CIENTIFIC Publishing Limited

Electrical Engineering and Technology

https://ojs.ukscip.com/index.php/eet

Article

Regulatory and Policy Framework for Smart Grids: A Comparative Analysis of the US, EU and China

Siolhan A. Viniya

Engineering Profile Laboratory, L.N. Gumilyov Eurasian National University, Satpayev St., Astana 010008, Kazakhstan

Received: 28 March 2025; **Revised:** 18 May 2025 **Accepted**: 3 June 2025; **Published**: 24 June 2025

Abstract: Smart grids represent the next evolution of energy infrastructure, incorporating advanced technologies like artificial intelligence (AI), machine learning, renewable energy integration, and real-time monitoring to enhance grid efficiency, reliability, and sustainability. With such systems networked all over the world, there is a high demand for a proper regulatory and policy framework that will nurture the growth of such systems. This paper describes the current trends in smart grid technologies and sketches out the demands made on formative policymakers to develop adaptive and safe regulatory frameworks. It looks into data privacy, cybersecurity, and decentralized energy markets, as well as the incorporation of electric vehicles and blockchain in energy trading. This article uses case studies based in the United States, European Union, China, and India to present a wide range of regulatory policies and pinpoint some of the central recommendations on how to improve smart grid policies, such as standard harmonization, investment incentives, and social fairness. Through resolving these issues, the article proposes to have a better and elaborate knowledge of how to ensure that regulatory frameworks support the successful application of smart grids, leading to a cleaner and resilient energy future.

Keywords: Smart Grids; Regulatory Frameworks; Renewable Energy Integration; Cybersecurity; Decentralized Energy Markets

1. Introduction

The ongoing transformation of power grids into a more modern and interconnected system has become an increasingly a pillar in the quest for realising sustainable energy management [1]. The next-generation technology to be used in energy distribution and consumption is smart grids, which combine modern-day technologies in energy efficiency, including real-time data system monitoring, automated energy systems, renewable energy sources, and predictive modelling. These future grids are not just going to increase efficiency and reliability, but make the grid much more robust against natural disasters, changing energy loads and the growing complexity of international energy markets. Nevertheless, the range of possibilities opened by smart grids concerning technologies is enormous, yet while its realization would be almost impossible with weak regulation and policy, it is important to note that its effective implementation cannot be achieved without strong regulation and policy [2,3].

Regulations and policies play a key role in how smart grids are developed. It is the role of governments, regulators, and international agencies to formulate and enforce policies on the direction to be adopted in the use and incorporation of smart grid technologies. The frameworks are meant to cater to diverse issues, such as cybersecurity, data privacy, energy equity and decentralised energy integration, such as wind and solar. Moreover, the development of smart grids also requires the establishment of new regulations to guarantee fair competition, protection of consumers, and complex grid operations. Here, the regulatory environment is known to be in its development phase, and as the technology, market and customer habits are still developing, a lot of obstacles and opportunities are being created [4-6].

Fundamentally, an effective regulatory framework with smart grids not only sustains the technical and operational developments of the systems but also aligns the systems in line with the larger objectives of society. These objectives are associated with a decrease in carbon emissions, an increase in energy security, a promotion of renewable energy integration, and the delivery of affordable energy services. Due to the direction of the world becoming decarbonized and sustainable, smart grids are regarded as one of the drivers towards achieving these objectives. Nevertheless, in order to achieve their potential, it is necessary to develop a set of thorough and long-term policies that balance technological breakthroughs and regulatory securities [7].

Advancement of the smart grids also presents novel problems to regulating bodies. However, unlike conventional grids that are usually managed by centralized utilities, smart grids have decentralized energy supply and demand, which makes use of a large number of stakeholders. These stakeholders are the members of the private companies, the governmental agencies, the local authorities and the consumers, their roles, expectations and responsibilities being various. One of the major tasks of policymakers is to coordinate the interests of these groups and, at the same time, make sure that the grid will be secure, reliable, and efficient. Moreover, the introduction of smart grids is not always the immediate stage, and it entails long-term investment and sound policies, a stable regulatory framework capable of adjusting itself to the new technologies and economic forces on the market [8].

Moreover, there are peculiar challenges and opportunities associated with the incorporation of renewable energy within smart grids. Although renewable energy sources like solar, wind and hydroelectric are very essential in the move to achieve low low-carbon economy, they are intermittent, causing challenges in managing the grid. Smart grid can contribute to avoiding such problems through the use of real-time data/energy storage applications to level it out. Nevertheless, the regulatory environment should be able to deal with the technological, market and social effects of such integration, such as energy prices, grid connections and renewable energy incentives. In terms of regulation, too, data confidentiality and cybersecurity make themselves known as rather critical concerns regarding smart grids. Smart grid systems use large quantities of data produced by smart meters, sensors, and other IoT devices that pose new threats to the privacy of consumers and grid security. In the era of more frequent data breaches, the protection of data of consumers and the security of grid infrastructure against cyberattacks has become the main concern of regulators. Therefore, a unified policy system should be found between increased collection and analysis of data to enhance the efficiency of the grid on the one hand and the importance of privacy and ensuring consumer confidence on the other hand [9].

Formulation of the regulatory framework is not just limited to technical requirements. Equally, it has a significant impact on social equity and accessibility. The process of moving to smart grids should be inclusive so that no part of society, especially the vulnerable and underserved community, should be denied the opportunity of receiving the efficiencies of renovated energy systems. Policymakers should make sure that the use of smart grid technologies will not increase disparities, e.g. due to energy poverty, and that every consumer has equal access to inexpensive and dependable electricity.In a worldwide context, the regulation of smart grids is highly diverse across nations. Governments in certain regions have played a proactive role in the process of encouraging smart grid technologies through government policies, incentives and regulatory changes. As another example, the European Union has set high targets regarding the integration of renewable energy and smart grid technologies, and countries such as the United States and China have put large-scale smart grids pilot projects with wealthy governmental support. On the other hand, in several developing economies, the implementation of smart grids is usually undermined by a lack of funds, limited regulatory facilities, and the necessity to meet institutional barriers. This difference in usage of smart grid technologies promotes the necessity of a flexible, adaptive policy framework that is aware of the local contexts and level of development. According to the purpose of this paper, it is meant to traverse the existing guidelines and policies that are currently defining how smart grids are being developed and deployed across the globe. The paper will aim to give a detailed discussion of the potential role of policies to facilitate or hinder the advancement of the smart grid by discussing the regulatory issues, opportunities, and innovations in different regions. The paper will also point out new trends in the regulation of smart grids, with suggestions on reinforcing the policies that will enable it to evolve further [10-14].

In so doing, this exploration will explain how a proper regulatory framework is key in making sure that smart grids become what they are supposed to become in terms of a pillar towards a sustainable, safe, and just energy future.

2. Background and Evolution of Smart Grid Regulations

The history and development of the smart grid regulations are a very important context in comprehending the process and formation of policies and regulations which govern the formulation of smart grids. Regulatory environment of smart grids has developed over the years due to market forces of technology development, policy goals and emerging energy industry issues. In this part, we will look at the history of smart grid regulation procedure, international outlook of smart grid policies, as well as the contribution of major stakeholders to the regulatory process [15-17].

2.1 History of the Developments

2.1.1 Introduction Smart Grid Deployment at Early Stages

In the early 2000s, a "smart grid" theoretical framework emerged as the result of a combination of the developments in the fields of digital communication, sensors, and computing. The advancement of smart grids is, however, not instantaneous, and the previous infrastructure of the smart grids remained that of the traditional electrical grids, which are proven to be centralized and unidirectional in generating power and transmitting it. These legacy grids were quite basic and could not handle the multiple demands of the modern energy systems that include the integration of renewable energy resources, two-way communication, and react to real-time changes in energy loads.

As the energy requirements of the world began to be more multidimensional, and as the adverse effects of climate change and energy savings became imminent, the necessity of smarter, more adaptable grids increased. At this time, the Smart grid initiatives started adopting the advanced metering infrastructure (AMI), automated control systems and communication networks into the smart grid to boost the grid reliability and lower the costs of operations and to make it more renewable energy friendly. This technological change became the precursor of the regulatory structures that were to come [18].

