A Review on Socio-technical Transition Pathway to European Super Smart Grid: Trends, Challenges and Way Forward via Enabling Technologies

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Abstract: This study adopts a retrospective empirical approach to review the innovative methods and techniques in the European Union perspective aimed at transitioning from a smart grid to a super smart grid. The European Union (EU) has embarked on an even more significant modernization of its electricity infrastructure. Central to this transformation is the development of a super smart grid, which leverages enabling technologies to augment grid intelligence and interconnectivity across Europe. The review critically examines the technical, regulatory, and economic measures adopted by the EU to facilitate this transition. It highlights the challenges posed by the integration of renewable energy systems (RES), such as intermittency, cybersecurity threats, and the need for advanced demand-supply balancing mechanisms. Furthermore, it addresses the systemic and market barriers to grid expansion and modernization, including the necessity for updated regulatory frameworks and enhanced public acceptance. The study also delves into innovative solutions like blockchain-based decentralized energy transactions, which offer promising avenues for secure, efficient, and autonomous energy balancing. The development of a super smart grid leverages artificial intelligence for predictive analytics, demand forecasting, and real-time decision-making, while the metaverse facilitates immersive simulation and optimization of energy systems through digital twins and virtual power plants. Furthermore, this study delivers a comprehensive overview of the potential challenges and issues encountered in super smart grids, emphasizing the crucial role of regulatory reforms and technological innovations in achieving a sustainable, intelligent, and interconnected European power grid.

Keywords: Super Smart Grid, Energy, Metaverse, Digital Twin, Blockchain, Artificial Intelligence

1. Introduction

In numerous nations, the electricity sector has experienced a remarkable shift towards the fostering of Renewable Energy Systems (RESs) [1], marking an initial phase of systemic transformation and disruptive innovation [2]. Regulation should not exclusively prioritize the cost-efficient utilization of current infrastructure and investments in reinforcement and replacement; innovation should also be a factor to consider. This transition primarily emphasizes the technical and economic validation of RESs, catalysing their diffusion within electricity systems. However, the evolving discourse now extends beyond the mere replacement of fossil fuel resources to encompass a broader consideration of the overall functionality of electricity systems. In this context, the integration of RESs necessitates a nuanced approach to balancing supply, and demand [3], along with storage, while ensuring high power quality and mitigating congestion [4] in power transmission and distribution along with storage infrastructures. These multifaceted requirements pose significant challenges to the operational paradigms of electricity grids, necessitating a comprehensive re-evaluation of all segments of the supply chain, not solely limited to generation.

The energy and power sector is expected to have a pivotal role in establishing a low-carbon economy [5]. Across all European Union (EU) decarbonization scenarios, renewable energy sources (RES) are integral to the solution [6,7]. However, existing grids present significant barriers to the future uptake of RES. Acknowledging the need to modernize the grids, the EU has advocated for the development of a "super smart grid." This initiative aims to interconnect European grids at a continental level and enhance the grid with information and communication technology (ICT). [8]. To achieve this goal, the EU has spearheaded research and development projects and established a unified legislative framework to facilitate the indispensable grid modernization across Europe [9].

Our study aims to provide both an overview and a critical assessment of the actions undertaken by the EU to transform the grids into the foundation of a decarbonized electricity system. It proposes that for aggressive and effective deployment of super smart grids, the existing regulatory framework must be re-evaluated, and it is imperative to incorporate the enabling technologies.

1.1. Challenges of Conventional Grid

Even the modern power systems are prone to challenges and achieving the national goal to accommodate the RE generation is still a problem for policymakers and regulators. These challenges include maintaining stable power due to intermittency, cyber-attacks, supply-demand balance, lessening the peak demand, uninterrupted supply, and the management of digital devices [10,11]. Hence, the need is to take a step further to develop a more resilient and reliable network with vitality metrics and simulations to prove their authenticity [12]. According to [13] the foremost obstacle in achieving the required grid expansion does not stem from technical or financial constraints but is primarily associated with the absence of apt regulatory frameworks and constrained public acceptance. Moreover, addressing this issue necessitates substantial modifications in the current regulatory process rather than minor amendments or just improving the current regulations.

