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Power system stability in the Era of energy Transition: Importance, Opportunities, Challenges, and future directions

Ahmed Mohammed Saleh [a,e,*], Vokony István [a], Muhammad Adnan Khan [b], Muhammad Waseem [c,f], Amgad Naji Ali Ahmed [d,e]

[a] Department of Electric Power Engineering, Faculty of Electrical Engineering and Informatics, Budapest University of Technology and Economics, BME V1 Building, Egry József u. 18, 1111 Budapest, Hungary
[b] School of Electrical Engineering, Chongqing University, Chongqing, 400044, China
[c] International Renewable and Energy System Integration Research Group (IRESI), Department of Electronic Engineering, Maynooth University, Co., Kildare, Ireland
[d] Óbuda University, Doctoral School on Safety and Security Sciences Népszínház str., 1081 Budapest, Hungary
[e] Department of Electrical Engineering, University of Aden, Aden, Yemen
[f] Science Foundation Ireland Research Centre for Software, School of Business, Innovation Value Institute (IVI), Maynooth University, Co., Kildare, Ireland

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ABSTRACT

Utilities are struggling to fulfil increased energy demand from domestic and industrial expansion. Conventional energy sources are insufficient to satisfy this burgeoning global energy demand, and the substantial emissions of pollutants associated with these sources are concerns. The energy transition is becoming more inevitable than ever for mitigating this situation. However, this transition threatens the power system stability by introducing intermittent and low inertia energy resources to the grid. In terms of the energy transition, there is abundant research about design purposes, but those considering the power system stability are still inadequate. The significance, opportunities, challenges, and future directions of the energy transition related to power system stability are covered thoroughly in this article. The IEEE 14-bus system is selected as a case study for renewable energy sources (RES) integration as it includes various voltage levels (132, 33, and 0.4) kV. Various scenarios of RES integration, fault, sudden change of generation and load are simulated using DIgSILENT /MATLAB software. The case study clarifies how power system stability is affected by the energy transition and how the energy storage system improves stability. It also discusses the future direction as a baseline for scholars and industries to accelerate the smooth energy transition.

1. Introduction

Rapid urbanization, industrial growth, and improving living standards burden utility companies heavily as they struggle to meet the demand with escalating energy requirements. In all scenarios of the IEA world energy outlook, during the next 20 years, there is expected to be a roughly 50 % increase in the electricity demand, with rising and developing nations receiving particular attention. According to this development direction, the trend could increase on acceleration and growth, electricity currently makes up less than 50 % of total consumption compared to oil, while by 2040, electricity may exceed oil as the main energy source [1]. Conventional energy sources are proving insufficient to satisfy the burgeoning global demands for electricity. Additionally, commencing in February 2022, the Ukraine war has intensified the prevailing global energy crisis that emerged from the impact of COVID-19. The war disrupted international energy trade routes and precipitated a substantial surge in energy prices [2]; for instance, in May 2022, crude oil prices reached $121.78 per barrel [3]. Moreover, the substantial emissions of pollutants associated with these traditional sources of the energy sector present profound environmental challenges [4,5], in 2022, above 75 % of all anthropogenic carbon emissions to the atmosphere come from our energy utilization [6]. For all the above reasons, energy transition is more inevitable than ever [7]. Over the past few decades, renewable and decentralized energy sources have emerged as substitutes for conventional energy resources. Utility engineers consider them as a promising option for fulfilling load requirements and effectively tackling power quality issues [7,8]. The Renewable Energy Sources (RESs) are Distributed Generation (DG) and

* Corresponding author.
E-mail address: engahmedsaleh14@gmail.com (A.M. Saleh).

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demonstrate exceptional performance and reliability, especially when the integrated more than one source i.e. Hybrid RES [9]. In addition, solar PV and wind turbines are among the least expensive power sources to accelerate the energy transition. By 2040, based on the IEA Sustainable Development Scenario, the average annual percentage of variable RES in total generation would be 45 % [1]. However, this hybridization leads to new grid paradigms with much equipment and several devices, resulting in increased control complexity i.e. introducing new technical challenges by integrating intermittent, low short-circuit level and inertia system, in turn, threatening the power system stability [7].

1.1. Background and Motivation

There is abundant research in the context of energy transition, as noted in Fig. 1. However, there is still a lack or connection between papers on power system stability and energy transition as shown in Fig. 2. This paper aims to analyze the opportunities and different aspects of challenges of the energy transition with consideration of power system stability. The Fig. 3 demonstrated the layout and structure of the paper. Moreover, the case study highlights the effects of the integration of variable RESs and how the energy storage system is essential in improving stability. The main contribution of this paper is a thorough overview of the opportunities presented by the energy transition, alongside its in-depth analysis of the new difficulties that emerge. These difficulties demand careful consideration, particularly those relating to system stability and the potential for cascading failure events and how to prevent these events before they happen. The paper also discusses the future direction as a baseline for scholars and industries to accelerate the smooth energy transition. This work is to find out why the energy transition is not taking place fast and how to accelerate it; this is the purpose of the study.

1.2. Importance of power system stability

The ability of a system to regain an equilibrium state after being subjected to a physical disturbance (fault, lightning, sudden change in generation/load) is called power system stability [10]. It might be viewed as a thermometer to measure network health, and it is crucial for various reasons as follows.

I Improving the system reliability

The reliability of a power system indicates the likelihood of its sustained performance in the extended term, signifying its capacity to consistently deliver sufficient electrical service with minimal interruptions over an extended duration [11]. A system which has a diversity of sources including RESs such as hydropower and geothermal power tends to be more reliable. In this system, the generators show remarkable flexibility, capable of meeting demands ranging from the lowest to the highest. If any generators were to fail for any reason, the supply would be disrupted unless an adequate backup generator of the same model was easily accessible [12].

A reliable power system is more stable to failures and is less likely to suffer a blackout. With the integration of intermittent nature RESs such

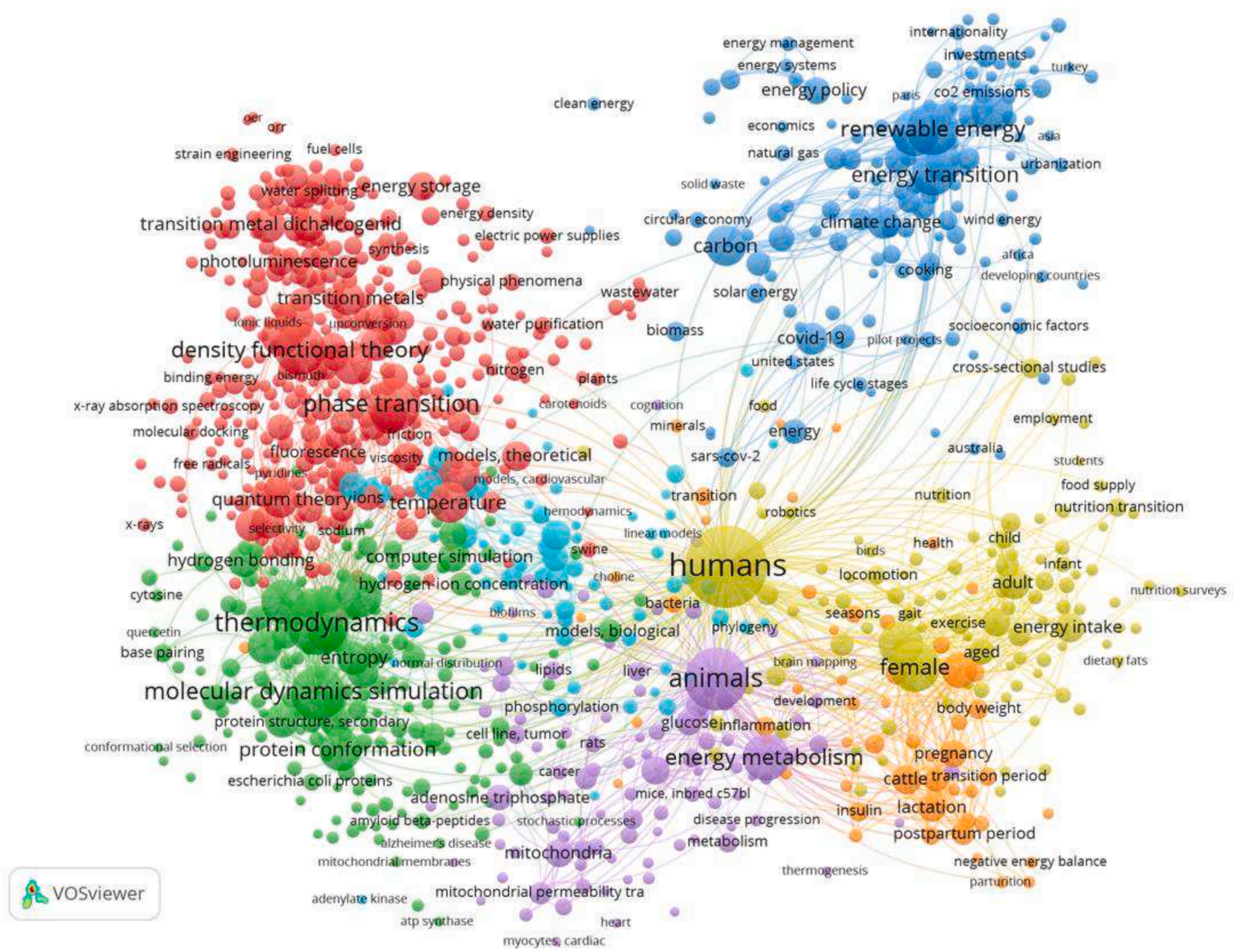


Fig. 1. Energy transition publications 2019–2023 (PubMed data).

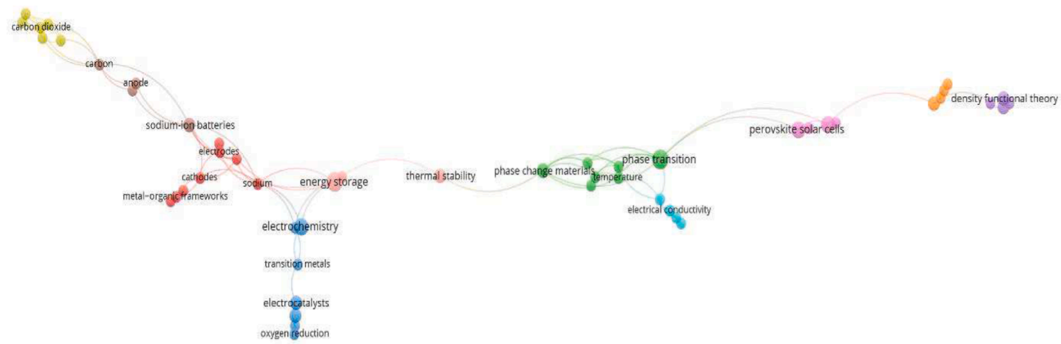


Fig.2. Energy transition publications considering power system stability, 2019–2023(PubMed data).