2.1.2 The Role of Policy and Regulation in the Adoption of Smart Grids

Local utilities and pilot projects were the main forces that influenced the early adoption of smart grid technologies. But in order to make such systems scalable and to achieve wide integration, national and international regulation models were required. Originally, the policy was brought towards the aim of enhancing energy efficiency and resilience of the grid; however, as renewable energy integration and demand response gained prime importance, the focus of smart grid policies turned towards broader sustainability and decarbonization priorities.

The early 2000s saw the arrival of a regulatory framework around the smart grid in the U.S. commenced with the EPAct of 2005 (EPAct) and the American Recovery and Reinvestment Act of 2009 (ARRA), which served as critical in establishing the foundation towards the development of the smart grid. Smart grid investment billions were allocated through the ARRA grants were given as part of smart grids research, development, and demonstration. This investment motivated regulatory organisations to advance towards the establishment of formal guidance on the use of smart grids.

Worldwide, the formulation of governing structures was under processes because nations saw an increased significance of energy transformation. Whereas countries such as the U.S. and the countries of the European Union developed the regulatory guidelines and the policies earlier, those in the developing world have had difficulty in developing the smart grid regulations because of infrastructural, financial and policy limitations [19-21].

2.2 The Katakis Smart Grid Worldwide Policies

2.2.1 United States

One of the first to develop and implement the smart grid technologies is the U.S. Many of the initial governmental policies affecting smart grids were overall federal policies, including the Energy Independence and Security Act (EISA) of 2007, which mandated that the grid be modernized to support renewable power generation, energy efficiency, and grid resiliency. The 2009 American Recovery and Reinvestment Act (ARRA) allocated more than 4 billion towards the deployment of smart grid technologies and advanced metering infrastructure [22].

The Federal Energy Regulatory Commission (FERC) is an important authority that regulates interstate transmission and promotes access to the grid in a reasonable manner. One such example is the FERC Order 745 that sought the role these demand responses play in the market operations, which became an act of regulation within the smart grid mandating demand-side management in the U.S policy [23].

2.2.2 European Union

The European Union (EU) has advocated solidly for the shift towards smart grids as part of its wider objectives of energy security, efficiency and sustainability. The Energy 2020 Strategy of the EU and the Clean Energy for All Europeans, which incorporates the European Green Deal, defines the objectives of the integration of renewable energy sources and smart grid technologies into the energy sector in order to decarbonize the latter.

The smart grid assumption has been created in the EU in order to focus on the cross-border collaboration, liberalization of the energy market and supporting the easy use of renewable energy. The EU Energy Efficiency Directive and the Electricity Directive are rooted in debt as they outline stewardship frameworks of smart grids in the member states. The EU also encourages the exercise of cross-border energy trading, and therefore, regulatory systems are supposed to be synchronized in the region [24,25].

2.2.3 China

The reason that China has invested a lot in developing smart grid infrastructure is because of its ambitions to modernize its energy sector and encourage energy efficiency. The Chinese government has also come up with a lot of regulations and benefits in order to encourage the use of smart grids. The National Smart Grid Development Strategy (2011) outlines the desire of the country to modernize its electricity network by adopting new technologies in the control of renewable energy and achieve grid flexibility.

In China, the regulatory system is defined by an active central government. The NEA and SGCC also take charge of the smart grid development, with the latter being one of the largest utility companies in the world. Chinese policies revolve around major infrastructure projects and technological innovations most of the time [26-28].

2.3 Major Affected Parties in the Regulatory Processes

2.3.1 Agencies and regulators of the government

National, regional, and local government agencies are pivotal in the regulation of the smart grid. Energy ministries/departments in most countries determine the national energy policies, whereas the policy implementation is the task of an independent regulatory agency. The examples are the Federal Energy Regulatory Commission (FERC) in the U.S., the European Commission in the E.U., and the National Energy Administration (NEA) in China. These institutions cooperate with industry stakeholders to fashion regulations which ensure that the technological, environmental, and economic objectives are balanced.

2.3.2 The Privatized Utility Companies and the Private Sector

The utility services and the personal energy providers are key players in the application of the smart grids. Most of these firms will have to adhere to the policies stipulated by the state. Nevertheless, utilities are also one of the main factors behind the innovation and the ways of deploying technology, as they tend to collaborate with technology firms in order to create and implement smart grid systems. One of the fields where the activity of the inhabitants of the private sector is especially notable is the construction of smart meters, energy storage facilities, and the implementation of renewable sources of energy.

2.3.3 Customer and Consumer Rights Groups

Consumers, being end users of smart grid technologies, are important stakeholders interested in the regulatory process. There is a need to come up with policies on consumer protection, filtering privacy issues, pricing systems and access to newer technologies. Consumer advocacy entities are significant in making regulations favour the rights and interests of the consumers and especially those with little income or unserved.

2.3.4 Standards Organizations

Regulatory agencies also partner with standards organizations so that smart grid technologies can be spoken the same way and operate with one another. In particular, the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC) are engaged in defining technical standards according to which the development and implementation of smart grid technologies happen. These standards are necessary to provide consistency, safety and interoperability to the systems. The history of smart grid regulations development indicates that their origins were rooted in the technological aspects; however, currently, they are much more policy-related to provide an understanding of the multifaceted environment of energy systems nowadays. The regulatory frameworks will have to change as the smart grid technologies will continue developing, and the associated challenges and opportunities will emerge [29,30].

3. Core Regulatory Aspects for Smart Grids

Smart grids represent a significant evolution in energy distribution, leveraging digital technologies, data analytics, and automation to manage electricity consumption and distribution more effectively. Given their complexity and the range of stakeholders involved, regulatory frameworks must address a variety of technical, economic, and social aspects to ensure the successful and sustainable deployment of smart grids. This section will delve into the core regulatory aspects for smart grids, focusing on the regulation of grid modernization, renewable energy integration, data privacy, cybersecurity, demand response, and energy efficiency standards.

3.1 Grid Modernisation and Infrastructure Investment

3.1.1 Policies Driving Grid Modernization

Modernization of the grid infrastructure so that electricity can be transmitted efficiently, reliably and flexibly is one of the main objectives of smart grid regulations. Conventional grids have been able to accommodate the centralized production of power, which is not capable of supporting the low-carbon-powered world interspersed with widespread integration of renewable energy, electric cars, and decentralized power generation. Regulatory policies need to encourage the use of new technologies, including advanced metering infrastructure (AMI), real-time monitoring systems, energy storage and fault detection and response systems to achieve a more modern grid. As an example, the Energy Independence and Security Act of 2007 (EISA) and the American Recovery and Reinvestment Act of 2009 (ARRA) in the U.S. facilitated the use of smart grid investments and funded research and pilot projects related to modernizing the grid facilities. Governmental policies can be most influential to the quickening of these upgrades by providing tax advantages, subsidies or awards to utility corporations and third-party service providers to fund infrastructure investments. In most cases, regulators must strike a balance between the desire to have such investments and the cost of energy services to the consumers. The incentives could cover the performance-based rates that would reward the utilities to enhance grid reliability and lower operational costs [31,32].

3.1.2 Cost Recovery Mechanism

Modernization of grids frequently means high costs at the beginning, which the utility has to be reimbursed for by rates paid by the consumers. Regulators need to have a keen eye in developing cost-recovery structures to make sure that such investments do not become too heavy on consumers, yet there is a willingness on the part of the utilities to make the smart grid investments. Such mechanisms are rate-of-return regulation, performance-based ratemaking, and cost pass-throughs under which utilities pass to ratepayers some of the costs they incur to modernize the grid.

3.1.3 PP public-private partnerships (PPP)

The other tool necessary in smart grid infrastructure investments is the public-private partnerships (PPPs). Since big-scale capital investments are necessary, the entrants of the public and the private sector can join their forces, sharing the risks and resources. PPPs can be promoted through a regulatory framework that ensures clarity on roles, responsibilities and revenue sharing between the government and the private companies taking part in the modernization of a grid.

3.2 Integration of Renewable Energy

Elaborating on the third bullet point, 3.2.1, raises the question of the challenges of renewable energy integration. The position to allow the control and integration of the renewable energy source, e.g., wind, solar, or hydroelectric power, is one of the most crucial features of the regulation of smart grids. Although these energy sources are sustainable and eco-friendly, they may be intermittent, which presents a problem to grid reliability and stability. The technologies to find solutions in smart grids are outlined as energy storage and demand response, monitoring in real-time, which needs to be planned carefully in bringing in the existing regulation systems.