In response to these challenges, the concept of smart grids has emerged as a strategic framework to enhance the efficiency and resilience of electricity systems [14]. Smart grids aim to facilitate the integration of decentralized electricity technologies, primarily focusing on generation, system operation, and potential transmission across national and international grids.

Characterizing a smart grid presents a formidable task due to its adaptable nature, which can be tailored according to specific applications. However, a consensus exists regarding its fundamental attributes, which serve as foundational pillars in grasping its transformative potential [15–17]. Conceptually, the smart grid is a refined iteration of a power distribution system, augmented with renewable energy sources, power electronic devices, and advanced automation. More recently, there has been a conceptual evolution of smart grids as clusters of interconnected microgrids being labeled as cyber-physical systems [18].

Smart grids with a bi-directional flow of energy and automacy exhibit both transformative and disruptive characteristics. The now emerging ownership models with decentralized generation require novel ways to balance demand and supply. The ownership can reside in a single person or energy communities, which can influence the incumbent institutions and firms of the traditional grid, thereby disrupting the energy markets and offering support to newly emerged prosumers. This sort of disruption requires a transition to upgraded technologies, such as those that support direct trading, system balancing, and improved demand response [19–22].

2. Methodology

This review paper presents a transformation pathway from a smart grid to a super smart grid and how it would help interconnect all the EU member countries and allow energy exchange between them with ease. We have also explored in detail the opportunities and challenges encountered during this transition. Super smart grids are fundamentally backed by high computation-based automation and advanced enabling technologies such as metaverse and artificial intelligence, which are discussed in this review.

In summary, this review paper answers the question, "What are the necessary steps for the transition from smart grids to super smart grids?". Also, "Why do smart grids require more upgradation?". Another interesting question that this study addresses is "What is the role of enabling technologies amidst this transition?". This question is answered by extensively reviewing the available literature body for systematic, infrastructural, and techno-economical affairs. The critical point is the influence of external factors such as regulatory affairs and policy actions that have a significant impact on this transition. The discussion on the role of enabling technologies in super smart grids provides a holistic view of the dynamics of elements at the core of this transition. The flow of methodology is shown in **Figure 1**.

The literature review indicates that most research has focused on smart grids, while the innovation of super smart grids has not yet been examined from a comprehensive socio-technical system perspective. This review is designed to identify key themes and technological advancements, as well as to understand the regulatory frameworks and economic implications associated with the transition to super smart grids. By synthesizing existing knowledge, the literature review lays a solid foundation for further analysis. A comparison with other studies is presentedError! Reference source not found..

The prime resource for the qualitative analysis relates to academic journals and conferences as well as review papers. It also includes industrial reports, technical standards, official documents, governmental reports, think tanks, and scientific research organizations. It also includes some archives of news articles, technical blogs, and websites. Official documents are sourced from the European Commission's database, along with publications of the International

Energy Agency (IEA). Scopus, IEEE Explore, Springer, Google Scholar, Web of Science, and Wiley are used for searching scientific papers. These databases were explored with Boolean search operators for keywords “Virtual Power Plants”, “innovation”, “Energy Transaction”, “regulatory affairs”, “policy”, “Technologies”, “AI”, “IoT”, “Metaverse”, and “Blockchain” etc. in combination with “Super Smart Grid”, “Smart Grid”, and “European Countries”.