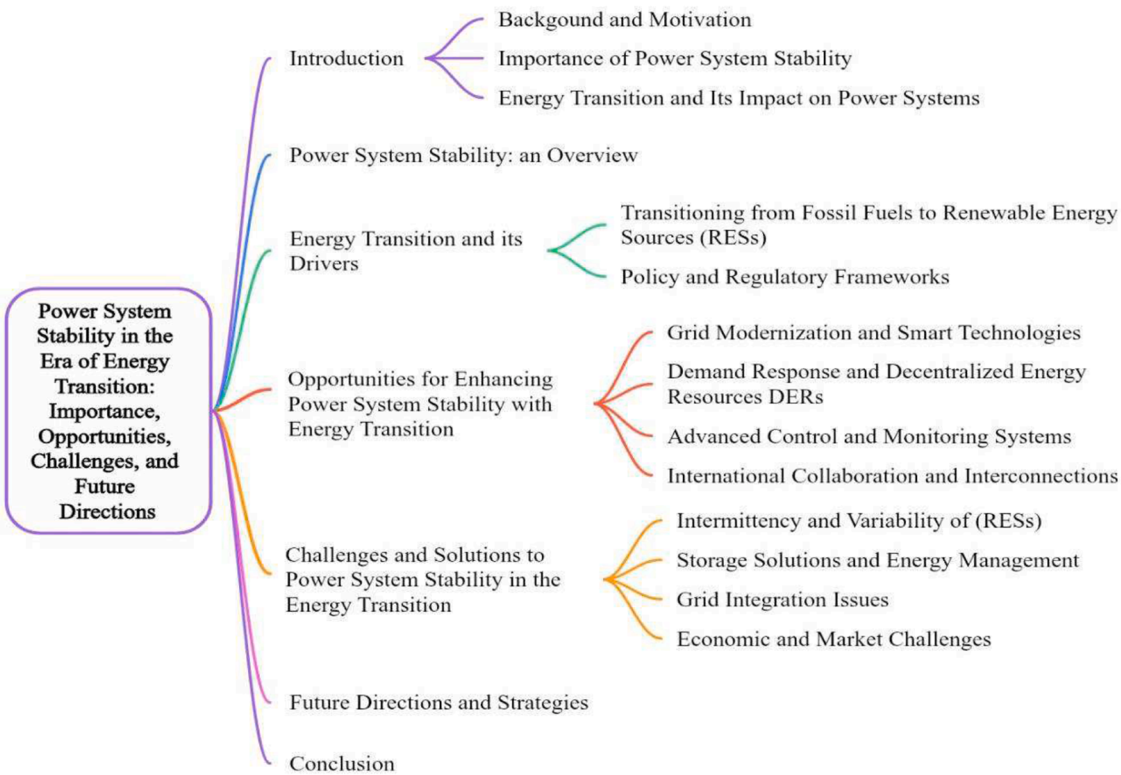


Fig. 3. Structure of the paper.

as solar and wind turbines the reliability of the system will be affected, and the other sources and backup generates are required to meet demand. Therefore, grid stability is improved by hybrid systems' which combine more than one source of energy to relieve energy intermittency of inherent individual source [13].

II Enhancing economic impact

The general living standards for industries, companies, and people are adversely affected due to power outages and grid instability. The likelihood of these outages decreases with a reliable power system, which lessens the economic effects of such service interruptions and attracts investors. Power outages can result in significant economic consequences for society, making it indispensable to assess the financial impacts of such incidents [14]. According to a study that aimed to quantify the financial losses to the US from severe weather-related power disruptions [15], based on 2019 values, the study calculated that a 1 % electricity outage in the industry would result in a $11.6 billion loss to the gross domestic product.

As the RESs are fuel-free, RESs integration with several sources and generators of consumers having different power output ranges could offer substantial economic benefits. This integration could avoid the need for constructing larger peak demand plants and necessitating upgrades to the system network. Moreover, optimal generator selection as close as possible to the load is simple and economical. Optimizing efficiency and performance is involved with this matching, which helps to achieve better fuel efficiency, and reduces wear and tear on the equipment due to avoiding overloading of the generators.

III Strengthening safety

Stable power systems improve the safety of electrical apparatuses. Unexpected instability or voltage swings can damage equipment, undermine the safety of the public and maintenance personnel, or in certain situations, influence heating, ventilation, and air conditioning (HVAC) systems, hospitals, emergency response centres, and water treatment facilities, traffic lights, street lighting, security cameras, and alarm systems raising the risk to public health. In recent years, a significant issue in both industrial and residential settings is the occurrence of sudden Overvoltage or Undervoltage, which can lead to damage to the utility and consumer equipment [16]. With the growing prevalence of electronic-based loads in both households and industrial applications, the sensitivity of these devices to voltage fluctuations has become increasingly pronounced [17].

IV Prevention of cascading failures

A single unstable or failing component in the power system may set off a cascade failure that results in widespread outages and the eventual collapse of the entire system. Keeping the system stable overall aids in preventing these kinds of cascade failures. Massive power outages originate from cascading failures, wherein the insulation breakdown of equipment or other disruptions trigger additional failures or disturbances across extensive sections of the electrical grid. Although such occurrences are infrequent, they carry the potential for substantial costs. Reliability planning and studies of power system stability aim to prevent circumstances that could allow for cascading failures while acknowledging that some isolated, routine outages are inevitable [18]. The widespread incorporation of RESs significantly influences how cascading failures spread within power systems, primarily because of reduced system inertia and the swift variations in the frequency and voltage [19]. The complexity of large-scale RES has caused cascade events in countries that have integrated these systems. Studies conducted in the United States have demonstrated that fast-acting inverter-based systems can cause microgrids to collapse in a cascade during extreme events, requiring sophisticated control techniques to reduce hazards [20]. In China, the large-scale wind farms by HVDC have increased the risk of cascading failures due to deep coupling among generators and the AC system, highlighting the need for robust emergency control methods [21]. In Denmark, cascading overload failures can happen in RES integration during multiple fault contingencies. This highlights the significance of transient stability assessments and load flow balancing [22]. To sum up, even while RES integration promotes sustainability, it presents serious difficulties for grid stability, especially during disruptions. Table 1 shows recent instances of significant power supply disturbances and blackouts [1,23–25].

1.3. Energy transition and its impact on power systems

Significant effects of energy transition can be observed in power systems, in the generation, transmission, and distribution network. In terms of the power flow, energy transition encourages the development of decentralized energy sources [26], such as rooftop solar panels, small-scale wind turbines, and energy storage systems of the consumer side integrated with a power grid which introduces a bi-directional power flow [27,28]. Policies and legislation that support RES integration by governments have led to the widespread these resources [29]. This concept of decentralization leads to a more distributed and diverse energy landscape. Power systems must be able to accommodate and manage these distributed resources effectively. Advanced monitoring, measuring, control and communication infrastructure systems as shown in Table 2 play a key role in achieving that adoption and making managing and balancing the generation and demand of electricity in real time possible, to construct a resilient and effective grid [30]. The consumers independently adjust their electricity consumption in response to grid frequency. With cost-effective tools such as smart meters, the grid frequency can be readily monitored from various locations. Maintaining grid stability is essential for balancing power supply and demand, ensuring economically sustainable and flexible grid operations [31].

2. Power system Stability: An overview

Power system stability is the characteristic of the system to maintain operation in the equilibrium under normal conditions, and to recover to acceptable conditions and operation limits after being subjected to disturbances. Power system stability in the traditional classification includes.

Rotor angle stability, Frequency stability, and Voltage stability [33], Nevertheless, the addition of converter-driven stability and resonance stability came with the widespread use of converters[34]. The stability of a power system can be impacted by several things. These elements play a crucial role in a power system's capacity to sustain synchronized operation and prevent disruptions. The most crucial elements are as follows.

Renewable Energy Sources Integration: the intermittent nature of these RESs impacts the power system stability especially at large-scale sharing [35]. Also, these RESs lead to a decrease in system inertia, which affects system frequency [36,37]. For instance, a 1000 MW thermally powered turbogenerator's inertia time constant is around 8–10 s, but grid-connected solar systems with an identical capacity have nearly zero inertia [38].This reduction of inertia (kinetic energy stored in the rotating masses) adversely affects the frequency by diminishing the system's ability to compensate for the frequency variations.

Load changes and uncertainties: a sudden variation in a large load can affect the system's stability. This can be understood by looking at variations in voltage and frequency as well as the performance of the equipment [39,40].These uncertainties impact the power quality also [41].

External and internal factors: external factors such as lightning strokes [42], and the internal factors such as fault occurrences [43], switching, line impedance and reactance [44] system damping, and generator characteristics [45] all significantly affect the stability of the power grid. Our Case Study will address the effects of these elements.

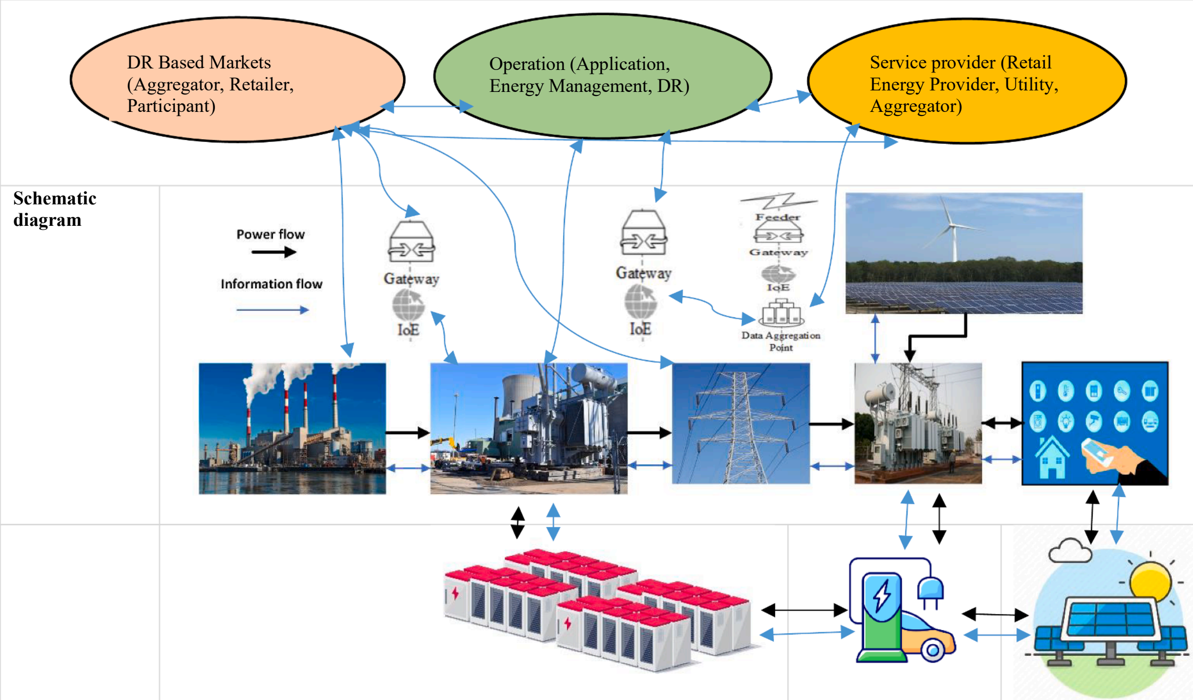
3. Energy transition and its Drivers

Numerous factors are combined to drive the shift to RESs that are more ecologically friendly and sustainable. This section examines the main forces underlying this energy transition. These factors are influenced by regulatory frameworks, state-of-the-art technology advancements, and shifting public attitudes.

Table 1
Worldwide power supply disturbances and blackouts.

Type of event	Year	Location	Key factor	Extent of blackout
Load shedding	2020	California	Heatwave	Intermittent power outages impacting as many as 3 million individuals for durations of up to 2.5 h over multiple days.
	2019		Wildfires	Transmission line closures led to a 3-day outage that impacted 11 % of PG&E's customers
	2019	UK	Lightning strike, operational security	One million individuals experiencing a delay of approximately 40 min, compounded by transportation disruptions.
Blackouts	2015–16	Ukraine	Cyber attacks	1–6 h, 200 000 + people
Long energy rationing period	2001	Brazil	Drought, inadequate investment framework	20 % of six months' worth of total energy use
Power outages	2015	TheNetherlands	Extreme weather conditions	Affected about 1 million people for 1.5 h
		Turkey	Lack of N-1 safety	Affected about 70 million people for 4 h
	2021	Greece	Fire from a short circuit	Affected about 1 million people for 1 h

Table 2
Integration of RES in smart grids using advanced communication, demand response, and storage systems for efficiency and stability [32].