The regulation systems have to facilitate the adaptability of the operations of the grid, and this comprises real-time adaptations as a response to the variability in renewable energy generation. This could imply the creation of policies that promote the use of energy storage systems (examples could include: batteries, pumped hydro storage) to store extra renewable production at times when renewable generation is high, and release in times when the production is low.

3.2.2 Renewable Energy Incentives

The policymakers should develop incentives to facilitate the adoption of renewable energy into the grid by utilities and independent power producers. This can be in terms of feed-in tariffs (which offer a specified payment per unit of energy generated by renewable sources), renewable portfolio standards (RPS) or power purchase agreements (PPAs) which stimulate the generation of renewable energy generating capacity.Net Metering and grid access: The ability to educate about and then facilitate the usage of the net meter and grid access to all is another regulatory approach that is vital to all consumers. There are net metering regulations that permit people to provide surplus power to the grid, and they are popular in most parts. The regulators should make sure that the policy on net metering is designed in a manner that consumers will be allowed access to sufficient payment for their contributions without experiencing overloading of renewable energy into the grid.

3.2.3 Distributed Energy Resources (DERs)

Regulations involving rising areas of decentralized energy creation, including domestic solar panels, little wind energy, and household battery storage, additionally need rules that support the distributed energy resources (DERs). Regulation of the smart grid should help in achieving equitable access to this grid by these systems, the possibility of effective integration of these systems into the grid, as well as encourage demand-side management techniques, which will encourage the consumers to consume energy in a more efficient way [33,34].

3.3 Data Privacy Laws and e-Security

3.3.1 Privacy of Data

Among the central components of smart grids is the vast amount of data produced by smart meters, sensors, as well as other interconnected gadgets. Such data points may feature some details of how consumers use energy, and this poses a certain threat to data privacy and possible misuse. There is need to have data privacy policies instituted by regulators to ensure that consumers are not subjected to unauthorised access of their energy consumption data. This involves formulating a guideline regarding the anonymisation of data and making sure that data is utilized only to fulfil the intended aim, i.e., grid optimization and/or billing, and not as a commercial means without the permission of consumers.

3.3.2 Cybersecurity

Smart grids are vulnerable to cyberattacks because of their digital nature, and this may unstable and insecure. Cybersecurity rules have been a necessary addition in smart grid systems with the increased threat of cyber risks. The policy makers should see to it that the utilities and grid operators ensure a cybersecurity mechanism is in place to prevent hacking, data breaches and other cyber-based attacks on the grid infrastructure. Frameworks governing regulatory standards, such as the National Institute of Standards and Technology (NIST) in the United States Cybersecurity Framework, have offered smart grid cybersecurity effective guidelines to follow. Regulatory authorities have the power to ensure that the utilities observe best practices when it comes to communication networks, data storage, and critical infrastructure in order to protect against malicious attacks and manage system resiliency [35].

3.4 DR and EE Standards

3.4.1 Demand Response (DR)

Demand response programs take central stage in these grid operations since consumers are enabled to change the way they consume their energy so that they can benefit at a discount or a given prize during such peak energy times. Regulators are important as they help to design programming that leaves no option to abuse by depriving all the consumers of a fair game. On top of it, demand response regulations should also consider the situation with vulnerable populations and the fact that they cannot be over-exposed to peak pricing or events of DR.To help utilities employ the tactic of dynamic pricing, the regulatory entities can require them to make changes to the prices of electricity in real-time. This will provide financial motivation to the consumers to use less during the peak demands, eliminating the pressure on the grid, and avoiding blackouts.

3.4.2 Consumption of Energy Effectiveness Standards

Smart grid initiatives aim to strive towards energy efficiency. Government bodies should impose performance levels of energy consumption of appliances, buildings and industrial processes, and thereby lessen the total need for electricity. Regulators can encourage energy efficiency and achieve environmental sustainability by demanding the usage of energy-saving technology and providing incentives to consumers to save energy and cut down their power expenditure.

Consumers can also be encouraged by the government to invest in energy-efficient technologies, including smart thermostats, LED lighting and energy-efficient appliances, which could be used as part of a smart grid system to enhance the performance of energy usage.

The fundamental regulating considerations in smart grids are complicated and should respond to a number of complicated issues regarding grid modernisation, incorporation of renewable energy, information protection, cybersecurity, request reaction and energy productivity. Policymakers and regulators should develop systems which promote innovation and the adoption or use of technology, but ensure a level playing field, consumer protection and long-term sustainability. In targeting all these areas of critical concern, smart grid regulations will help shift to more stable equilibrium energy systems, efficient energy use, and sustainable energy, leading to a low-carbon-based future [36].

4. Challenges in Regulatory and Policy Frameworks for Smart Grids

Smart grid deployment and performance rely on well-crafted regulatory and policy frameworks. There are, however, many challenges in the development of sound regulations for smart grids. These issues are due to the overall complexity of the process of new technology integration, the need to coordinate various stakeholders, the need to meet the changing consumer behaviours, and the outcome of smart grids benefits must be shared across the board and not destroyed in the process of implementation. In the following sections, we will discuss the major policy and regulation barriers in policymakers and regulators on their way to constructing smart grid frameworks, which are regulatory fragmentation, uncertainty in technology and market, legal and institutional barriers and social acceptance and equity.

4.1 Fragmentation in regulations

4.1.1 Various Regulatory Solutions

Non-standardization of the scope within the region, country, and jurisdiction is one of the crucial issues when preparing a more comprehensive smart grid regulatory framework. Depending on national interests, grid networks, and the style of regulation, the regulatory environment may vary significantly among countries. Whereas other countries, including the United States and member countries of the European Union, have gone miles further in terms of ensuring that they have in place a national or a regional concept of smart grids, other countries remain lacking in the required regulatory framework that would facilitate the implementation of the concept of smart grids.

The differentiated handling of regulations may cause ineffective bidding and irregularities in the use of smart grids. This could include, as an example, in the U.S., energy regulation may be in the province of the state, so that there can exist a large variance in smart grid policies between states. This fragmentation may offer a challenge to utilities and service providers who seek to cover jurisdictions and areas, and this has been specifically very evident when it comes to such things as access to grids, pricing models, as well as data privacy, regulatory needs. Likewise, the EU striving to achieve harmonization of the regulation in different member states may be challenged by separate countries with other priorities or other energy systems.

4.1.2 National-local coordination

The second factor of regulatory fragmentation is coordination among national, regional and local governments. Although national governments can lay down high-level policies or objectives of smart grid adoption, it is the local utilities and regional governments that need to oversee these policies on the ground. It may not be an easy task to make sure that the national objectives correspond to the local realities because local utilities can have various financial, technological, and infrastructure limitations. In addition to that, regional regulatory agencies can differ in their interpretation of the national policies or can simply lack the resources to implement them successfully. The problem of regulatory fragmentation may also be a hindrance to cross-border energy collaboration, especially in areas with interconnected grids. This is especially so in the European Union, where international electricity trading and grid security need regulatory frameworks to align. The absence of harmonized and uniform regulations may lead to a situation where borders are becoming a barrier to the efficient integration of the grid, incurring a risk of missing out on the potential benefits of smart grids [37,38].

4.2 Market and technological Uncertainty

4.1 Fast pace in Technology

Smart grids are constructed on fast-changing technologies, which include energy storage, demand forecasting based on machine learning, real-time monitoring and advanced metering infrastructure (AMI). Regulators are forced to play a reactive role, what with the speedy change of technology, which they are struggling to keep pace with, and frequent changes that keep on redefining energy utilisation. Smart grid systems are supposed to be flexible and adaptable; however, the regulations should be forward-thinking and must be able to fit in new technologies that could be coming up in the future.

Policymakers have to balance the need to keep regulations that may squash innovation on the one hand and maintain consumer and grid operator safety measures against potential risks that using unproven technologies may present on the other. The difficulty is that an adequate regulatory structure should be designed to encourage innovation, and at the same time, the new technologies must be implemented into the grid safely, securely and fairly. Furthermore, the regulators need to coordinate activities with respected industry experts to comprehend the possible impacts of new technology on grid and energy markets, as well as consumer patterns.

4.1.2 Uncertainties of Market Structures

Smart grids are frequently tied to the evolution in the market, which comprises the emergence of decentralized energy systems, peer-to-peer trading in energy, exertion of consumer involvement in energy markets. Development of prosumers (who both consume and produce energy) and small-scale renewable energy producers has opened up the possibilities of energy entering the market; however, there has been a reduced centralized and more distributed behaviour of the grid. Such transformations create new challenges to regulators as they should be able to make energy markets competitive, transparent and fair.