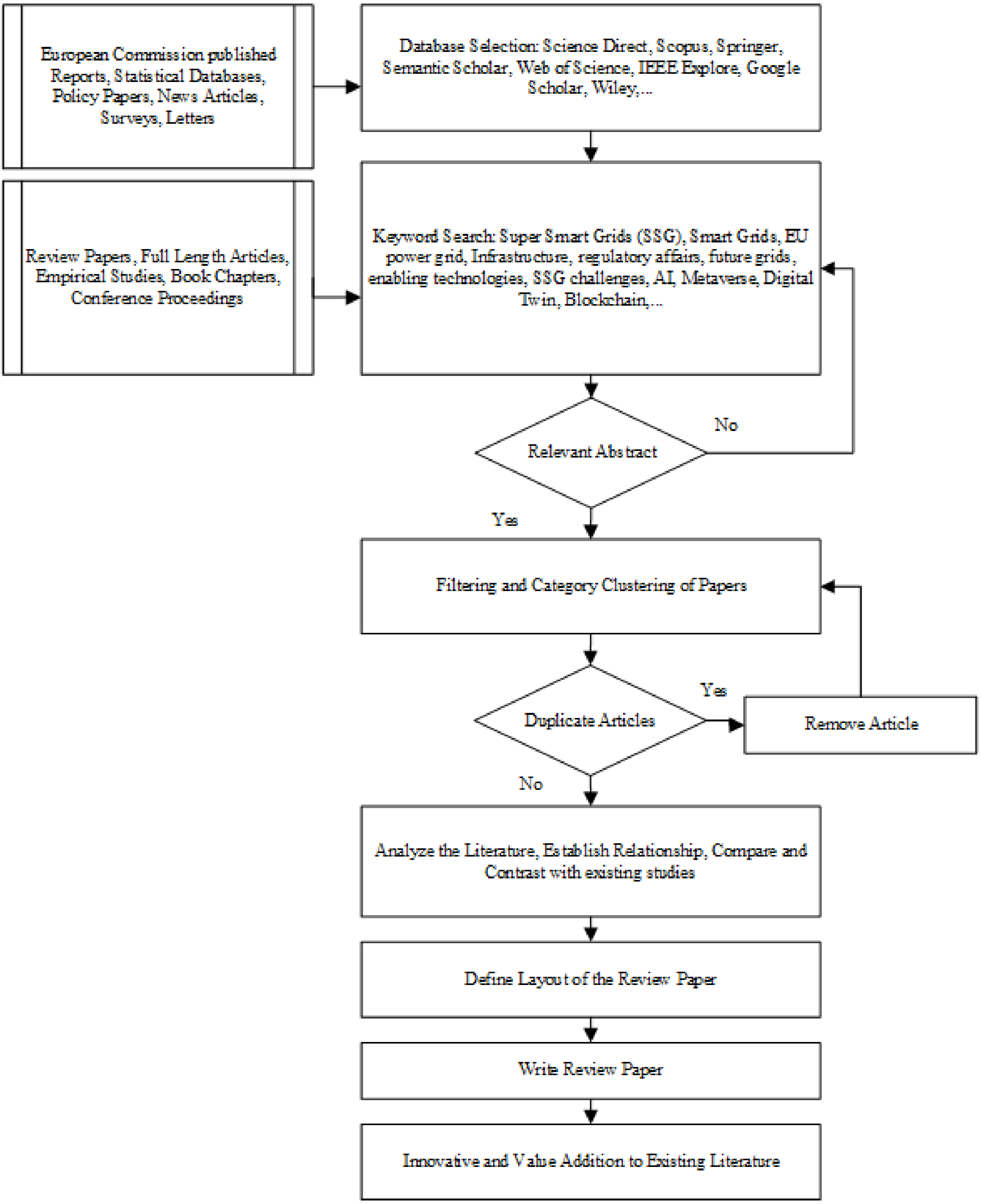

Figure 1. Flow Chart for this review paper

In the initial search, more than 500 journal publications, reports, website links, and articles were found. The paper's theme and parameters served as the key exclusion criteria. A few resources referring to power electronics and grid integration techniques related to renewable resources were excluded. Other excluded articles discussed microgrids and energy markets, which were not in the scope of this article. Moreover, some blog posts and website pages are excluded because of the questionable validity of their origin.