Power flow	Generation Network →	**Power transformer** →	Transmission Network →	**Transmission substation** →	Distribution Network →	Distribution Substation ↔	End-user
Information flow	Wide area network (WAN)			Neighborhood Area Network (NAN)		Home Area Network (HAN)	
Schematic diagram							
Wired communication technologies	Fibre optical; Digital subscriber line (DSL); WiMAX			(DSL); Coaxial cable; Ethernet; Fiber optical		Ethernet; Power Line Communication (PLC)	
Wireless communication technologies	Low Power Area (SIGFOX, LoRA);Cellular(LTE-MTC,2G-4G, proposed 5G);Satellite			Wi-Fi; WiMAX; Cellular (2G-4G, proposed 5G); ZigBee-NAN(6LoWPAN)		Z-wave; Thread(6LoWPAN); ZigBee; Wi-Fi; Energy and Metering Standards (KNX,M-Bus)	
Security	Access Control, Authentication, Avoidance of Cyber-attacks, Improved Reliability, Integrity Protection, Encryption, Private Networking, Substation /Local Control						

3.1. *Transitioning from fossil fuels to RESs*

Lack of resources: The supply of fossil fuels is limited, non-renewable, and will drastically diminish in future. All of these make energy transition crucial to meet electricity needs. However, over the next thirty years, this transition will be exceedingly challenging due to several factors, including economic and technical ones [7,46].

Environmental concerns: greenhouse gas (GHG) emissions and their connection to worldwide climate change are becoming a global concern. It is noteworthy that in 2020, fossil fuels, including coal, natural gas, and oil, were responsible for a substantial 61.3 % of global electricity generation [47]. Shifting direction to constrain global warming to 1.5 °C without exceeding this limit will necessitate substantial decreases in GHG emissions in the future. In scenarios modelled to achieve this objective, GHG emissions must peak no later than 2025, followed by a swift and substantial decline, with a reduction of 43 % by 2030 and a 60 % reduction by 2035 compared to 2019 levels [48].

3.2. *Policy and regulatory frameworks*

Renewable energy targets: Many countries are taking steps toward energy transition shift away from fossil. Clean energy transition is the term used to describe the route used to reach this objective [49]. Some countries have planned to reach a “net-zero” state by 2050. The UK became the first significant economy to pass legislation enshrining “net-zero” by 2050 in June 2019. Additionally, in 2008, the UK set a legal policy aiming for an 80 % reduction in national climate change emissions by 2050. These targets are often backed by incentives, subsidies, and regulatory mechanisms to encourage the growth of the share of RESs in the energy mix. Several significant policy tools have been introduced and changed over the past 20 years, such as mandatory energy labelling (Energy Performance Certificates, or EPCs) and display energy certificates, improved construction and design standards (like building control regulations), and a somewhat erratic range of financial penalties and incentives (like the Green Deal, Feed-in Tariffs, and Energy Efficiency Opportunities Scheme) [50].

4. Opportunities for enhancing power system stability with energy transition

Numerous opportunities arise from shifting to cleaner energy sources, including grid modernization, decentralized energy resources, enhanced control systems, and international cooperation. These prospects are critical for tackling the energy transition’s issues and guiding power systems towards increased resilience and dependability in the face of shifting energy paradigms.

4.1. Grid modernization and smart technologies

Globally, how energy is generated, transported, used, and applied is changing in recent years providing the bidirectional participation of the end user. Given the widespread use of intelligent systems in contemporary energy distribution systems, smart grids are useful tools for integrating a variety of cutting-edge technologies to enhance the energy supply process [51]. In the global electrical industry, there has been much discussion on the potential for a smart power system. Table 2 and its diagram shows the operational process of how modern grids integrate RES, using advanced communication networks, and apply demand response and storage systems to manage the variability of RES, supporting both operational efficiency and system stability by supporting real-time data sharing between grid components, and in turn, facilitate the controlling operation of the grid. Technologies like smart meters and DR services enable end-users to participate actively in the grid, potentially adjusting their consumption patterns based on grid needs.

Decentralization, digitalization, and decarburization are seen to be the primary forces behind this change in the electricity system [52] as shown in Fig. 4 a modern grid arranges the effective incorporation of Distributed Energy Resources (DERs) at every phase of distribution system planning and operations, ensuring that the great potential of these resources is harnessed without incurring unnecessary expenses or delays. This approach enables markets and customers to maximize the value of these resources, if it remains a cost-effective option for ratepayers, while also guaranteeing fair access to the benefits offered by DERs. Furthermore, a modern grid enhances grid safety and reliability through technological innovations, such as electric vehicles, energy storage systems, and virtual power plants, as long as these innovations prove to be cost-effective in comparison to more traditional, less modern investments [53–56]. This modern grid may interrelate with other networks such as transportation, gas, and water networks, creating a multi-carrier energy network or what is called "Electricity of Things" (EoT). From this, many energy networks need to function together efficiently and depend on one another [51].

The use of *smart meters* can play a significant role in accelerating the energy transition between these networks and consumers through participation in the adoption of RES with financial incentive rates; however, it has pros and cons as follows.

I. *Pros of Using the Smart Meters*

A. Precise Energy Usage Data.

Real-time data on energy use from smart meters allows users to track their consumption patterns and determine when they might turn back on or off. Using this data, customers may make knowledgeable decisions about how much energy they use and implement energy-saving techniques. The author of [57] noticed that enrolment in a time-of-use tariff smart meter scheme considerably decreases demand in Ireland. Furthermore, these data (current, voltage and power) can be included in sophisticated forecasting models, such as those that use machine learning and neural networks [58] to manage the demand; in turn, enhancing the power system stability.

B. Remote Monitoring and Control.

With a smart meter, users and energy providers may limit power use and it can receive instructions for remote control. They can control peak demand, identify outages, improve grid performance, and regulate energy use remotely with smart meters. The ability to operate remotely also makes demand response programs possible, in which users may modify how much energy they use in response to price signals or grid circumstances [59].

C. Enhanced Grid Efficiency.

By giving utilities access to real-time data on energy flows and system conditions, smart meters assist utilities in increasing grid efficiency [60]. Utilities may use this data to improve power distribution and lower transmission losses by identifying inefficiencies in the network. Because smart meters can detect the intermittent output from solar and wind power facilities, they also help utilities integrate renewable energy sources more effectively.

D. Increased Reliance.

By allowing utilities to react swiftly to outages and facilitating early identification of possible events, smart meters can improve grid

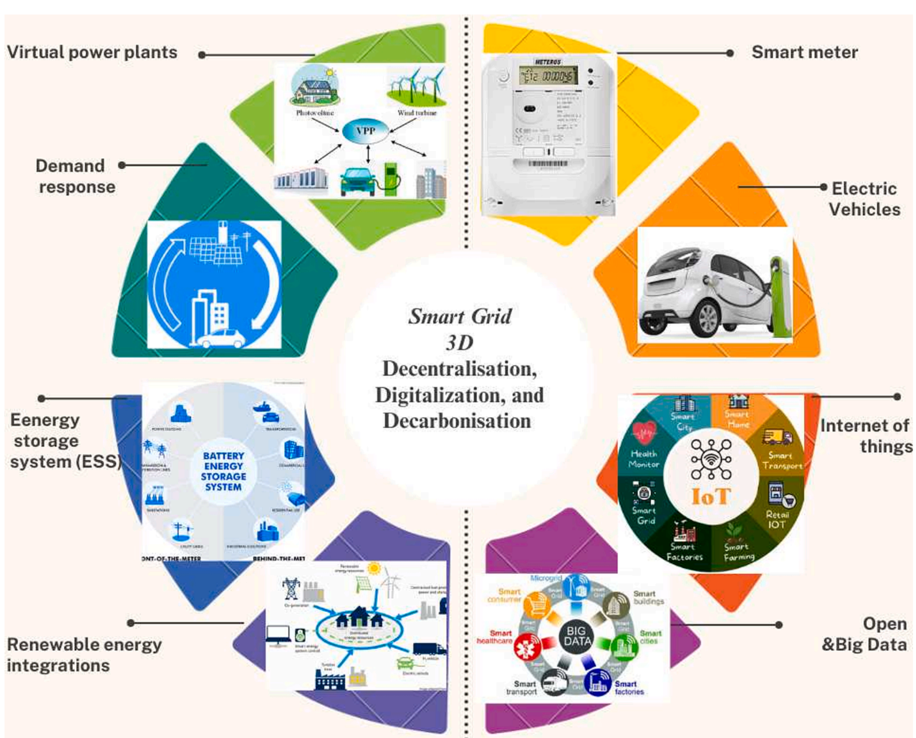


Fig. 4. Decentralization, digitalization, and decarburization (3D) and smart grid technologies [51–53].

reliability. Utilities can more effectively locate failure, isolate impacted regions, and restore electricity due to the real-time data from smart meters [61].

E. Increased RESs and EV Integration

Electric vehicles and rooftop solar panels are two examples that can be more easily integrated into the grid with the help of smart meters. They make it possible for RESs and the utility to communicate in both directions, which enables RESs monitoring and control to enhance energy efficiency and optimize grid operations [59,62].

II. *Cons of Using a Smart Meter*

A. Cost.

As with any significant investment in public infrastructure, installing smart meters can come with a considerable initial cost, especially for large-scale installations [63]. Widespread implementation may be constrained by the expense of data management systems, communication infrastructure, and smart meters [64].

B. Cybersecurity and Data Privacy Issues.

Smart meters are vulnerable to hackers since they gather and communicate sensitive data about energy use and refer to the natural activities of consumers or utilities. Therefore, securing smart meters and the communication infrastructure is crucial to protecting consumer privacy and preventing unauthorized access to energy data. Also, when electric vehicles charge through a smart meter, the charging infrastructure needs to be planned with these security considerations in mind [65]. If users are worried about their energy use data being used without authorization or shared with outside parties, they could hesitate to install smart meters [66].

To sum up, smart meters are essential to the smart grid since they provide usage data and make it easier to integrate EVs and RESs. Their advantages in terms of better grid management and energy efficiency make them an important part of smart grid technologies, despite implementation difficulties including cost and cybersecurity issues.

These advantages are further enhanced by smart meters' facilitation of the Internet of Energy (IoE) as shown in Table 2, which permits real-time monitoring, data collecting, and management across multiple power grid points. Smart meters optimize energy distribution, forecast energy demand, and facilitate more efficient resource management by collecting comprehensive energy usage data, facilitating connectivity throughout the grid, and facilitating remote monitoring and control. A more robust, effective, and sustainable energy infrastructure is a result of the collaboration between smart meters and the Internet of Energy.

4.2. Virtual power plant (VPP)

VPP represents a contemporary energy management system specifically engineered to tackle the challenges that arise with energy transition. VPPs merge various small-scale generation and storage assets, including solar PV, wind turbines, batteries, and electric vehicles, within a unified and adaptable system. Leveraging advanced information and communication technologies, VPPs can efficiently coordinate, and supervise the performance of all these distributed energy resources in response to fluctuations in grid conditions and market signals. Furthermore, VPPs can offer s upplementary services like frequency regulation, voltage support, and capacity reserves, all of which are vital for maintaining the stability and resilience of the grid [67].

Concerning the energy transition and the stability of power systems, the bi-directional power flow of the modern grid, the incorporation of advanced bidirectional relays, cyber-physical systems, and other protective measures should be considered. This integration would reinforce the system's capacity to identify various fault types swiftly and establish effective communication with the control centre. Such a system could ensure the timely implementation of necessary preventive actions to prevent any need for load shedding in the system [51].