The application of decentralized energy schemes needs to introduce new market platforms facilitating effective energy dealings among the grid operators, utilities and consumers. But these market designs may sometimes be challenging, especially in places where the traditional market structures are well established. In addition, the regulatory agencies should take into consideration long-term stability as well as the sustainability of these markets. Inappropriately designed or tight regulations may impede the process of shifting to flexible and dynamic energy markets, which are the key to the success of smart grids.

4.3 Institutional and Legal Obstacles

4.3.1 Legal Fragmentation and Fragmentation

The legal environment of smart grids is frequently decentralised as several layers of regulation exist to cover the relevant issues, such as grid access, energy prices, data privacy, and cybersecurity. The legal complexity is a result of both the multiple laws and regulations of the different levels of government (local, regional, and national) and of the interaction of the fields (public and private sector) of interests. As an illustration, issues regarding ownership of data or access to a grid infrastructure may pose legal difficulties, particularly in case there is a need to involve third-party service providers or new parties to the market.

In most areas, the current regulations might not align with the requirements of the new smart grid system, and new regulations might be necessary to solve emerging problems. Take the U.S. as an example, the typical regulatory framework for utilities has been grounded in a centralized and monopoly-prone approach. However, the introduction of smart grids forces regulators to modify the current body of legal framework to enable decentralized energy generation, demand response, and information-sharing among different parties. This will involve major legal changes, and this might be opposed by vested interests.

4.3.2 Resistance to change at the Institutional level

Institutional inertia in regulatory bodies and utilities is the other important barrier. Older utilities and regulatory organizations might not want to adopt new strategies due to fear of disrupting dominant business models, or they may not want to incur modernization expenses in making their infrastructure modernized. Established utilities that were provided on a monopoly basis might resist the competition factors, like peer-to-peer energy trading or admission of third-party service providers. There are also instances where institutional interests established over time might lobby to block changes that might diminish their influence on the operations of the grid or the level of their income stream.

To evade institutional resistance, there has to be an all-around policy change, stakeholder consultations, as well as strategic planning. Regulators and utilities need to be led to a situation where they can be confident that they can address the need to adapt to new technology and new market structures without jeopardizing the reliability of the grid and the protection of consumers [39,40].

4.4 Social Equity and Acceptance in Society

4.4.1 Smart grid technologies faced public Resistance

One of such barriers could be the public acceptance of smart grids, especially when such acceptance is hindered by the fear of privacy security and the fear of added costs. New technologies requiring details about their energy consumption habits may expose consumers to certain dangers, as they are afraid of losing their privacy or paying more because of dynamic pricing or demand response initiatives. Outreach and education are important aspects in explaining these concerns to improve the amount of trust in smart grid technologies.

Smart grid technologies are also capital-intensive in terms of infrastructure that needs investments, forcing increased initial costs. Those consumers who live in areas that are already burdened by high energy bills might oppose the introduction of policies that further require rate hikes or other charges to be met to promote grid modernization projects. To garner the necessary support, there is a need on the part of the policymakers to show the long-term implications of smart grids to the public in terms of low energy cost, enhancing reliability and overall sustainability in terms of environmental sustainability.

4.4.2 Equity and Accessibility Social

The need to have smart grids that are inclusive and equitable is pertinent among policymakers. Smart grids and their benefits are huge, but the possible disadvantage is that disadvantaged communities or those with low income will be left behind. These groups of people may not be able to access the latest power technologies, miss the financial flexibility to pay more for power tools that are energy-efficient or not have the digital literacy required to contribute to new programs of energy distribution, such as demand response or time-of-use pricing.

Regulatory systems should also make sure that the benefits of a smart grid system are accessible by all consumers irrespective of details like income and social status. This will involve giving subsidies or cash compensation to the low-income families to use smart meters or energy-saving technologies. Along with that, policymakers need to take care of the demands of vulnerable populations and offer protection against the possibility of negative impacts of the smart grid technologies, including those related to the rise in the price of electricity at peak hours. The difficulties associated with the design of effective regulatory and policy frameworks to guide smart grids are quite serious but not impossible to overcome. There is regulatory fragmentation, technological as well as market uncertainties, legal and institutional impediments, and also there is the problem of mass acceptance, and all these are the problems that need to be handled very carefully. They should work actively to establish more fluid, flexible models that can deal with the rapid changes in energy technologies, as well as making sure that the advantages of smart grids are shared equally. With these challenges taken care of, smart grids have a chance to be an epicentre of green, safe, and efficient power systems across the globe [41].

5. Case Studies of Regulatory Frameworks

Smart grid is not a universal strategy and all countries have played it differently based on their energy environment, technological quality and economic needs. Case studies are vital in providing information on how various countries have set up, modified and executed their regulatory models to suit the smart grids. Case studies of the United States, European Union and China will be presented in detail in this section. The identified regions have been engaged in implementing certain approaches to bypass regional challenges that must be surpassed to shift toward smart grids. Through these various ways of regulatory practices, we are able to gain a clear picture of the rest of the world regarding smart grid regulation [42].

5.1 United States

Smart grid development has taken a central role in the United States, which has seen numerous regulatory initiatives both at the federal and state levels to modernize the electric grid. The U.S. regulatory system is somewhat fragmented, and there exist a number of variations both in the employment of smart grid technologies between states and the overall levels of enthusiasm in different states. Nevertheless, there are a number of national policies that have been influential toward the development of the entire regulatory set-up of smart grids [43].

5.1.1 Federal Products and Dominance

The Energy Independence and Security Act of 2007, enacted by the U.S. federal government, preconditioned the implementation of smart grid technologies. The bill requested the modernisation of the electricity grid and the promotion of advanced metering infrastructure (AMI) and other smart grid technologies. It further required that a smart grid implementation strategy be created by the U.S. Department of Energy (DOE) and provide guidelines that should govern the incorporation of renewable energy into the grid.

One of the turning points with regard to the smart grid initiative was the enactment of the American Recovery and Reinvestment Act of 2009 whereby it provided funding of $4.5 billion to be used in the development and deployment of smart grid technologies. This money was basically spent on the utility firms on erection of smart meters, grid sensors and other crucial technologies which are the hallmarks of smart grids. It also gave the grants on pilot projects and grid modernization research.

In America, energy control is set at different states level implying such that every state is allowed to practice various policies regarding smart grid integration. California, amongst others, has been almost ahead in developing the smart grids so much that it passed its own laws to promote energy efficiency and integration of renewable using smart grid technologies. The California Public Utilities Commission has adopted progressive policies to facilitate renewable energy integration, demand response and update grids.

Competitive retail energy markets, such as those available in states like Texas, are to be found, where the consumers are able to select their energy providers, and this would even include those providers that offer energy services that are connected to the aspect of smart grid technology. Such decentralized energy markets need new regulatory models that will make the smart grids work in a reasonable and fair way among different parties in the market [44].

5.1.2 Problems and Future:

The fact that energy regulation has been fragmented is one of the greatest predicaments in the U.S. Our current situation has been quite challenging in standardizing the nationwide approach to smart grid technology because of the state-based policies. Variation also exists in the amount of investment in grid infrastructure per state; hence, differences in smart grid adoption and operation exist. Considering the great volumes of information produced by the intelligent grid system, the U.S. has been experiencing major issues with data security and security and privacy of information. Some such regulation already exists in the form of FERC Order 745 and the NIST Cybersecurity Framework, but it will require all-encompassing legislation to be able to deal with more powerful threats.

5.2 European Union (EU)

The European Union has achieved a lot by rallying its member states to hold a shared vision regarding the deployment of the smart grid. The EU has implemented a plan to embark on rationalising the electricity network, incorporating renewable energy sources and reducing carbon-emission targets, in terms of its larger Energy Union and Clean Energy for All Europeans project.

5.2.1 Uniform Regulatory System on EU-Level:

The EU has developed the Energy 2020 strategy that aims at developing a more comprehensive, more sustainable energy market and more efficient energy market within the union. The focus of this strategy is on the enlargement of the renewable portion of the energy mix and enhancing grid efficiency, thus highlighting the significance of the smart grids in the implementation process.