This review paper is structured as follows. Section 3 presents the European power grid transition from smart grid to super smart grid. It also includes novel techniques for energy transactions among various stakeholders in a super smart grid. Section 4 explains the regulatory framework and policy interventions pertinent to the super smart grid. In Section 5, State of the art enabling technologies are discussed in detail. This section also presents the challenges associated with the uptake of a super smart grid. Finally, the study concludes with Section 6 with a discussion on emerging challenges with super smart grid and potential solutions as well as proposing suggestions for future research.

Table 1. Comparison of this study with available literature

	Technical Aspects		**Social Aspects**	**Enabling Technologies**					**Socio-technical**
Reference	**Super Smart Grid**	**Energy Transaction**	**Regulations and Policies**	**Metaverse and Digital Twin**	**Artificial Intelligence**	**Big Data**	**IoT, 5G, and Edge Computing**	**Blockchain**	**Challenges and Solutions**
[23]	×	×	✓	×	×	×	×	×	×
[24]	×	×	×	×	✓	✓	✓	✓	✓
[25]	×	×	×	✓	✓	×	✓	✓	✓
[26]	×	×	×	×	×	✓	✓	×	✓
[18]	×	×	✓	×	×	×	×	×	×
[27]	×	✓	✓	×	×	×	×	✓	✓
[28]	✓	×	×	×	✓	×	×	×	✓
This Study	✓	✓	✓	✓	✓	✓	✓	✓	✓

3. European Power Grid

The European power grid is the most intact and resilient in the world, with fully integrated energy markets. This modernized infrastructure ensures reliable and inexpensive clean energy for consumers. However, the European Union (EU) is expected to experience a rise in electricity demand by 60% by the year 2030. This high demand is attributed to the increasing share of renewable energy (RE) generation, electric vehicles, heating systems, and growing demand for hydrogen production as well as storage. In realistic terms, the grid needs to be more decentralized, flexible, and digitalized by the end of the decade. According to the European Green Deal, [29,30],[31] upgradation of the conventional grid and increasing the cross-border transmission capacity requires an investment of 584 billion euros, while ENTSO-E projects an investment of 700 billion euros till the year 2050 [32].

To meet the target of achieving 50-55% energy from RE resources, the European Commission (EC) needs to make significant extensions throughout the grid, both at the national level as well as transnational level. In this context, the SUSPLAN project [33] assesses the barriers and strategies for RE penetration in nine different European regions. It also evaluates the cost and benefit of the modernized infrastructure through economic optimization under various scenarios of RE penetration. With reference to the EU's Grid Action Plan [34,35], establishing cross-border linkages for energy transactions is a priority across Europe, with an extensive transmission grid as its backbone.

According to the EU Wind Power Action Plan [30,36], offshore wind will have a substantial role in advancing the EU's climate and energy objectives in the coming years. Member States have collaboratively established ambitious targets for offshore RE production by 2050, delineating intermediate milestones for 2030 and 2040 within each of the EU's five maritime basins. Achieving the newly established EU objective of having at least 42.5% renewable energy by 2030, with a goal to achieve 45%, necessitates a substantial augmentation in wind installed capacity. This entails a projected surge from 204 GW (in the year 2022) to surpass 500 GW (by the year 2030) just for wind energy.

As of 2022, the cumulative offshore installed capacity in the EU-27 reached 16.3 GW. To address the disparity between the 111 GW pledged by Member States and the existing capacity, the installation rate of about 12 GW annually is required – a magnitude that exceeds the recent 1.2 GW installed last year by a factor of ten [36–38]. However, this ambitious target comes with an array of challenges among which are a highly constrained grid, unfair trade practices, and irregular energy markets.