4.3. Demand response and distributed energy resources (DERs)

The energy transition has aided the growth of distributed energy resources (DERs), which have many advantages but also introduce major grid integration challenges. The main focus of these challenges is variability, and uncertainty, in their generated power. Significant fluctuations in generation can adversely affect grid stability, disrupting grid balancing and scheduling between supply and demand. To mitigate this variability, modern storage technologies, such as pumped hydroelectric energy storage, and other large-scale BESS provide crucial support in stabilizing fluctuating power and enhancing overall power balance with their wide storage capacity. Similarly, demand response (DR) programs help balance supply and demand by encouraging consumers to adjust their energy usage during peak times in exchange for rewards, such as lower tariff rates. A modern solution to address the challenges of large-scale integration is to create localized grids that can operate independently from the main grid. This approach enhances resilience and flexibility in managing DERs while minimizing uncertainty and imbalance at a larger scale. The integrated microgrids of different regional grids can further facilitate energy exchange, providing a buffer against localized variability and enhancing overall stability. Furthermore, Table 3 presents the potential solutions and Techniques for Mitigating Power System Stability Amid the Energy Transition. Presently, the predominant trend emphasizes the integration of demand-side management (DSM), DERs, ESS, EVs, and PV installations into smart grids (SG) through communication technologies. This integration introduces a bi-directional flow of power and communication, facilitating interaction between the utility grid and prosumers in sharing their energy resources [68]. Recently, demand-side management has attracted a lot of interest as a potential remedy for managing energy demand. Consequently, this incentivizes consumers to engage in activities such as DSM, DR, energy conservation, and energy trading, all aimed at achieving optimal control and stability within the energy systems [69].

DERs participate in the wholesale and local energy markets in the modern grid. As widely recognized, these are markets in which energy is traded at the distribution system level, and bulk system power is merely viewed as another player in the market. Transactive energy is the general term used to describe this kind of localized energy trading on the distribution system. In theory, transmission efficiency is achieved by DER owners' exchanging energy with nearby neighbours. This helps to balance accurately the supply and energy demand for a given area utilizing price signals, hence reducing transmission losses [70]. Time-of-use (ToU) pricing represents an economic approach to DR, aimed at motivating users to enhance their energy efficiency and reduce peak energy demand[71]. However, using the ToU tariff structure may not entirely mitigate certain social challenges. Lower-income households with young children, seeking the advantages of more affordable rates, may encounter difficulties meeting their essential needs. Furthermore, even the average consumer might face difficulty when selecting a plan that aligns with their specific requirements. To bridge these gaps, there is a need for an automated system that is compatible with DR operations. This system should possess the capability to adapt to a dynamic environment, learn, and respond to the requests and requirements of users [72].

This participation increases the flexibility of the grid and improves the voltage profile, but of course, effective, and reliable control, monitoring, and communication techniques are necessary to address the challenges associated with large-scale RES integration and optimization.

4.4. Advanced control and monitoring systems

The modern grid is an extensively dispersed system, comprising DERs or power electronic converter (PEC) spread across various locations and interconnected via transmission and distribution networks. It incorporates elements like real and reactive power compensators. Additionally, due to the deregulation and expansion of the power

Table 3
Techniques for Mitigating Power System Stability Amid the Energy Transition.

Type	Advantages	Limitation	Application	Ref.
Battery Energy Storage System	−Fast response time −Flexibility −Improved grid stability by supporting P, and Q power. −Increased resilience	−High initial investment and revenue risk −Limited energy density −limited life expectancy	−RESs and EVs integration at different levels and locations −Backup power −Grid frequency support −Peak shaving and load shifting	[83–86]
Synchronous Condensers	−longer service life, and larger and stronger overload capacity compared to electronic VAR compensations to support Q power. −can provide short-circuit current and reinforce weak grids −A grid-stabilizing source	− Have a risk of transient angle instability near the Wind Turbine (WT) − High costs, maintenance and operating costs, and significant construction difficulties. −Small inertia; adding shaft mass is required; response uncontrolled, unsustainable	−Voltage Stability of WT Transmission via HVDC system −Improving the Frequency of Management	[87–90]
Static Synchronous Compensators (STATCOMs)	− Fast dynamic response − Good management and control − minimal maintenance needs	−More expensive than the SVC −Harmonics generation	To improve the critical-clearing-time −Voltage support	[91–93]
High-voltage direct current (HVDC) Transmission	−Lower losses over long distances with huge transfer power. −Suitable for asynchronous interconnections or different frequency − Independent voltage and power control	−Higher initial capital cost − Complexity in design and maintenance for complex converters with high rating −Protection system challenges.	− RESs integration −Interconnecting regional power grids −Long-distance power transmission extended to the continents	[94,95]
Demand Response Programs	−Reducing electric bills − Decreasing peak demand − Peak shaving − Minimizes need for ESSs − Enhances grid's efficiency and reliability	−Data complexity, and real-time implementation. −Dependent on consumer participation	−Flexible RESs and EVs integration. −Smoothing of the demand curve − Smart Grid Technologies	[32,96]

industry, power system components are obliged to operate at or near their maximum capacity. Consequently, smooth operation is a challenge, rendering the system more susceptible [73]. The primary causes of stability problems with high integration of RESs are the power network's low short-circuit strength, the failure ride-through (FRT) strategy and capabilities of the PEC-interfaced RES, and the decrease in synchronous inertia and reactive power reserve. Consequently, the controlled operation of power systems emerges as a pivotal and foremost necessity to attain stability in the power system. Furthermore, the FRT has an impact on both active and reactive power, PEC-interfaced RES capabilities and tactics are also crucial to the stability of the electrical grid [74]. The authors of [73] emphasize the application of intelligent systems, including neural networks, fuzzy logic, and bio-inspired optimization algorithms, for enhancing the resilience and effectiveness of power system controllers. The authors of [75] examine the possibilities presented by Information and Communication Technologies (ICT)in shaping the control of future power systems. They underscore the importance of geographically distributed cyber-physical networks in maintaining power balance, quality, stability, and control.

4.5. International collaboration and interconnections

Global cooperation is necessary to provide the level of funding required to accomplish a clean and smooth energy transition. This cooperation may include sharing knowledge, skills, or even resources between nations and communities [76]. Successful implementation of the energy transition necessitates cooperative efforts among local and international stakeholders, supported by effective policies, infrastructure development, technology adaptation, smart grid utilization, and diverse modelling and optimization tools for informed decision-making [77].

The inherent variability and geographic constraints of RESs necessitate strategies to ensure grid stability. Interconnecting grids across different nations is a viable solution to address this variability. This approach enhances the diversity of weather conditions among interconnected grids. For instance, while one region may experience cloudy weather, another region in a different nation might have abundant sunshine, resulting in varying energy production levels. This interconnection allows for the mutual exchange of energy. One of the biggest regionally integrated power networks in the world is the European power grid.

This grid's integration and use of RESs sets a magnificent example for other nations and can aid in the promotion of energy transition and the achievement of a high percentage of integration of RESs [78] Additionally, there is an electrical link between Morocco and Spain, as well as between Algeria and Spain, as a connection between Europe and African continents [79]. Furthermore, A large-scale generating project (11.5GW) of solar and wind called Xlinks is being considered to build a new 3.6 GW underwater. HVDC cable that would connect Morocco and the UK [80]. This would enable the direct delivery of green power to the UK without utilizing the current infrastructure in Spain and France. Fig. 5 illustrates how the broad interconnection of the geographic grid – specifically, the grid of European power – provides diversity in resources [81], and from the perspective of controlling variable RESs, it is easier and smoother.

5. Challenges and solutions to power system stability in the energy transition

The difficulties connected with adding additional RES to the electrical grid pose challenges to the system's stability throughout the energy transition. RESs are unpredictable energy sources [49]. Attaining equilibrium between demand and generation poses a challenge, which may impact the grid's stability [50]. Grid operators must possess the flexibility and resilience to handle changes and uncertainties in power supply and demand to preserve the stability of the power system. Creating new laws, regulations, and cooperative efforts, planning, and forecasting are a few potential remedies to improve the power system stability. The challenges and the solutions to power system stability in the energy transition are multifaceted and complex. Some of the key challenges are as follows.

5.1. Intermittency and variability of RESs

RESs, like solar and wind power, are sporadic and fluctuating, indicating they change with the seasons and the day's weather [82].

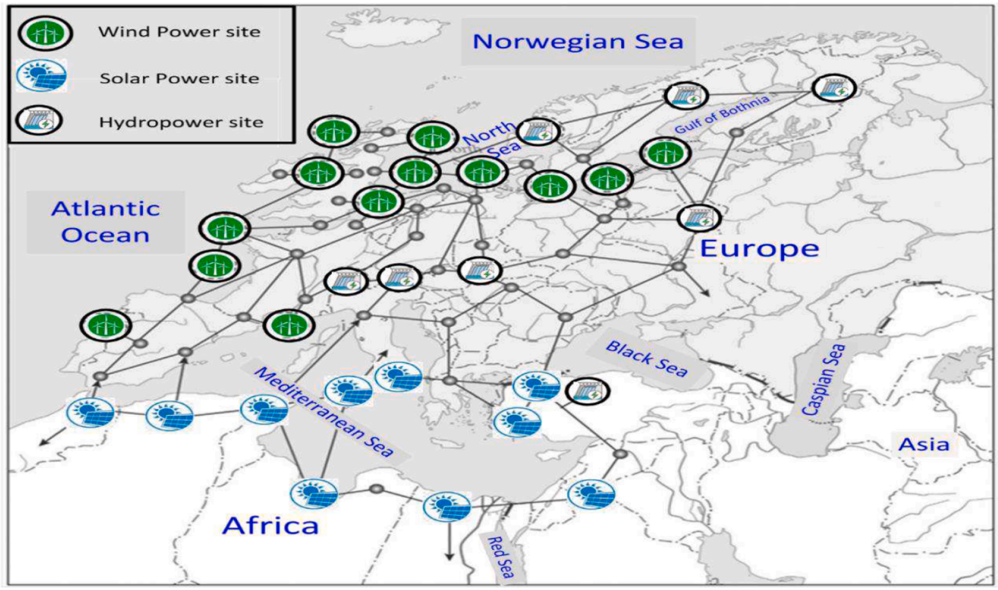


Fig. 5. European Super grid Concept: Linking Renewables [174].

This results in imbalances and variations in the supply and demand for electricity and the grid's stability. Utilizing demand response (DR) programs, which provide consumers with incentives to cut back on their energy use during periods of high demand, is an option to mitigate this intermittent and its consequences effects, i.e. DR offers consumers a chance to actively participate in the electric grid's functioning and decision-making by adjusting their electricity consumption, either by reducing or shifting usage during peak periods. This adaptation is prompted by time-based rates or various financial incentives [97]. However, Demand response aims not just to reduce costs but also to enhance reliability by integrating diverse resources [50,98]. Furthermore, energy storage devices can absorb energy during periods of low demand and release it during periods of high demand, aiding in the management of intermittency [99].

5.2. Storage solutions and energy management

Since RESs are unpredictable, long-term supply and demand must be balanced through efficient energy storage technology. Developing new energy storage technologies, like hydro energy storage and batteries, which can store extra energy produced by RESs during periods of low demand and can release it during periods of high need, is one way to address this difficulty [100,101]. By matching RESs to demand, energy management systems can also aid in maximizing their use. Utilizing energy management systems, which may maximize the utilization of RESs and minimize energy losses, is an additional option for developing new energy storage technology [102,103]. The formulation of smart grids involves a robust integration of energy storage, two-way digital communication links, and consumer participation through smart metering systems. Smart Grids enable interoperation across different energy producers and consumers, Such as commercial, production, and households. The objective is to minimize power disruptions caused by component failures, natural disasters, capacity constraints, or variable RESs by implementing real-time smart power monitoring and control systems. SGs Offer advanced services through automated monitoring and self-regenerating features. Additionally, they facilitate demand management by forecasting energy consumption [104]. Table 3 introduce techniques for mitigating power system stability amid the energy transition with their advantages, limitations, and applications.

