016/j.esr.2021.100656.

[363] S. Sgouridis, M. Carbajales-Dale, D. Csala, M. Chiesa, and U. Bardi, "Comparative net energy analysis of renewable electricity and carbon capture and storage," *Nature Energy*, vol. 4, no. 6, pp. 456–465, Apr. 2019, doi: 10.1038/s41560-019-0365-7.

[364] J. Rogelj, P. M. Forster, E. Kriegler, C. J. Smith, and R. Séférian, "Estimating and tracking the remaining carbon budget for stringent climate targets," *Nature*, vol. 571, no. 7765, pp. 335–342, Jul. 2019, doi: 10.1038/s41586-019-1368-z.

[365] *Global Warming of 1.5°C*, [IPCC] Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2018. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf

[366] T. M. Lenton, J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, and H. J. Schellnhuber, "Climate tipping points—Too risky to bet against," *Nature*, vol. 575, pp. 593–595, Nov. 2019.

[367] M. R. Turetsky, B. W. Abbott, M. C. Jones, K. W. Anthony, D. Olefeldt, E. A. G. Schuur, G. Grosse, P. Kuhry, G. Hugelius, C. Koven, D. M. Lawrence, C. Gibson, A. B. K. Sannel, and A. D. McGuire, "Carbon release through abrupt permafrost thaw," *Nature Geosci.*, vol. 13, no. 2, pp. 138–143, Feb. 2020, doi: 10.1038/s41561-019-0526-0.

[368] M. D. King, I. M. Howat, S. G. Candela, M. J. Noh, S. Jeong, M. R. van den Broeke, B. Wouters, and A. Negrete, "Dynamic ice loss from the Greenland ice sheet driven by sustained glacier retreat," *Commun. Earth Environ.*, vol. 1, no. 1, pp. 1–7, Aug. 2020, doi: 10.1038/s43247-020-0001-2.

[369] A. Levermann and J. Feldmann, "Scaling of instability timescales of Antarctic outlet glaciers based on one-dimensional similitude analysis," *Cryosphere*, vol. 13, no. 6, pp. 1621–1633, Jun. 2019, doi: 10.5194/tc-13-1621-2019.

[370] J. Hansen, M. Sato, P. Kharecha, K. Von Schuckmann, and D. J. Beerling, "Earth system dynamics young people's burden: Requirement of negative CO_2 emissions," *Earth Syst. Dyn.*, vol. 8, no. 3, pp. 577–616, 2017.

[371] C. Azar and H. Rodhe, "Targets for stabilization of atmospheric CO_2," *Science*, vol. 276, pp. 1818–1819, Jun. 1997.

[372] C. Breyer et al., "On the history and future of 100% renewable energy systems research," *IEEE Access*, vol. 10, pp. 78176–78218, 2022, doi: 10.1109/ACCESS.2022.3193402.

[373] T. T. Pedersen, E. K. Gøtske, A. Dvorak, G. B. Andresen, and M. Victoria, "Long-term implications of reduced gas imports on the decarbonization of the European energy system," *Joule*, vol. 6, no. 7, pp. 1566–1580, Jul. 2022.

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