Currently, almost 40% of the EU power grid is more than 40 years old infrastructure and does not support such a large penetration of RE. The conventional grid topology means concentrated power generation plants having fixed points on the grid, supplying the large load centers only, before stepping down energy at the consumer level. With the emergence of distributed RE, this topology has become irrelevant and unrealistic. European countries have different energy generation and load patterns.

The future smart grid should be able to allow the integration of all regional grids and maintain a balance between such a "system of systems". An intelligent grid should be able to balance regional surpluses and deficits at all times. By 2050, achieving a 100% RE in Europe is economically viable and technically attainable through the implementation of cost-effective, flexible generation methods, enhanced energy storage solutions, and increased connectivity in transmission networks [39].

3.1. Smart to Super Smart Grid Transformation

The transformation of conventional grids to smart grids involves substantial challenges related to policy intervention, technological upgradation, and social aspects. It is essentially a convergence of ICT and the evolving energy systems [40–42]. The smart grid (SG) with a European perspective is an electricity network with intelligent integration of all stakeholders –

generators, consumers, and operators. They all work together to achieve the common goal of an economic, secure, and sustainable electricity system.

An SG conjoins innovative technology and services in a system with inherent intelligence of control, monitoring, communication, and self-healing [43–45]. Markets and commercial aspects are also a crucial part of this new landscape, backed up by regulatory framework, environmental consideration, standardization usage, and societal requirements [46]. A Super Smart Grid would have the capability to connect EU member countries through a single grid, without the limits of national boundaries, and ensure ease in energy exchange between countries.

The present-day electricity grid confronts multifaceted challenges and issues such as privacy concerns between energy providers and consumers [47], cybersecurity threats originating from potential cyber-attacks [48], and the need to align with national objectives for integrating green energy sources. Moreover, the grid contends with heightened intricacy in maintaining grid stability in the event of intermittent power supply, as well as necessary action to mitigate peak demand surges to optimize energy utilization and reserve adequacy.

The incessant demand for uninterrupted power supply further amplifies the complexity. Additionally, the proliferation of digitally controlled devices introduces a transformative shift in electrical load dynamics. Addressing these challenges mandates the evolution of a self-regulating, intelligent, and seamlessly integrated electric grid, facilitated by modern information and communication technology (ICT) techniques for efficient data manipulation and sharing. In this evolving landscape, Smart grids offer a responsive solution to these pressing demands, thereby making the foundation for a resilient and sustainable electricity network [49].

The study examines surplus power generation and the residual load scenario in 30 European countries in case of 100% RE penetration. For individual countries, approximately 24% of the total electricity consumption in a year requires balancing. However, this lessens to 15% when all countries are interconnected with unrestricted interconnectors, thereby getting the benefit of the maximum achievable transmission. The unconstrained interconnectors exhibit a Net Transfer Capacity about 11.5 times greater than current values. Nonetheless, constrained interconnector capacities, at 5.7 times the current value, deliver 98% of the maximum feasible transmission benefit [50].

A research study employing the "LUT Energy System Transition model" simulates two distinct pathways toward achieving a 100% RE power sector in Europe by 2050 [39]. The first scenario models regions independently, while the Area scenario incorporates transmission interconnections between regions. The modeling framework accounts for current power plant capacities and ages, along with anticipated increases in future electricity demands. The optimization results suggest that the levelized cost of electricity could potentially decrease from 69 €/MWh to 56 €/MWh in the regional scenario and 51 €/MWh in the area scenario, enabled by the adoption of cost-effective, flexible renewable energy generation and energy storage solutions. The second scenario supports the idea of the transition from a smart to a super smart grid.

SGs are imperative to take maximum advantage of most intermittent RE resources (RER) due to their capability to manage and monitor the delivery of the energy in real-time by means of a communication device for automatic reconfiguration of RER. One aspect of SG deployment is to reduce the peak demand, thus making way to incorporate new loads such as electric vehicles. The bidirectional flow of data provides consumers with insights into electricity consumed and price. Now, in case of transition from smart grids to super-grids, serving as large-scale transmission networks between wide geographical areas, make use of high-voltage direct current (HVDC) technology. One example of the super-grid is the project under the Desertec program, which links RER from North Africa and Europe [51]. **Table 2** provides a comparison of attributes in case of transition from conventional to super grid [51–53].