5.3. Grid integration issues

The integration of RESs has made it more complex to design and operate the power system. For instance, greater dispersed generation-like solar panels put on rooftops may have an influence on grid stability [105]. The likelihood of tripping power plants and cascading failures can rise with increased connectivity across regions, especially at large-scale integration RES with the weak grid. Additionally, sophisticated automation and communication are needed for the network to operate well. This increase in automation and digitization could make the power sector more vulnerable to hackers. Table 1 shows the Ukraine blackout case. New technologies like smart inverters and power electronics can be employed to help integrate RESs into the grid more successfully [106]. Furthermore, real-time monitoring and dynamic line rating, which are novel grid management techniques, can contribute to increased grid stability and dependability.

5.4. Economic and market challenges

Integrating RES presents economic benefits, as it is almost free of operating fuel costs [7] and has low carbon emissions. However, researchers have identified numerous models where the RES integration and efficient technologies associated with energy transition are not widespread and are often still limited to those with higher incomes. Scholars have similarly concluded concerning technologies such as low-emission and electric vehicles [107,108], residential solar photovoltaic panels [109,110], community solar [111], smart meters [112], efficient appliances [113], and LED light bulbs [114]. This limited technical accessibility is usually linked to the high initial expenses of modern technologies, incentives that may exclude those with weaker credit or without tax liabilities and a mismatch between the requirements for installation and use of these technologies and living conditions, especially in the case of rental properties [115].

In addition to these challenges, the authors of [116] addressed the challenges concerning the developing nations' energy transition. Some of these challenges include:

- In residential activities such as cooking and heating, especially in the countryside where access to energy is a difficult option, there is persistent dominance of conventional untreated biomass in the energy combination, such as charcoal, animal dung, and fuel wood [117,118].

- Power networks and systems are limited by size and prone to unreliability, in the case of higher demand and low power generation, a load-shedding strategy takes place. At higher power generation, a curtailment strategy is used to prevent overload. In both strategies structural and organizational issues exist within the power systems. These circumstances contribute to under-funded power firms, constraints on available capital for expenditures, or excessive investments, significant reliance on fuel or equipment imports, and limited income streams, among other concerns [119,120]. poorer countries introduced electricity sector reforms, allowing private ownership, and promoting competition. While competition improved productivity and electricity generation, financial issues arose when government support was lacking or electricity bills went unpaid, making private investment challenging [121,122].
- Resolving regulatory and financial challenges to power sector reforms to promote energy transition in developing nations. During the 1980 s and 1990 s, also, with limited data accessibility arising from extensive informal economies and non-monetary transactions [123], this data is essential for strategic planning and the monitoring and evaluation of development strategies, this is again a challenge [124].
- The transportation industry is seeing an enormous increase in demand and depends mostly on imported fossil fuels. Rapid economic expansion is driving up demand for transportation in developing nations [125].
- The developing nations frequently have unfair conditions, slight democratic processes, and low levels of public engagement and understanding concerning energy transition. People in these nations are generally unaware of the nature of energy projects and the decision-making process around them since energy planning is typically carried out by the government with little involvement from the public [123,126].
- Renewable energy harvesting technologies still need a large area [127] which is considered an environmental challenge, and an ongoing source of criticism towards renewable energy projects has been the aesthetic effects on the landscape [128]. However, the project's sites can be utilized for various purposes, such as farming and animal grazing.

6. Future directions and strategies

By 2028, the RES capacity integration is expected to grow, with solar PV and wind power accounting for a record 96 % of this increase. This is because, in most nations, their generation costs are lower than those of both fossil and non-fossil alternatives, and policies continue to promote them. Compared to 2022, solar PV and wind additions are expected to more than double to record over 710 GW in 2028 [129]. According to the International Renewable Energy Agency (IRENA) data shown in Table 4 below which compares the key performance indicators and annual investment requirements for attaining 1.5 °C from 2023 to 2030 and 2023 to 2050 with the anticipated energy projections [130–132] the future energy transition will include many technologies and strategies such as the widespread of EVs, Hydrogen, and building electrification of the end consumer. Furthermore, the RES map viewpoint, Fig. 6 provides a thorough study of how RES is anticipated to be used in final energy consumption by 2050. This prediction attempts to slow down global warming through energy transition. The figure illustrates an energy of the future in which RESs make up much of the energy mix [133].To facilitate the broad growth and effective energy transition in the future without violating the power system stability criteria, the idea of electric interconnection appears to be essential. To achieve sustainable energy utilisation by connecting power grids and improving the distribution of energy resources worldwide, China has suggested the notion of global energy linkage by transmitting electricity using ultra-high voltage direct current (UHVDC)[134]. This global integration will extremely mitigate

Table 4
Key performance indicators to achieve the 1.5 °C Scenario 2020 and 2050.

Comparison point	Indicators	Recent years	2030	2050
Electrification with renewables	Share of RES in Generation (%)	28 (2020)	68	91
	RESs capacity additions (GW /year)	295 (2022)	975	1 066
	Solar PV additions (GW /year)	191 (2022)	551	615
	Wind energy additions (GW /year)	75 (2022)	329	335
	Required Investments for RESs Generation (USD billion/yr.)	486 (2022)	1300	1380
Renewables in end-uses and district heat	Share of RESs in final energy consumption (%)	17 (2020)	35	82
	Solar thermal collector area (million m^2/yr.)	585 (2021)	1552	3882
	Direct utilising bioenergy (Exajoule EJ)	21 (2020)	46	53
	Geothermal consumption (Exajoule EJ)	0.9 (2020)	1.4	2.2
	RESs-based district heat generation (EJ)	0.9 (2020)	4.3	13
	Investment requirements for district heating and RESs end users (USD billion/yr.)	13 (2022)	290	210
Energy efficiency	Rate of improvement in energy intensity (%/yr.)	1.7 (2010–2020)	3.3	2.8
	Investment requirements for efficiency and conservation of energy (USD billion/yr.)	295 (2021)	1780	1525
Electrification	Direct electricity's share of total energy usage (%)	22(2020)	29	51
	Investments required for EV charging infrastructure and assistance with EV adoption (USD billion/ yr.)	30 (2022)	137	364
	Requirements for heat pump investments (USD billion/yr.)	64(2022)	237	230
Hydrogen (H_2)	Producing clean hydrogen (Megatonne Mt/yr.)	0.7 (2021)	125	523
	Capacity of Electrolyser (GW)	0.5 (2022)	428	5722
	Infrastructure requirements for derivatives and clean hydrogen investments (USD billion/yr.)	1.1 (2022)	100	170

the intermittent nature of RESs and power system stability challenges, since the sun never sets completely in the sky, there is a chance to utilize solar energy generation that is continuous by connecting areas of the earth that are always in daylight to those that are always in the dark. Through this connection, solar energy is made available as a reliable and sustainable power source.

However, this proposal is in its early stages and faces hurdles, such as the expensive cost of the UHVDC system, and cooperation between nations. Therefore, the demand response and consumer participation by their RESs with the grid is another mitigation solution. In addition to that, the requirement to properly include new market processes and grid codes to effectively use developing technology in the energy transition in future [135]. Unfortunately, there is currently a lack of technical standards or grid code requirements for grid formation control operation. This is due to the absence of explicit industry criteria for creating new grid-forming control with BES generation that complies with emerging power system paradigms. Furthermore, installing

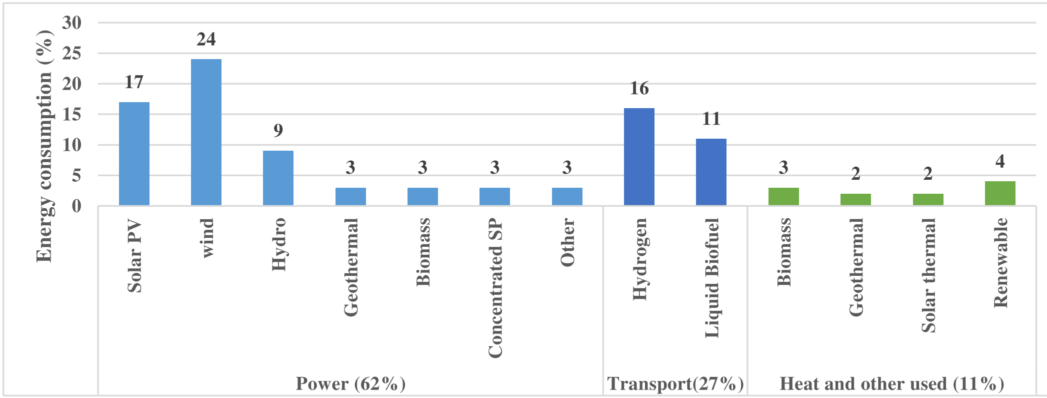


Fig. 6. Projection of the Energy Transition Map for 2050.

synchronous condensers will be essential to maintaining the stability of power systems that rely up to 100 % on inverter-based resources due to the decreasing inertia [136], therefore, advanced research and development are required.

6.1. Research and Development Needs

Significant action and in-depth research are needed to accelerate the energy transition, especially in terms of lowering the cost of developing new technologies and control to maintain the power system stability at different penetration levels of RESs. This means conducting thorough research on cutting-edge strategies and tactics to improve the accessibility and cost of RES solutions. We may expedite the broad acceptance of energy transition by giving priority to cost-cutting measures in conjunction with technology breakthroughs, thus facilitating a more sustainable and ecologically beneficial energy landscape. For instance, improvements in energy storage technology may be able to better integrate RESs into the grid by addressing their fluctuation and intermittency.

Similarly, as power systems move towards greater percentages of RESs, advancements in hardware and software for grid management might increase. According to [137] the potential study areas include non-fundamental component stability, such as wideband frequency and control oscillation, and fundamental component stability. Furthermore, the design optimization and modelling of HRES with hydrogen technologies [138], and Resilience enhancement strategies [139] are other categories of future research directions as shown in Fig. 7. In the following context, these topics will be briefly discussed.

A. Research Prospects of Fundamental Component Stability.

1) Voltage Stability.