The development of smart grids is included in the Clean Energy for All Europeans Package, which is composed of the Energy Efficiency Directive and Electricity Regulation. These regulations establish the main paradigm of the integration of renewable energy, demand response, and digital solutions into the European electricity market.

The European Commission is the key in laying down the entire strategy of smart grids in the EU. The EU has been doing so through the establishment of tools such as the European Smart Grids Task Force, which has been striving towards aligning policies regarding the deployment of smart grids and making sure that the countries in

the EU collaborate with each other when it comes to energy trade and the management of the grid.
ACER (Agency for the Cooperation of Energy Regulators) and ENTSO-E (European Network of Transmission System Operators for Electricity) are two of the most important agencies assisting on the implementation of smart grid regulations because of the coordination side of the European Union in efforts made within the EU member states and because of the optimization that the integrations made on the grids acquire.

5.2.2 Problems and Future Work

An integration of the power grid of the EU member states into a more competitive and coherent electricity market is one of the main obstacles that the EU has to overcome. Regulatory systems should deal with grid management and cross-border energy trading harmonization in addition to the integration of renewable energy so that efficiency and reliability can be achieved along the national lines. Similarly to the U.S., concerns abound in the EU with regard to the security and privacy of the data being produced by smart grids. The General Data Protection Regulation (GDPR) is significant in solving privacy issues, yet there is a need to implement further security measures in cybersecurity to defend the grid against a possible cyberattack [45,46].

5.3 China

China has directly become an international giant in the development of the smart grid, and it is greatly focused on the investments it makes in infrastructure and on the development of technologies. Government policies and initiatives of modernizing the energy sector and minimizing the country's carbon footprint have a strong impact on the regulatory framework of smart grids in the country.

Chapter 5.3.1 National Smart Grid Development Strategy

In 2011, China released its National Smart Grid Development Strategy, which set the objectives that the country has on developing a modern intelligent grid system that could facilitate increased energy demand and incorporate renewable energy. The plan envisaged the mass usage of smart grid technologies such as advanced metering, smart transmission systems, and energy storage.
A subsidiary of the largest utility worldwide is the State Grid Corporation of China (SGCC), which is a major force behind a smart grid in China. A significant line of work that SGCC has engaged in is the development of a nationwide smart grid in which it facilitates the use of renewable energy, such as wind and solar power, in the grid.

5.3.2 State Support and Funding

The Chinese government has played a very active role in the promotion of smart grids with deep pockets when it comes to the deployment of smart grid infrastructure. The 12th Five-Year Plan and the succeeding policies offered a funding boost to the implementation of the smart meters, the grid automation, and the energy management system.
China has also been emphasizing the construction of high-voltage direct current (HVDC) transmission and long-distance transmission lines, both of which are important in the integration of renewable energy in remote areas to the national grid.

5.3.2 Issues and Future Perspectives

As China has achieved much success in its urban contexts, it is difficult to implement the smart grid in rural regions. The gap in the development of the infrastructure in urban and rural areas poses inhibitions to fair smart grid adoption. Smart grid systems should also be secured because, with China growing more dependent on digital technologies to manage the grid, cybersecurity is becoming a priority in the country. Regulators should design structures to protect against the possible effects of cyberattacks.
The case studies U.S., EU, and China show the different regulations and various problems in the implementation of smart grid technologies among different regions. Although there are similarities in the importance of the smart grids in the development of a sustainable, resilient and efficient energy future, the ways to achieve them differ across the regions, as well as technological innovations and policy priorities. Every example teaches useful lessons to other territories aiming at creating or improving their smart grid system. The international legal framework concerning smart grids remains dynamic, and as these case studies indicate, successful policy implementation must be able to keep up with new technologies and market forces as well as societal requirements [47].

6. Emerging Trends and Innovations in Smart Grid Regulations

The changing nature of the smart grids, the existing regulatory regimes that support them have to change as well. New trends and innovations in the regulation field have been introduced by the emergence of new technologies, changes in time-consuming behaviour, and the world's attention to the idea of sustainability and energy efficiency. The task Policymakers and regulators are posed with is that they need to ensure that regulations are flexible, future-oriented, and able to accommodate such new developments. In this section, a few of the current trends and innovations that are defining the future of smart grid regulations have been examined such as Artificial Intelligence (AI) and Machine Learning (ML) integration, blockchain technology, integration of electric vehicles (EV), 5G networks and advanced metering infrastructure (AMI).

6.1 Smart Grids Applications of Artificial Intelligence (AI) and Machine Learning (ML)

The incorporation of Artificial Intelligence (AI) and Machine Learning (ML) algorithms into the smart grids is the most anticipated development that can be expected to bring major benefits in grid optimization, real-time monitoring, and fault detection. AI and ML allow predicting demands in energy demands, determining in advance possible failures in systems, the possibility of optimising energy distribution, and energy balance recommendations/advice in real time. As an example, predictive analytics denting AI can assist utilities to perform the prognostication of energy demands by utilizing past data, weather predictions, and socio-economic terms. By doing so, the AI will have the potential to save wastes by predicting a demand more accurately and increasing the grid efficiency.

Integration of AI and ML into grid management implies a number of regulatory concerns. The policymakers will require drawing standards that can make the AI decision-making processes transparent and accountable. To illustrate, in the case of making energy distribution decisions or demand response program decisions with the help of AI, the regulators should make sure that decisions are made on the basis of clearly defined, clear, and non-discriminatory considerations. More than that, there will be a necessity to have regulations that would maintain security and non-vulnerability of AI systems in the smart grid to prevent potentially malicious manipulation and bias. Regulatory frameworks will also have to consider ethical issues, like making sure that the usage of AI systems does not have an unfair impact on the consumer masses [48,49].

6.2 Security and Energy Trading with the help of Blockchain Technology

Blockchain technology, which is mostly attributed to cryptocurrencies such as Bitcoin, has also been leveraged by the smart grid sector. It may be able to support peer-to-peer (P2P) energy trading, where the consumers may sell energy to each other without the use of a centralized intermediary such as a utility company. It's a secure, transparent, and tamper-proof mobile ledger system that enables this to be a decentralised energy market.

Using blockchain can also make energy markets more flexible, as small-scale producers (including houses with solar panels) will be able to sell extra energy directly to people at the consumer level, or to be bought by businesses in their neighbourhood. This will cause a more efficient utilization of renewable energy and enable consumers to become active participants in the energy market, which may reduce the cost of energy.

Blockchain has great potential, but regulators need to overcome the legal, financial and technical barriers of its use. To illustrate, grid access to the peers and equitable payment of energy exchanges are to be regulated in peer-to-peer trading. The right regulation of fair pricing of energy, the transparency in transactions and the ownership of the energy credits (e.g. renewable energy certificate) will have to be formulated by the policymakers.

Besides, regulators will have to determine the relationship between the blockchain-based energy market and the current utility infrastructure and how their transactions on such decentralized systems will not interfere with the stability of the whole grid. Besides, regulators will be forced to address consumer protection issues and make certain that the dispute resolution model is clearly defined in blockchain-based systems and fraud is avoided in these systems [50].

6.3 EV Integration and Smart Charging

The emergence of electric vehicles (EVs) brings both challenges and opportunities to smart grids. With the rise in EVs, placing them on the grid will be more important in making the grid more flexible and efficient. The EVs may be considered as energy storage units with mobility, which can consume and store energy. Innovative technologies such as the vehicle-to-grid (V2G) have the capability to enable EVs to deliver energy to the grid

during peak hours and, in effect, stabilise the grid and raise the level of energy efficiency.
Another critical indicator of the EV implementation in the smart grid is the creation of intelligent charging points that can interact with the grid to adjust the charging rates and schedules to meet energy needs in real time. These charging points can be set to charge cars when less electricity is in demand, that is, at off-peak and utmost strain is not given to the grid and the consumer is charged less energy.
The regulatory frameworks to promote EV integration into smart grids must touch upon the three key challenges pertaining to grid access, charging infrastructure, and the position of EV owners as energy market participants. In order to achieve smooth communication and optimal energy consumption, regulators will be required to establish interoperability standards among EVs, charging stations and the grid. Rewards to EV usage, EV charging equipment, and smart grid system integrations will have to be worked out. Policy makers should also think of regulating prices with regard to EV charging services to prevent price gouging, low-cost charging to customers and making such services and practices greener, like charging with renewable energy [51].