Table 2. The difference in attributes of Conventional, smart, and super smart grid

Attributes	Conventional Grid	Smart Grid	Smart Super Grid
Energy Generation	Central	Distributed	Distributed
Grid Topology	Radial/Ring	Dispersed Network	Dispersed Network
Provision of Distributed RE	Constrained	Flexible	Unconstrained
Self-Monitoring and Self-Healing	No	Yes	Yes
Flow of Energy and Information	One-way	Two-way	Two-way
System Testing	Manuel	Remote	Autonomous Reconfiguration
Carbon Emissions	Abundant	Environment Friendly	Environment Friendly
Advanced Metering Infrastructure	No	Yes	Yes
Accounts Demand Response	No	Yes	Yes
Ease of Data Collection	No	Real-Time	Real-Time
Energy Markets	Limited Scope	Multilateral	Multilateral
Energy Trading	Constrained	Possible	Possible with Ease
Energy trading Geographical spread	Constrained	Within Restricted Area	Wide Area
Cyber Security	No provision	Required	Necessary
Overall Efficiency	Low	High	Very High

A review on smart grid technology [49,54], put forward possible ways to manage the large data and optimization of resources through cloud computing. The scalable and adaptable features of a cloud infrastructure can address the security and latency issues of an SG. It can also support with ease dynamic applications such as demand response, load balancing, and energy demand forecasting. However, such a platform needs to be highly responsive in case of scheduling latency-sensitive applications as well as must-have privacy preservation. Another way to manage this complex network is through multi-agent systems (MAS). MAS [55–58] is one of the pioneering distributed architectures for a digital market, based on Game Theory [59–62] and microeconomics [63]. Later on, it further evolved into various models like Decision Making Assistant (DMA)[64], Problem Formulator and Attributes Evaluator (PROFATE), the Electricity Market Multi-Agent System (EMMAS) [56,65,66], and Power-Matcher (cluster-based) [67]. **Figure 2.** 7-Layer architecture of a Smart Grid given in [27].