At high integration of RESs and high-power electronic converters (PECs) is dominant, problems like cascading failures, dynamic interactions, severe nonlinearities, and intermittent sources threaten the power system's voltage stability. Future studies should focus on the following areas for voltage instability issues:

As RESs are weather-dependent and non-dispatchable sources, their integration has a significant impact on grid stability, particularly at high integration, therefore, it is recommended to utilize sophisticated prediction and forecasting models in conjunction with adaptable and flexible control systems and energy storage options [140]. Otherwise, voltage fluctuations and cascading faults may arise. Reactive power management techniques and grid reinforcement are two examples of these controls. Moreover, the PECs are essential and vastly known as Grid Forming Converters (GFC) which can generate more stable voltage [141]. However, GFC lacks the Black Start system to recover from a blackout; and the hardware limitations require the GFC currents to be kept within an acceptable range, necessitating the use of appropriate current limiting principles [142]. In addition, some of the suggested methods lack reactive power regulation, which limits their transient stability performance. Furthermore, the effectiveness of Proportional-Integral (PI) controller-based systems is restricted due to their lack of robustness. Moreover, instability problems in the mathematical modelling and numerical computing related to the VI-based controllers perturb their transient stability performance. Although PI controllers are widely used in industry, they lack adaptability and self-learning capabilities. Artificial intelligence (AI) forecasting and control methods show

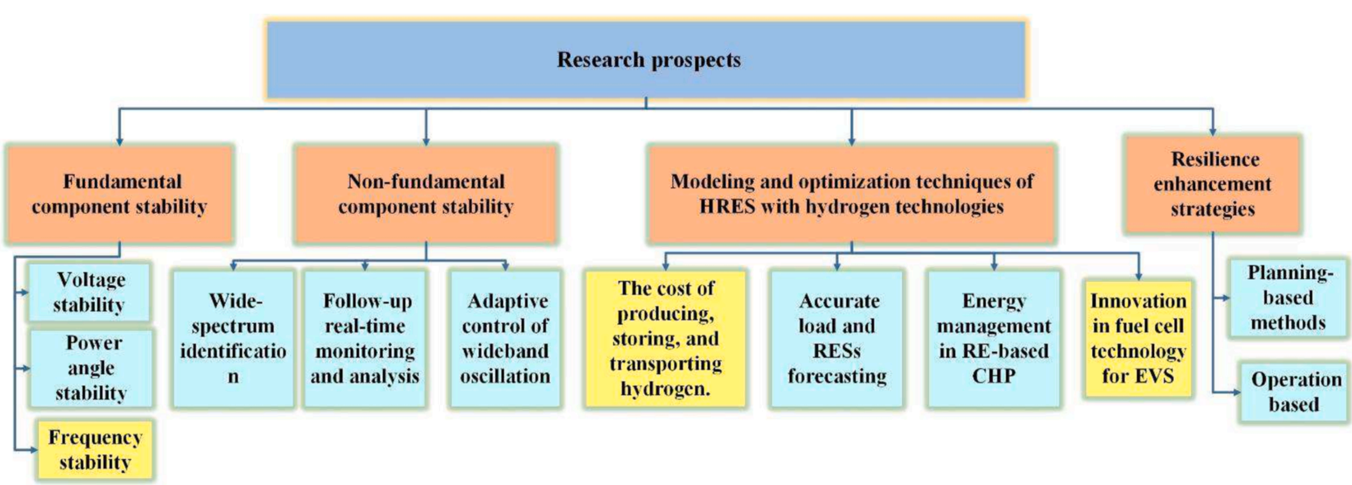


Fig. 7. Future of research directions.

promise in temporary stability situations when PI controller flaws should be resolved [141] Additionally, examining how complicated rapid control and large-scale grid-connected equipment interact to study the DC control and protection system under various disturbances, and a quantitative approach for calculating the transmitting end's voltage safety zone need to be suggested [137].

2) Power Angle/Synchronous Stability.

The synchronous stability of the dual high-penetrated power system is directly related to the synchronization of the converted interfaced generators (CIGs) with the grid. The primary factors influencing angle/synchronous stability include the distribution of inertia, the magnitude of power flow, and the strength of the grid, among others. Currently, the power grid's following regulation technique is the prevailing method for connecting CIGs to the network. The control mode of the power grid converter is undergoing a steady transition from grid following to grid-forming. In contrast to its predecessor, the grid-forming converter can offer standard settings for frequency and voltage, enabling direct adjustment of these parameters [143]. To overcome the issue of reduced inertia in a dual high-penetrated system, a grid-forming converter should exhibit load sharing, sagging, and black start behaviour similar to turbogenerators (TGs). In contrast to the TGs, the control mode does not employ any real synchronization and stabilization devices, nor does it offer any physical inertial response. Hence, the essential activities of the synchronous machine necessitate the implementation of converter control and autonomous energy storage. While the future converter-based grid may not require these services, it is anticipated that there will be a lengthy transition period. During this time, it is crucial for the TGs and grid-formation converters to effectively operate and ensure system stability. The future electric network necessitates a comprehensive examination of methods for quantifying grid strength and selecting an appropriate control structure. This includes determining the optimal proportion of the control structure and identifying the impact points within the electric network. The stability of networking equipment in enhancing the access system of large-scale phase-locked loop-based power electronic equipment is examined in Ref.[144], with a focus on grid strength. The stability characteristics of the power system are significantly influenced by the grid structure [145]. Hence, the investigation strategies for effectively designing the grid structure to mitigate the potential for system instability is also a subject of scholarly inquiry. Currently, the stability of certain typical structures in specific scenarios is generally attributed to the reliance on technical knowledge and physical intuition for determining the synchronous control structure of power electronic equipment. The determination of an appropriate synchronization control structure for power systems with a significant presence of power electronic equipment, as well as the development of an optimal design for such a structure, remains an unresolved issue.

The angle stability is also influenced by the magnitude of the power flow. The future holds promise for the utilization of modern artificial intelligence and big data in accurately predicting load demand for flexible resources, and intelligently scheduling and dispatching them. This has the potential to contribute to the development of a secure and stable power system [146,147]. The conventional theories of power system operation and control, which rely on models, encounter several obstacles including significant uncertainty, intricate security mechanisms, and limited flexibility. The conventional power system regulation theory, which is guided by models, is unable to accommodate this phenomenon. Therefore, there is a pressing need to integrate data-driven and model-driven methodologies to provide a novel framework for intelligent regulation and control. This framework will facilitate the transition from automation to the development of intelligent systems [148]. The utilization of sophisticated AI algorithms enables the effective management of intricate security limitations, such as the regulation of power flow to mitigate the potential risks associated with oscillatory stability, including angle stability [149]. A viable approach could involve utilizing bio-inspired learning algorithms to optimize scheduling with intricate high-dimensional constraints [150,151].

3) Frequency Stability.

The current power system's frequency stability in the dual high-penetration scenario is challenged by issues such as low inertia, multi-time, and poor tolerance. It is necessary to investigate the variations in frequency response characteristics of different types of CIGs across different time scales. Furthermore, it is imperative to elucidate the mechanism and characteristics governing the temporal evolution of the low inertia system. It is recommended to propose rapid computation and run time monitoring of the primary frequency stability indices. It is imperative to assess the acceptable level of frequency fluctuation and recovery time following a disruption in real time, particularly when dealing with intricate system settings. The theory of adaptive coordination control in frequency dynamics has the potential to enhance the stability of full-time frequency levels, transitioning from a state of "inertial support" to a state of three-stage frequency modulation [137].

B. Research Prospects of Non-Fundamental Component Stability.

The stability of non-fundamental components consists of the wideband oscillation instability, which encompasses subsynchronous resonance/subsynchronous control interaction (SSR)/ (SSCI) and harmonic resonance phenomena in dual high-penetration power systems. This instability is primarily attributed to the dynamic interaction between PECs and their controls with the alternating current/direct current grid. Wideband oscillation monitoring and control encounter challenges related to wide-spectrum frequency, time-varying characteristics, and nonlinearity [152]. The feasibility of employing conventional methods such as modelling, offline analysis, and control of oscillation stability is limited. The proposed concept involves a departure from the conventional approach of oscillation stability analysis and suppression. Instead, it advocates for a more comprehensive approach that encompasses wideband frequency, real-time analysis, and intelligent/adaptive control, as outlined in the reference [74]. The synchrophasor technology has conventionally been developed to measure fundamental phasors at a low reporting rate. Nevertheless, it is anticipated that contemporary synchro wave/synchrophasor measurement units will possess the capability to capture voltage/current waveforms in real-time, accompanied by timestamps and a notable reporting rate. The authors Wilsun et al. [153] have produced a seminal study that elucidates the potential uses of "synchronized waveforms" in the domains of apparatus monitoring, protection, and system control. The promise of synchrophasor technology for monitoring, analysis, and management of emergent oscillatory stability was also emphasized by Meegahapola et al.[154]. In this study, the authors delineate three research avenues for the comprehensive and immediate detection, surveillance, subsequent examination, and regulation of emergent oscillatory stability.

1) Wideband Spectrum Identification

Wideband Spectrum identification means to enable rapid and precise detection along with tracking of broadband oscillation phases and frequency-varying models by integrating broad-spectrum sensors into the power grid. For instance, the study conducted by [148] used a multiple support vector machine (SVM) model to extract the characteristics of the disturbance and determine the most suitable classifier among the available SVM models. The sub-synchronous oscillation (SSO) identification technique was evaluated using field measured Phasor Measurement Unit data. References [155,156] employed an adaptable modified Kalman filtering methodology to monitor SSO in real-time. This approach can also be applied to detect SSO events in real-time. By measuring the synchronized waveform and preserving and identifying the information of wideband oscillation, it is possible to construct various algorithms [151,152]. Power grids' operating efficiency and stability are greatly improved by wideband spectrum identification. Utilities may take proactive measures to maintain grid stability, optimise resource utilisation, and guarantee dependable power delivery to customers by facilitating the prompt and accurate identification of broadband oscillations and monitoring frequency-varying models.

2) Follow-up real-time monitoring and analysis.

Real-time monitoring and assessment can be performed by novel data analysis tools to analyse emergent oscillation in real-time [153]. Moreover, the collected oscillatory waveform data can be utilized to calculate the real-time impedance model of power electronic devices. The incorporation of real-time monitoring and management capabilities within the control centre can serve as a viable strategy to mitigate instability and facilitate informed decision-making. For instance, the power flow linked to the multi-frequency oscillation can be ascertained, thus enabling the identification of the oscillation's origin [154,155].

Reference [156] introduced a system-wide protection mechanism based on distributed synchro wave/synchrophasor measurement units to address the SSCI in a practical huge-scale wind power system. According to the sub-/super-synchronous frequencies, the impedance modelling of the wind farms was considered and subsequently transmitted to the control centre for real-time analysis. A particular variety of offshore wind turbines were hooked until the oscillation reached a stable state, based on the predetermined parameters and the calculated sensitivity index. The utilization of synchronized waveform measurements holds potential for practical applications at the device and system levels, namely in the realm of monitoring and analysing emerging wideband oscillation, i.e. The accurate subsynchronous voltage and current phasor calculation of WTGs serve as a basis for the impedance measurement in real-time monitoring representing the working circumstances of the WTG system. For the protection system to provide fairness, fewer WTGs tripping, and real-time protection performance, the decision-making process for tripping WTGs is structured as an optimisation problem with extremely low computing complexity. This tripping guarantees that the entire system will not be affected as WTGs are a relatively small portion of the grid's overall capacity.

3) Adaptive Control of Wideband Oscillations.

The frequency of the wideband oscillation in the current system is influenced by the operating conditions of the system, and the control settings and characteristics of the electronic converter-based devices. The control system's overall structure and parametric design encounter significant challenges in terms of adaptability and resilience. It is imperative to consider the temporal fluctuations in the oscillation frequency resulting from alterations in operational circumstances. The detection and estimation of multi-frequency oscillations can be achieved through the utilization of synchronized waveform technologies [153,157]. The appropriate manipulation of wideband oscillation relies on the measurement of wideband frequency, enabling the adjustment of individual fluctuations and overall device interaction in an adaptive manner. In a recent study [158], the authors employed a frequency adaptive damping control technique to regulate the SSO in Doubly Fed Induction Generator (DFIG)-based farms that are interconnected with a series-compensated network. The accurate determination of oscillation frequency and the implementation of appropriate countermeasures are crucial for ensuring the stable functioning of contemporary power systems. From a pragmatic standpoint, there exists a dearth of exceptionally effective practical apparatus or equipment to mitigate the non-fundamental/wideband oscillation, which, as previously said, constitutes a key prerequisite for achieving stability in contemporary power systems.