6.4. Smart Grid Communication in 5G Networks

The introduction of 5G networks, the communication in the smart grids is set to experience a paradigm shift since the network will be of high speed and low latency with the capability to connect millions of devices like smart meters, sensors, distributed energy resources and much more. The main way that 5G can benefit smart grids is due to the real-time ultra-reliable communication it is capable of delivering, and these communications are highly important in the application of real-time grid monitoring, demand response, and fault identification.5G networks would also increase the flexibility and responsiveness of smart grids so that the operators would be able to make faster decisions with real-time data. This will go a long way in matching the responsiveness of the grid to any changes in supplies and demand, and overall reliability.
As the 5G circles, regulators are to address various issues concerning spectra, data privacy and cyberattacks. The bandwidth needed to cover the 5G networks, especially in urban regions, will pose a great challenge that needs strict control to make sure that communication systems serving smart grid services will not be compromised by other important services.
The development of greater interconnectivity is also going to pose security risks that policymakers will have to take care of. Seeing that 5G networks will give the possibility to transfer high volumes of sensitive data throughout the grid, the regulatory environment should guarantee safety and minimise the possibility of the data being attacked by hackers [52].

6.5 AMI and Data Regulation

One of the technologies that supports smart grids is the Advanced Metering Infrastructure (AMI), which facilitates communication and real-time monitoring between utilities and consumers. The granular data are sensors of AMI systems and can be utilized in billing, managing grids and serving customers. The AMI has enabled dynamic pricing where consumers are charged at different rates because of the existing real-time demand as well as energy prices. Since the AMI systems will produce large volumes of data, the policymakers will be required to come up with policies associated with data privacy, ownership, and security. As an example, data about consumers, which is gathered by means of AMI systems, should be secured so that it cannot be stolen or used by offenders. Regulators will have to make sure that utilities adhere to data protection guidelines, especially amid increasing interest in the privacy of consumers in the digital era. Regulators should also develop policies that can facilitate the AMI systems to interface with other technologies in the smart grid and energy management systems. The ease with which different systems and platforms will share their data will play a decisive role in ensuring the effective operation of smart grids and the success of programs such as demand response.
New technologies and best practices in the smart grid are changing the electricity industry and creating new challenges and opportunities for regulators. The combination of AI and ML, blockchain, electric vehicles, 5G networks, and advanced meter infrastructure will allow improvement of the grid performance, increase consumer involvement, and integration of renewable energy. But such innovations need regulation that is dynamic, prospective and ready to deal with the intricacies of emerging technologies. With the change in trends, regulators should be ready to make policies that embrace the use of smart grids in a secure, efficient, and fair way, which can lead to the future of sustainable energy [53,54].

7. Recommendations for Strengthening Regulatory and Policy Frameworks

The high rates of smart grid technologies development and the growing complexity of energy systems incumbent on the further development of regulatory and policy frameworks would help innovation and make the transition towards the smart grids fair, safe, and sustainable. The integration of renewable energy, distributed energy resources, electric vehicles, and other emerging technologies into the grid will also require effective regulation. Here, we will highlight some imperative prescriptions in enhancing the regulatory and policy framework to help in the successful implementation of smart grids as well as meeting some of the challenges, including technological uncertainty, market fragmentation, cybersecurity, data privacy, and social equity.

7.1 Standardisation and Regulation

It has been cited that one of the greatest challenges in implementing the smart grid is the lack of consistency in regulations in various regions as well as countries. As the energy market is a global marketplace, and the energy grids are becoming more and more interconnected across borders, the regulatory standards and frameworks should become harmonized.

Standards. The comparison of different countries should be based on regional regulatory authorities like the European Network of Transmission System Operators for Electricity (ENTSO-E). Respectively, to enable common technical and operational standards of smart grids and interoperability between systems and countries, such global standards bodies as the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) can be involved.

The European Union has gone far in achieving regulatory harmonization with the Clean Energy for All Europeans Package, defining common objectives on energy efficiency, renewable energy, and smart grids integration. The same schemes of cooperation could be implemented in other geographical areas, like ASEAN (Association of Southeast Asian Nations), to provide regulations about grid modernization and establish a more integrated energy market. Since smart grids are based on real-time data collection and transmission, the issue of countries and regions using common data sets and communication protocols to enable various smart grid components (e.g. smart meters, sensors, energy storage systems) to interact with each other efficiently is of high concern. Introduction of a general data exchange and interoperability standard will eliminate some degree of technical barriers and allow utilities to integrate new technologies with less effort [55].

7.2 Smart grid Deployment incentives and financial support

Financial resources are extremely costly when it comes to the implementation of smart grids, and this matter can prove problematic in a developing country or a region that has a strict budget. PPP (public-private partnerships) has the potential to relieve the financial burden and make smart grids faster to implement.

Direct governments can offer pure financial incentives like subsidies, tax holidays, subsidized finance rate loans to utilities, technology providers, and consumers to assist in implementing smart grids. An applicable model used was the U.S. American Recovery and Reinvestment Act (ARRA) of 2009 which offered several billions of dollars to be put in investments in smart grid. As well as traditional financing mechanisms, governments can promote green financing mechanisms and impact investing in order to bring in additional private financing in smart grid projects. These investment models dwell upon environmentally sustainable and socially responsible investments, which very much coincide with the objectives of smart grid implementation.

Regulators are able to develop performance-based incentive programs that place value on meeting certain objectives associated with grid reliability, energy efficiency and integration of renewable energy, thus rewarding the utilities and grid operators. As an example, utilities may be given some financial incentives that are based on performance measures, including a lower level of energy consumption or a better ability to support the grid.

7.3 Change with Technological Modifications and Innovations in the Market

Distributed energy resources (DERs), peer-to-peer energy trading and virtual power plants (VPPs) are seen as disruptive to the traditional model of energy regulation. To counteract these new market realities, regulators have to become more flexible and introduce new technology-neutral regulatory structures that balance innovation and grid stability and security. The frameworks to regulate them should be used to facilitate the involvement of DERs by introducing regulations on their use of energy markets. This may involve regulations for aggregators (organizations that bundle DERS to sell in the wholesale market) and ways of compensating consumers with the energy they produce and inject into the grid.

Regulators are able to stimulate the installation of energy storage devices and utilization of dynamic pricing models to improve balancing of the supply and demand. To give an example, time-of-use tariffs would encourage consumers to use their energy at off-peak times, thus preventing a surge on the grid at the time that it is in high demand. The regulators need to create decentralized energy markets in order to support the increasing consumer participation in the end energy production. Smart grids are perfectly designed to facilitate peer-to-peer trading of energy in which consumers are able to trade any surplus energy available to other consumers (e.g. produced by solar panels).
Such decentralised transactions involving energy could be enabled with the help of blockchain technology that would allow keeping a transparent yet secure ledger of trading. The rules regarding the functioning of such markets will have to be established by the regulators, and, most importantly, transactions have to be fair, efficient, and smoothly incorporated into the rest of the energy market. Adoption of these decentralised solutions has the potential to reduce energy prices, energy access, and offer incentives to convert to renewable energy types [56,57].

7.4 Facilitating Equity and Inclusiveness within Smart Grid Policies

How to make low-income communities not left behind is one of the critical subjects in switching over to smart grids. Although the smart grid can give consumers benefits, like energy saving, a reliable grid, and renewable energy access, such benefits should be available to consumers irrespective of their income level.
The governments can design initiatives to assist low-income households convert to smart grid technologies by subsidising Smart meters or subsidising energy conservation projects. As an illustration, you could provide beginners with a smart grid in which a rebate or grant is offered on the first purchase of smart appliances or energy-saving machines. The policymakers can develop demand response programs that suit the low-income communities. When these programs incentivise people to consume less energy at peak times, this should not affect them and their inability to pay high electricity bills in a way that causes excessive financial strains. The transition to a smart grid can also create a high number of jobs in such areas as finding renewable energy sources, information analysis, organizing grids and cybersecurity. Regulators ought to encourage the workforce development schemes, so that the surrounding communities have the capacity of utilizing such new employment opportunities. Governments have the opportunity to invest in training to provide new skills required in expanding the smart grid industry, like fitting and servicing smart meters or energy storage systems. This will make the benefits of the smart grid movement equally distributed and help the local economy [58].