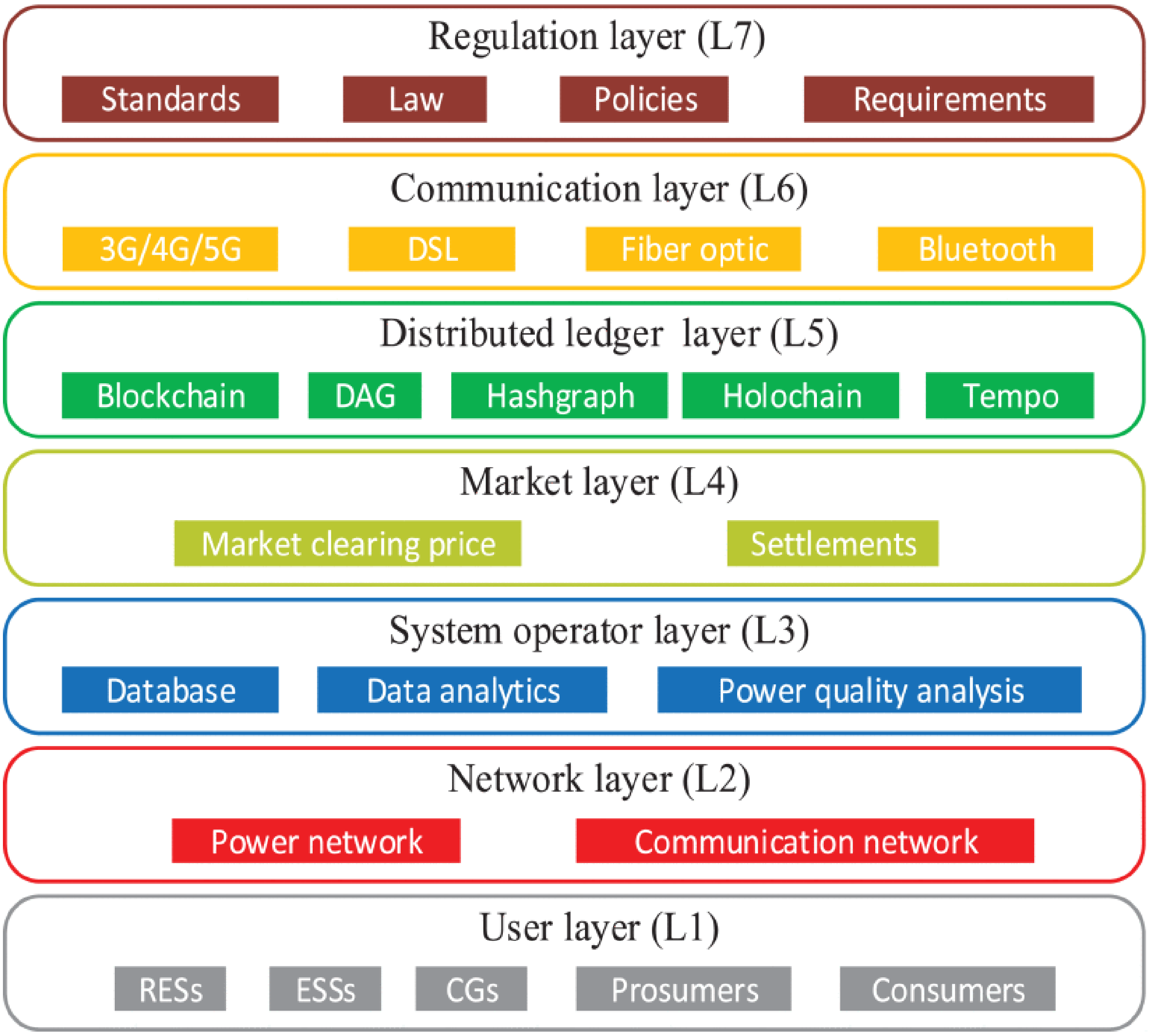

Figure 2. 7-Layer architecture of a Smart Grid [27]

Smart grids are now evolving by employing efficient energy management systems, better automation with the Internet of Things, the capability to balance the grid with electric vehicles, and providing support for big data [26]. In the futuristic super smart grid environment, strategic energy demand management can be done through a fuzzy logic-based controller [68]. Ease of energy storage is one of the unique features of a SG, that makes energy readily available on the grid, thereby minimizing losses. It adds to the system's efficiency but also compensates for the intermittency and variability of the distributed resources.

In the event of a supply-demand imbalance, the energy storage can balance the difference by either charging or discharging itself [69–72]. Electric vehicles, pumped hydro, and hydrogen storage are the modern means of energy storage. Till the year 2021, the EU has made a huge funding contribution in this transformational process and invested 135 million EUR in France, 155 million EUR in Germany, and 157.2 million EUR in Spain. This large investment covers projects related to DG and storage integration, smart networks, and DSM [73]. **Table 3** Compares the indicators of SG development in the EU countries [18,74] [75–78].