C. Modelling and Stability Analysis Research Prospects.

The stability of power systems according to classical theory requires a synchronous generator and a basic phasor model. The stability of the electricity system and its mechanisms undergo substantial changes in the dual high-penetration scenario. Multiple control loops, strong coupling, complicated grid-connected situations, and significant nonlinearity generated by control switching/saturation make power electronic equipment modelling and stability analysis more challenging than conventional power systems. If the dynamics of the stability concerns at hand are linked to the nonutility/wideband frequency or the utility/fundamental frequency, then the device-level modelling will be appropriate for studying the dynamic behaviour of the power system during the dual high-penetration scenario. There has to be an extensive investigation into whether or not current equipment-level modelling can be used to investigate the new instability. Understanding the processes and characteristics of the emerging power system stability issues is challenging because, unlike the traditional power system that is dominated by TGs, there is currently no mature modelling method for presenting the relationship between CIGs and other system equipment. New kinds of oscillatory difficulties are popping up as a result of the growing complexity of today's power systems. The processes and/or underlying reasons of several of the recorded occurrences remain a mystery. Take the following issues as an example; with generic models, we still don't know everything there is to know about their mechanism and attributes.

Interconnected issues like frequency and voltage stability are brought about by the significant adoption of renewables. A major risk to the reliability and safety of the electrical grid is the propagation and spread of effects from individual failures to the whole grid. Limiters, switching functions, and delays are examples of control nonlinearities that are often encountered in the functioning of converter-based devices during fault situations. Overvoltage and current issues, brought on by improper control settings, might reduce the control's effectiveness in fault situations. To ensure that converter-based equipment performs to expectations, it is crucial to comprehend the instability mechanism, since this equipment is dependent on the control configuration and settings. A major wideband oscillation issue, dominated by converter control, with oscillation frequencies that range from a few hertz up to several kilohertz, is caused by a large number of PECs. The power systems of many countries, notably China, the United Kingdom, and the United States, have experienced similar wideband oscillation episodes [137].

1) Modelling in Time-Domain

The lack of vendor-provided comprehensive EMT models is one obstacle to thorough examinations of new unstable. Because power electronic equipment often has a high order, taking all aspects of the model into account makes analysis much more complex, particularly when dealing with multi-machine systems. So, future research should focus on finding a happy medium between the analysis model's accuracy and its low-order features in order to suggest a reduced-order model that works well for synchronous stability analysis. It is critical to create new modelling and analytic tools that can accurately describe these problems in order to comprehend them completely and put effective solutions into action. The electromechanical model of simulation is obsolete from a simulation standpoint. Currently, more research is required to address the numerical stability issue brought on by the electromagnetic transient model's numerous time scales as well as the simulation speed difficulty created by large-scale high-order equations. Opportunities for data-driven modelling, real-time monitoring and analysis, and adaptive management of growing stability challenges might be explored in new domains like artificial intelligence and big data [148,157–159]. Considering the kind of instability, the amount of disturbance, and the time duration, a thorough assessment of WTG modelling is presented in reference. The design of the control structure of a CIG from various suppliers may vary greatly and is often kept proprietary, making it difficult to build a generic model for diverse converter-based equipment or CIGs. However, it is possible to create a generic model of CIGs that can be fitted with modelling components from various vendors to create a fully functional detailed model [160] The stability of the system as a whole will be impacted by the growing share of converter-based equipment in the distribution system. Some manufacturers are also switching to the new generation of inverters, which are known as grid-forming converters. Analytical modelling of converter-based equipment for evaluating distinct emergent stability concerns should take the number of details into consideration. The specifics of the stability issue that is being studied dictate the modelling features of converter-based equipment. We need more efficient and standardized modelling tools for stability analysis since the complexity of stability phenomena is rising due to the quick innovations. The analysis findings are only valid at a given operating point, which is a key restriction of the linearized modelling-based analysis methodologies. Another difficulty is that it is necessary to know the control structure and settings of all converter-based equipment in advance. Efforts to create efficient and precise dynamic phasor-based interface models for time-domain hybrid simulation have been made recently [161,162]. Multiple time-step interface models, including transmission lines and interface transformers, are already available in commercial software and hardware simulation platforms including RTDS, PSCAD, and ETAP's eMT. These platforms are ideal for hybrid simulations. Both an offline tool and an FPGA-based real-time simulator are used to create a scalable and efficient multi-rate co-simulation platform in Refs. [163,164]. by looking at real-life SSR/SSO incidents that occurred in large-scale power networks, its efficacy was confirmed [165]. A potential method for the efficient and accurate modelling of a system with numerous MMCs was suggested in reference [166]: shifted-frequency models of power converters. Improved methodologies for the rapid, accurate, and efficient analysis of hybrid models and simulations of dual high-penetrated power systems are urgently required.

2) Modelling in frequency-domain

Frequency domain impedance estimation and measurement are widely used for studying wideband oscillation [161,167]. One of the key benefits is the ability to model equipment even without full knowledge of its control structure and parameters. This is particularly useful for devices that are considered grey or black box devices. Additionally, the impedance models of converter-based equipment along with various system elements can be coupled to create a network of impedances. This network can then be used to analyse system stability in the frequency domain. 3) Impedance modelling and stability evaluation can be conducted across various time scales to examine instabilities at multiple frequencies. Obtaining the impedance model of power electronic equipment involves utilizing the harmonic linearization method. This method entails injecting a small perturbation signal of a specific frequency and measuring the resulting response. Impedance measurements can be performed using EMT-based computational models or actual time simulations. The impedance models can be combined in either a source-load configuration or an impedance network framework to apply one of the stabilization criteria, such as the standardized Nyquist as well as reactance-frequency switching criteria [168]. The accuracy of the stability results relies on the precision of the impedance models at the device or system level. The precision of impedance models of power electronics devices relies on the inclusion of particulars like phase-locked loops, outer feedback loops,and fluctuations in the impedance modelling [149]. For instance, when analysing SSO, it is important to consider the outer loop control, as its bandwidth is in the sub/super-synchronous frequency variation range. Here are some exciting research potentials in this field.

3) Considering the Frequency Coupling Effects.

For a precise impedance model, it is important to consider the frequency coupling effect of the power electronic converter control [169,170]. When a grid disturbance occurs in a grid-tied power electronic converter device, it can cause a voltage deviation component at the connection point. This, in turn, affects the output angle of the converter's phase-locked loop, as well as the effective values of the DC and AC voltages. It's important to note that these frequency components have a complement frequency of 2f0 − fS, where f0 represents the utility or fundamental frequency. Once the internal loop control and PWM are in place, the converter current will generate the associated frequency fs and s upplementary frequency 2f0 − fS components. Reference [171] developed frequency-coupled impedance models for converter-based WTGs and validated them using controller hardware in looped models. Considering the presence or absence of frequency coupling effects can have a significant impact on the stability results and the level of complexity in the analysis. Typically, it's advised to consider the impact of frequency coupling on oscillatory instabilities that occur at lower frequencies, like those in the low to medium range. When dealing with higher harmonic/oscillation frequencies, such as those exceeding a fourth of the primary frequency, the frequency coupling effect is relatively weak. Therefore, disregarding it would not significantly impact the stability analysis results. When frequency coupling effects are considered, the impedance model becomes a two-dimensional matrix, which makes the identification and analysis of the model more challenging.

4) Inclusion of nonlinearities.

Deviations such as PWM and current limiters within the control loops have a significant impact on the intensity of the sustained wideband oscillation. In a previous study, a method was proposed to address nonlinear features in the converter control by considering the large-signal impedance [172,173]. In their study, Yanhui et al. employed the characterization function method to accurately model the nonlinearities. They also utilized the more general Nyquist criterion to conduct SSO analysis specifically in wind farms [174]. These constitute a few notable initial functions by Tianhao et al. [175] on calculating different irregularities in the converter control for analysis of stability. However, more extensive research is needed to better understand and measure the impact of nonlinearities on wideband oscillation.

5) Operating Point Independency.

Investigations into the wideband oscillations reveal that the stability issues are highly influenced by various system operating conditions such as the velocity of the wind, solar radiation, grid power, and converter control mechanisms and settings. However, the current impedance modelling methods are specific to the operating point and require recalculation when the operating point changes. This primarily pertains to nonlinear/converter-based devices such as WTGs, PV converters, FACTS components, and similar equipment. When dealing with linear components like transmission lines and transformers, it is possible to directly obtain the impedance models without considering any changes in the operating circumstances. Despite some initial attempts to separate the impedance model from the running points, this remains a significant challenge that researchers are working to address[176].

6) Challenges in the Frequency Domain Analysis Methods:

There are two commonly employed techniques for impedance-based analysis. 1) Analysis of source load impedance, and 2) Analysis of impedance network models. The source-load impedance method presumes that both separated subsystems are open-loop stable. Therefore, the stability results are influenced by selecting the separation point that segments an entire system into two subsystems: source and load. The impedance network method presumes that all system modes are accessible at the node where the impedance of the whole system is being observed. The aggregated impedance might not accurately capture the behaviour of certain local modes if they exist, that cannot be observed at the aggregation node.

Assessing the stability of the source-load modelling system can be done by analysing the phase margins. Having a smaller phase margin increases the system's vulnerability to instability. No specific threshold has been defined yet for determining marginal stability for achievable power systems. It heavily relies on the system operator's willingness to take risks and the reliability of the models used to assess stability. By resolving the zeros of the accumulated impedance, one can obtain the system modes in the impedance network-based assessment method. Calculating the damping proportion and oscillating frequency is possible for an oscillation mode. Following a disturbance, the system dynamics would be dominated by unstable or under-damped modes in an actual power system. The system's electrical damping provides valuable insights into the stability of the system. Until now, there has been no conclusive evidence linking the phase margin to electrical damping [137].

7. Case study

As the voltage level in the future network will be diverse in the range of low voltage (LV) of consumer generation and medium voltage (MV) of distribution network or even high voltage (HV) of transmission network, we take the IEEE 14 bus in as a case study that contains voltage levels (132, 33, and 0.4) kV at a frequency of 60 Hz and bus-1 as the slack bus. The IEEE consists of 14 busses, 5 synchronous generators, and 20 branches as shown in Fig. 8. This simulates the real network integration when the consumer is participated by their generation to examine power flow, stability, and the incorporation of RES and BES.

First, we have simulated the IEEE 14 network at different levels of integration of RESs such as PV and wind generation as shown in Fig. 9 which shows that some buses' voltages may exceed allowed limits due to the growing penetration of RESs if appropriate measures are not taken. Second, five different scenarios are simulated using Stability Analysis Functions (RMS)/ Electromagnetic Transients (EMT); DIgSILENT powerfactory 2024 and MATLAB software. The scenarios are as follows: The base case simulation involves simulating the exciting load/generators without integrating RES and BES. The second scenario integrates RES, (solar or wind power), but excludes BES, allowing for the analysis of RES's impact on grid stability and performance. The third scenario includes both RES and BES to enhance the power system's stability, mitigating the intermittency of RES and ensuring a more stable and reliable power supply, referred to this scenario as Case 3. Building on Case 3, the fourth scenario introduces a sudden change in the generation due to the weather conditions (some generators are out of service and a decrease in power generation is simulated in this scenario), the final scenario assesses the system's performance with the same parameters of case 3 under a substantial load change in the different seasons (a large-scale load is taken out of service, i.e. a load shedding or load curtailment is simulated in this scenario. This process involves intentionally reducing the load on the power system to maintain stability and prevent overloading). It is critical to understand how the grid responds to significant and sudden increases/decreases in power demand, testing its resilience and stability. Collectively, these scenarios provide a comprehensive analysis of the grid's performance under various conditions, highlighting the importance of integrating BES alongside RES integration to enhance power system stability and reliability.

Fig. 10 and Fig. 11 show the simulation result of the 3-phase fault occurring in Line_0002_0005 at 132 kV (worst case transmission line) as a disturbance at 2 sec., this fault will be cleared by the protection system at 2.3 sec.