7.5 Data Privacy and Cybersecurity Regulations

Due to the higher level of digitization and the interconnection of smart grids, the risk of cyberattacks is growing. Regulatory measures should focus primarily on cybersecurity to secure the stability of the grid infrastructure, consumer data, and financial transactions against a possible breach. Regulators must consider placing regulations that require the utility firms and energy service providers to follow the national standards on cybersecurity and also undertake security audits and evaluations at routine intervals.
Regulators must have utilities implement best practices over the security of their critical infrastructure, which are the best practices developed by agencies like the National Institute of Standards and Technology (NIST) and the International Organization of Standardization (ISO). They are also expected to promote the use of encryption and secure communication protocols to secure sensitive information that would travel the grid.As more and more data continue to be gathered using smart meters, sensors and other devices that are connected to the grid, the privacy of consumer data becomes an immediate concern. Regulators should set strict principles on data ownership, access and usage such that consumers own their data and they are guarded against its usage and abuse. Data being collected must be made known to the consumers on how they are going to be utilized. The laws ought to require utilities to have the signed consent of consumers of personal data to be used for marketing purposes and for studying energy efficiency. To guarantee that the smart grids could develop in a sustainable, secure, equitable, and adaptive manner to new technologies, the regulatory and policy structures of the smart grids should be enhanced. The primary factor to consider by regulators is the harmonization of standards, financial incentives, adjustment to technological changes, social equity, cybersecurity and data privacy to establish the environment where innovation is encouraged, and the benefits of smart grids are widely distributed. Smart grids can provide an essential element of the shift to a clean, efficient, and resilient energy system through purposeful and innovative regulation [59,60].

8. Conclusions

Transformation to smart grids is a milestone in the production of a more viable, efficient, and resilient energy future. The emergence of high-tech technologies like Artificial Intelligence, machine learning, blockchain, and electric vehicles offers an opportunity to perfect the field of energy production, consumption, and management through the introduction of smart grids. Nevertheless, the full potential of smart grids cannot be maintained without effective regulatory, policy systems that can simultaneously respond to the high rate of technological innovations and cope with the complicated nature of cybersecurity, data protection and integration of the market. Regulatory environment in smart grids is not yet mature and different regions have made important progress in creating a regulatory environment which encourages innovation, provides reliability to the grids and supports sustainability. Nevertheless, issues like regulatory fragmentation, technological uncertainty, legal impediment, the second demand of equitable access are very common. All the case studies presented above which include case studies of the United States, European Union, China and India shows how various countries are addressing these challenges each demonstrating a variety of approaches doing what is necessary to facilitate adoption of smart grids in their situations.

Smart grid technologies are emerging trends that cannot be gauged using rigid regulations that cannot be summed up in today and in the future a flexible, prospective regulatory framework is required to ensure that it can adapt to the changing trends in technology. Policymakers should make sure that the regulations not only serve the technical subject but are also inclusive, secure the consumer rights, and eliminate possible risks, such as data breaches and cybersecurity threats. The suggestions provided in this article stress the importance of unified standards, a high level of financial incentives and the policies aimed at technological innovation and overcoming the issues of the vulnerable communities. The regulators can facilitate the development of a smart grid ecosystem that will work in the best interests of all stakeholders by fostering partnerships between the government and the industry, encouraging the use of smart grid technologies, and making these policies flexible in order to accommodate future challenges. In the end, the effective arrangement and control of smart grids would lie at the centre of accomplishing the energy transition worldwide. With adequate policies, advanced grids can also enhance the efficiency and reliability of energy systems, besides the move towards a cleaner, even more sustainable energy future. Ongoing evolution in the energy landscape is such that the role of regulators will be instrumental in helping to achieve the full potential of smart grids, a basis upon which sustainable energy development can be achieved, and the global energy system will be a more resilient entity.

References

[1] Aguero JR, Takayesu E, Novosel D, Masiello R. Modernizing the grid: Challenges and opportunities for a sustainable future. IEEE Power and Energy Magazine. 2017 Apr 14;15(3):74-83.

[2] Surarapu P. Emerging Trends in Smart Grid Technologies: An Overview of Future Power Systems. International Journal of Reciprocal Symmetry and Theoretical Physics. 2016;3(1):17-24.

[3] Kabeyi MJ, Olanrewaju OA. Sustainable energy transition for renewable and low carbon grid electricity generation and supply. Frontiers in Energy research. 2022 Mar 24;9:743114.

[4] Singh R, Akram SV, Gehlot A, Buddhi D, Priyadarshi N, Twala B. Energy System 4.0: Digitalization of the energy sector with inclination towards sustainability. Sensors. 2022 Sep 1;22(17):6619.

[5] Liu J, Hu H, Yu SS, Trinh H. Virtual power plant with renewable energy sources and energy storage systems for sustainable power grid-formation, control techniques and demand response. Energies. 2023 Apr 26;16(9):3705.

[6] Zhong QC, Hornik T. Control of power inverters in renewable energy and smart grid integration. John Wiley & Sons; 2012 Nov 16.

[7] Tuballa ML, Abundo ML. A review of the development of Smart Grid technologies. Renewable and

Sustainable Energy Reviews. 2016 Jun 1;59:710-25.

[8] Hassan Q, Hsu CY, Mounich K, Algburi S, Jaszczur M, Telba AA, Viktor P, Awwad EM, Ahsan M, Ali BM, Al-Jiboory AK. Enhancing smart grid integrated renewable distributed generation capacities: Implications for sustainable energy transformation. Sustainable Energy Technologies and Assessments. 2024 Jun 1;66:103793.

[9] Phuangpornpitak N, Tia S. Opportunities and challenges of integrating renewable energy in smart grid system. Energy Procedia. 2013 Jan 1;34:282-90.

[10] Kataray T, Nitesh B, Yarram B, Sinha S, Cuce E, Shaik S, Vigneshwaran P, Roy A. Integration of smart grid with renewable energy sources: Opportunities and challenges–A comprehensive review. Sustainable Energy Technologies and Assessments. 2023 Aug 1;58:103363.

[11] Rehmani MH, Reisslein M, Rachedi A, Erol-Kantarci M, Radenkovic M. Integrating renewable energy resources into the smart grid: Recent developments in information and communication technologies. IEEE Transactions on Industrial Informatics. 2018 Mar 26;14(7):2814-25.

[12] Abir SA, Anwar A, Choi J, Kayes A. Iot-enabled smart energy grid: Applications and challenges. IEEE access. 2021 Mar 19;9:50961-81.

[13] Ahmad T, Madonski R, Zhang D, Huang C, Mujeeb A. Data-driven probabilistic machine learning in sustainable smart energy/smart energy systems: Key developments, challenges, and future research opportunities in the context of smart grid paradigm. Renewable and Sustainable Energy Reviews. 2022 May 1;160:112128.

[14] Amin SM. Smart grid: Overview, issues and opportunities. advances and challenges in sensing, modeling, simulation, optimization and control. European Journal of Control. 2011 Jan 1;17(5-6):547-67.

[15] Zheng H. Research on low-carbon development path of new energy industry under the background of smart grid. Journal of King Saud University-Science. 2024 Mar 1;36(3):103105.

[16] Stephens JC, Wilson EJ, Peterson TR. Smart grid (R) evolution. Cambridge University Press; 2015 Feb 26.

[17] Winfield M, Weiler S. Institutional diversity, policy niches, and smart grids: A review of the evolution of Smart Grid policy and practice in Ontario, Canada. Renewable and Sustainable Energy Reviews. 2018 Feb 1;82:1931-8.

[18] Emmanuel M, Rayudu R. Communication technologies for smart grid applications: A survey. Journal of Network and Computer Applications. 2016 Oct 1;74:133-48.

[19] Borlase S, editor. Smart grids: infrastructure, technology, and solutions. CRC press; 2017 Dec 19.

[20] Dedrick J, Venkatesh M, Stanton JM, Zheng Y, Ramnarine-Rieks A. Adoption of smart grid technologies by electric utilities: factors influencing organizational innovation in a regulated environment. Electronic Markets. 2015 Mar;25:17-29.

[21] Wokutch AS. The Role Of Non-Utility Service Providers In Smart Grid Development: Should They Be Regulated, And If So, Who Can Regulate Them. J. on Telecomm. & High Tech. L.. 2011;9:531.

[22] Kaplan SM. Smart Grid: Modernizing electric power transmission and distribution; Energy independence, Storage and security; Energy independence and security act of 2007 (EISA); Improving electrical grid efficiency, communication, reliability, and resiliency; integrating new and renewable energy sources. The Capitol Net Inc; 2009.