Fig. 10 and Fig. 11 show the Bus_0013 frequency and voltage respectively at fault and sudden large change in generation and load demand disturbances. In Fig. 10 due to the lower inertia of RESs especially during the fault period (2–2.3 sec.), the system with integration RES without BES goes the lowest nadir frequency compared to other scenarios as the system without integration has higher mass inertia of the machine compensates for the oscillation in the frequency. Thus, the more quickly the protection system clears faults, the more stable the system becomes, preventing the system frequency from reaching the frequency relays' pickup setting and ensuring the RESs stay connected (at least 0.5 sec.) to prevent system tripping and cascading failures, as RES plant goes disconnected; it can have an impact on surrounding power plants, potentially causing them to shut down as well. This chain reaction may spread throughout the grid, resulting in a blackout.

Additionally, the figure illustrates that the most stable scenario regarding RES integration is for the system to be connected to the BES via power electronic converters since energy can be stored at high generation and released when needed. However, the power electronic converter has a lower power short-circuit level and does not produce higher short-circuit currents in the event of a fault to make the detection of a fault easier, therefore, a minimum fault level is required to guarantee that the voltage/frequency remains within the specified limits at

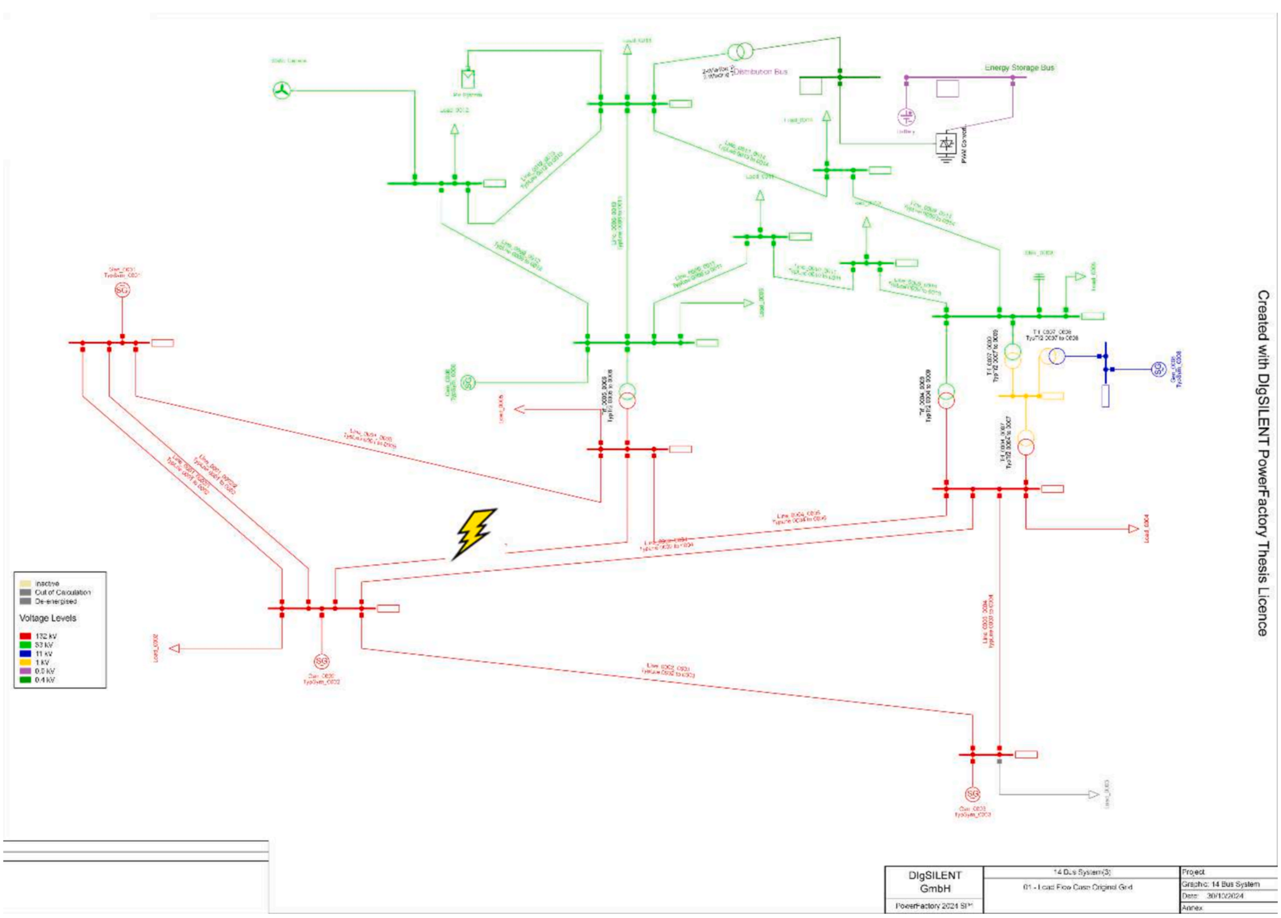


Fig. 8. IEEE 14 bus model simulation with the wind turbine, BES and PV integration

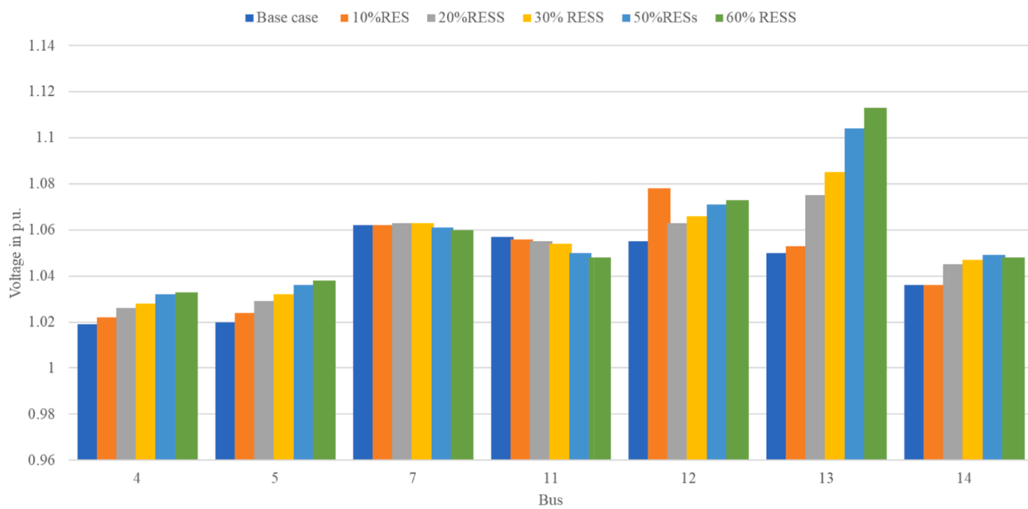


Fig. 9. Bus voltage at different levels of RESs.

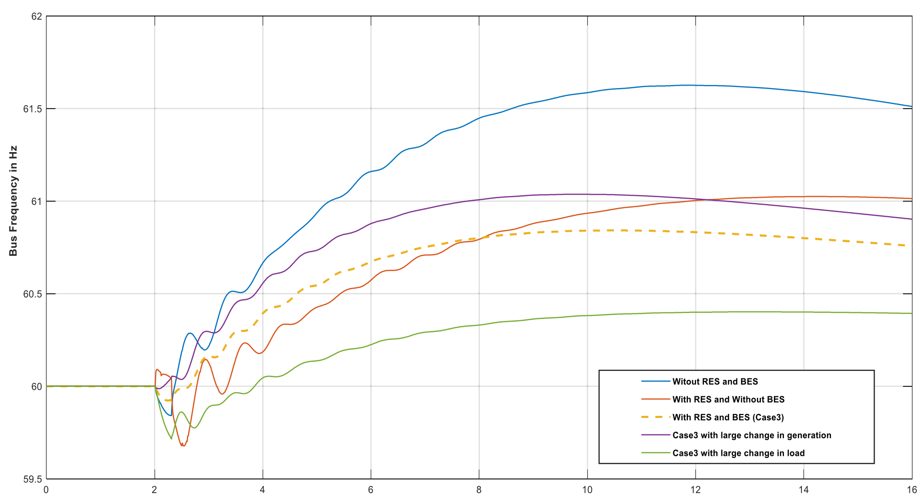


Fig. 10. Bus Frequency at different Scenarios.

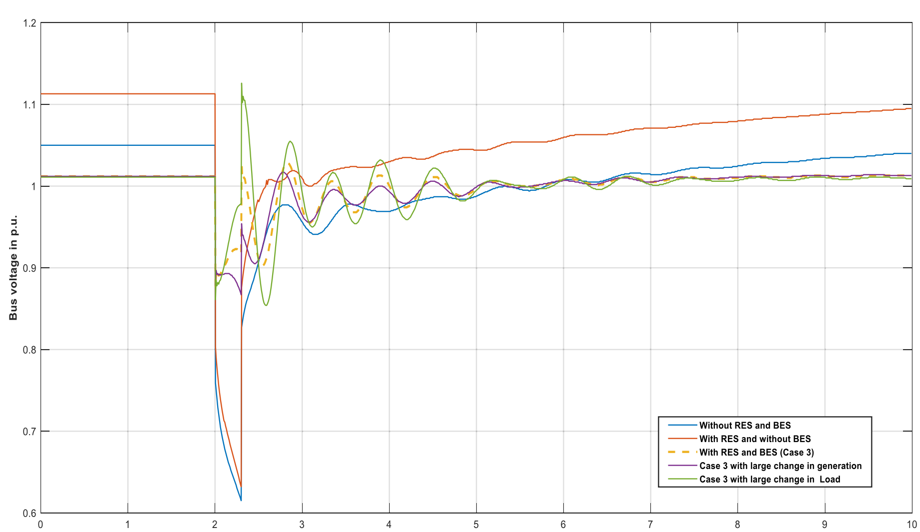


Fig. 11. Bus voltage at different scenarios.

disturbance events.

Fig. 11 shows how the integration of RES may raise the voltage above 1.1per unit (p.u.) even in normal operation. However, using BES can help to lessen this issue by absorbing the surplus power through the charging process. When Renewable Energy Sources and Battery Energy Storage systems are integrated, the bus voltage levels –both pre-fault and post-fault-are considered the most suitable scenario. This is explained by the fact that during the pre-fault situation, they were close to the allowed limit, roughly 1p.u., which indicates effective and ideal system operation. The system experiences a disturbance during the fault state, but there is not a noticeable voltage overshoot. This indicates that the voltage is not momentarily above the allowable limit, preventing possible system damage. After a disturbance occurs, the bus voltage rapidly stabilizes and reaches a stable operating condition in less than five seconds. This quick stabilization is essential to preserving the power's stability violation. It is found that Case 3 is more stable during fault situations when compared to the scenario of load decrease. This is demonstrated by the fact that, in the case with a large reduction in load, the bus voltage reaches 1.1p.u., whereas in Case 3, it does not. The system's capacity to keep voltage levels within acceptable limits, avoiding excessive voltage oscillations that may threaten system operation, is what accounts for Case 3′s stability.

8. Conclusion

With the increasing energy demand, energy transition is becoming more important than ever, However, this transition faces many challenges but has opportunities. This paper thoroughly examines these challenges from the operator's perspective and the consumer's. To increase the smooth energy transition; hybridization of RES and BES and cutting-edge techniques, global cooperation are needed regarding knowledge and energy resources to save our world. The power system stability is a thermometer of grid health, and maintaining stability with energy transition is a challenge, Therefore, many measures should be introduced such as large-scale energy storage systems or even nuclear power plants. Our case study illustrates the effect of a huge percentage of RESs and the effects of energy storage systems on power system stability.

CRediT authorship contribution statement

Ahmed Mohammed Saleh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vokony István:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Muhammad Adnan Khan:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Waseem:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Amgad Naji Ali Ahmed:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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