[23] Brown MA, Zhou S, Ahmadi M. Smart grid governance: An international review of evolving policy issues and innovations. Wiley Interdisciplinary Reviews: Energy and Environment. 2018 Sep;7(5):e290.

[24] Dunlap A, Laratte L. European Green Deal necropolitics: Exploring ‘green’energy transition, degrowth & infrastructural colonization. Political Geography. 2022 Aug 1;97:102640.

[25] Horstink L, Wittmayer JM, Ng K. Pluralising the European energy landscape: Collective renewable energy prosumers and the EU's clean energy vision. Energy Policy. 2021 Jun 1;153:112262.

[26] Yuan J, Shen J, Pan L, Zhao C, Kang J. Smart grids in China. Renewable and Sustainable Energy Reviews. 2014 Sep 1;37:896-906.

[27] Xiufeng F. Smart grids in China: industry regulation and foreign direct investment. Energy LJ. 2016;37:135.

[28] Yu Y, Yang J, Chen B. The smart grids in China—A review. Energies. 2012 May 4;5(5):1321-38.

[29] Yuan J, Shen J, Pan L, Zhao C, Kang J. Smart grids in China. Renewable and Sustainable Energy Reviews. 2014 Sep 1;37:896-906.

[30] Federal Energy Regulatory Commission. FERC. US Department of Energy, Federal Energy Regulatory Commission; 1984.

[31] Aghahadi M, Bosisio A, Merlo M, Berizzi A, Pegoiani A, Forciniti S. Digitalization processes in distribution grids: a comprehensive review of strategies and challenges. Applied Sciences. 2024 May 25;14(11):4528.

[32] Shahidehpour M, Fotuhi-Friuzabad M. Grid modernization for enhancing the resilience, reliability, economics, sustainability, and security of electricity grid in an uncertain environment. Scientia Iranica. 2016 Dec 1;23(6):2862-73.

[33] Madrigal M, Uluski R, Gaba KM. Practical Guidance for Defining a Smart Grid Modernization Strategy: The Case of Distribution (Revised Edition). World Bank Publications; 2017 Mar 22.

[34] Borgaonkar R, Anne Tøndel I, Zenebe Degefa M, Gilje Jaatun M. Improving smart grid security through 5G enabled IoT and edge computing. Concurrency and Computation: Practice and Experience. 2021 Sep 25;33(18):e6466.

[35] Borgaonkar R, Anne Tøndel I, Zenebe Degefa M, Gilje Jaatun M. Improving smart grid security through 5G enabled IoT and edge computing. Concurrency and Computation: Practice and Experience. 2021 Sep 25;33(18):e6466.

[36] Siano P. Demand response and smart grids—A survey. Renewable and sustainable energy reviews. 2014 Feb 1;30:461-78.

[37] Jia T, He W, Ma W. Optimizing urban energy management: A strategic examination of smart grids and policy regulations. Sustainable Cities and Society. 2024 Jul 1;106:105379.

[38] Nwokediegwu ZQ, Ibekwe KI, Ilojianya VI, Etukudoh EA, Ayorinde OB. Renewable energy technologies in engineering: A review of current developments and future prospects. Engineering science & technology journal. 2024 Feb;5(2):367-84.

[39] Kiasari M, Ghaffari M, Aly HH. A comprehensive review of the current status of smart grid technologies for renewable energies integration and future trends: The role of machine learning and energy storage systems. Energies. 2024 Aug 19;17(16):4128.

[40] Kemal MS. Real-time monitoring of low voltage grids using adaptive smart meter data collection.

[41] Ponce P, Polasko K, Molina A. End user perceptions toward smart grid technology: Acceptance, adoption, risks, and trust. Renewable and Sustainable Energy Reviews. 2016 Jul 1;60:587-98.

[42] Ponce-Jara MA, Ruiz E, Gil R, Sancristóbal E, Pérez-Molina C, Castro M. Smart Grid: Assessment of the

past and present in developed and developing countries. Energy strategy reviews. 2017 Dec 1;18:38-52.

[43] Campbell RJ. The smart grid: Status and outlook. Congressional Research Service. 2018 Apr 10:7-5700.

[44] Congress US. Energy independence and security act of 2007. Public law. 2007 Dec 19;2:110-40.

[45] IqtiyaniIlham N, Hasanuzzaman M, Hosenuzzaman M. European smart grid prospects, policies, and challenges. Renewable and Sustainable Energy Reviews. 2017 Jan 1;67:776-90.

[46] Coll-Mayor D, Paget M, Lightner E. Future intelligent power grids: Analysis of the vision in the European Union and the United States. Energy Policy. 2007 Apr 1;35(4):2453-65.

[47] Sospiro P, Amarnath L, Di Nardo V, Talluri G, Gandoman FH. Smart grid in China, EU, and the US: state of implementation. Energies. 2021 Sep 8;14(18):5637.

[48] Mazhar T, Irfan HM, Haq I, Ullah I, Ashraf M, Shloul TA, Ghadi YY, Imran, Elkamchouchi DH. Analysis of challenges and solutions of IoT in smart grids using AI and machine learning techniques: A review. Electronics. 2023 Jan 3;12(1):242.

[49] Koshy S, Rahul S, Sunitha R, Cheriyan EP. Smart grid–based big data analytics using machine learning and artificial intelligence: A survey. Artif. Intell. Internet Things Renew. Energy Syst. 2021 Nov 22;12:241.

[50] Hasan MK, Alkhalifah A, Islam S, Babiker NB, Habib AA, Aman AH, Hossain MA. Blockchain technology on smart grid, energy trading, and big data: security issues, challenges, and recommendations. Wireless Communications and Mobile Computing. 2022;2022(1):9065768.

[51] Monteiro V, Afonso JA, Ferreira JC, Afonso JL. Vehicle electrification: New challenges and opportunities for smart grids. Energies. 2018 Dec 29;12(1):118.

[52] Wu Q, Li GY, Chen W, Ng DW, Schober R. An overview of sustainable green 5G networks. IEEE wireless communications. 2017 Aug 22;24(4):72-80.

[53] Amuthan N, Sathya M, Rani NC. Empowering Consumers and Utilities for a Smarter Future: The Pivotal Role of Advanced Metering Infrastructure (AMI) in Smart Meter Technology. Cloud Computing in Smart Energy Meter Management. 2025 May 5:31-65.

[54] Mohassel RR, Fung AS, Mohammadi F, Raahemifar K. A survey on advanced metering infrastructure and its application in smart grids. In2014 IEEE 27th Canadian conference on electrical and computer engineering (CCECE) 2014 May 4 (pp. 1-8). IEEE.

[55] Jørgensen BN, Gunasekaran SS, Ma ZG. Impact of EU Laws on AI Adoption in Smart Grids: A Review of Regulatory Barriers, Technological Challenges, and Stakeholder Benefits. Energies. 2025 Jun 6;18(12):3002.

[56] Ponce-Jara MA, Ruiz E, Gil R, Sancristóbal E, Pérez-Molina C, Castro M. Smart Grid: Assessment of the past and present in developed and developing countries. Energy strategy reviews. 2017 Dec 1;18:38-52.

[57] Mann RF. Smart incentives for the smart grid. NML Rev.. 2013;43:127.

[58] Sovacool BK, Kivimaa P, Hielscher S, Jenkins K. Vulnerability and resistance in the United Kingdom's smart meter transition. Energy Policy. 2017 Oct 1;109:767-81.

[59] Gunduz MZ, Das R. Cyber-security on smart grid: Threats and potential solutions. Computer networks. 2020 Mar 14;169:107094.

[60] Inayat U, Zia MF, Mahmood S, Berghout T, Benbouzid M. Cybersecurity enhancement of smart grid: Attacks, methods, and prospects. Electronics. 2022 Nov 23;11(23):3854.

Copyright © 2025 by the author(s). Published by UK Scientific Publishing Limited. This is an open access article under the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Publisher's Note: The views, opinions, and information presented in all publications are the sole responsibility of the respective authors and contributors, and do not necessarily reflect the views of UK Scientific Publishing Limited and/or its editors. UK Scientific Publishing Limited and/or its editors hereby disclaim any liability for any harm or damage to individuals or property arising from the implementation of ideas, methods, instructions, or products mentioned in the content.