Table 3. Comparing indicators of SG development in EU countries

Parameter	Netherlands	Germany	Denmark	Norway	France
Population (millions)	17.53	83.13	5.85	5.40	67.5
Total investment in SG projects (EUR/capita)	10	4.5	16	6	4
Primary energy consumption (exajoules)	3.54	12.3	0.68	1.9	8.39
Total electricity generation (GWh)	117,440	250,385	32,793	39,412	530,418
RE generation (%)	34.8	41.80	78.14	98.80	23.25
Electricity demand (MWh per capita)	6.62	6.16	6.23	25.17	7.19
PV penetration rate (%)	11.8	10.9	5.0	0.1	3.6
Wind power capacity (%)	14.7	25	39.1	7.49	6.76
Offshore power capacity (%)	5	3	12	0.01	0.01
Number of EVs per 1,000 population	21.7	15.7	24.7	117.3	11.6
Total charging station (per 1000 EV)	200	38	20	30	68
Operational battery storage (MW)	37	570	2	6	19
Effective electrochemical storage by population (W/capita)	2.11	9.02	0.341	1.19	0.28
Smart metering rolling out (%)	85.2	15	80	98	80–90
CO_2 emissions per capita (tonnes)	8.06	8.09	5.05	7.57	4.74
Electricity market flexibility for DMS	low	medium	low	low	medium
Level of the concentration System operator	medium	low	low	low	very high
Companies/organizations involved in the SG projects (count)	476	835	430	245	680
Collaborations with other EU countries for SG projects (per 1000 population) (count)	0.31	0.42	3.02	0.87	0.41

3.2. Way Forward to Futuristic Super Smart Grids

The emergence of a Super Smart Grid (SSG) which interconnects European electricity grids at the continental scale and imbues them with intelligence through ICT and advanced computation, constitutes a pivotal strategy in the European Union for the seamless integration of RES [79,80]. The SSG is a self-reliance and intelligent system with advanced control methods, the most modern sensors, and the latest communication devices coupled with advanced technologies. It can balance supply-demand over a wider area than a smart grid, **Figure 3** is a visual representation of SSG.

The distinct attributes of super smart grids are wide area coverage and distributed generation (DG). The abundant use of renewable resource-based DGs comes with critical issues i.e., transient stability and load-flow balancing of the grid [28]. A conceptual sustainable grid network is devised, linking Denmark and Norway, aimed at resolving transient stability concerns within SSGs. A comprehensive probabilistic model is crafted to bolster system stability. Findings unequivocally demonstrate that integrating the Unified Power Flow Controller [81] proves highly effective in fortifying the resilience of power system networks as well as transient stability.

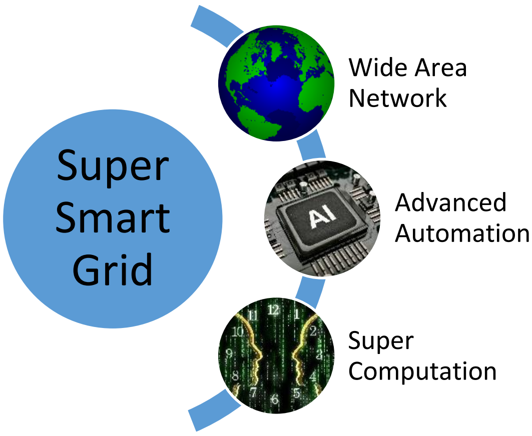

Figure 3. Scalability of Super Smart Grid

Energy management [82] with computational capabilities is a pivotal part of the super smart grid environment. It enhances the grid observability; and improves performance, reliability, and security as well as better control over assets. It also surpasses the smart grid in terms of benefits for the improved environmental factors. While smart grids integrate renewable resources, micro-grids, and demand response [83–86], the super smart grids manage the ever-increasing size and complexity of smart grids paired with advanced communication systems thereby increasing the reliability [87,88] for the prosumers.

In true nature, SSG is a large-scale smart grid with enhanced automation, even higher computation, and complex control strategies. Developing national and regional smart grid platforms can advance SSG projects by bringing together various stakeholders to facilitate the transition to smarter grids. These platforms promote collaborative initiatives, share best practices, and exchange lessons learned, fostering innovation and progress in smart grid technology on both local and national levels [78,89].

Three principal systems of any SG are investigated in [90–93], the smart infrastructure system, the smart management system, and the smart protection system. Within the smart infrastructure system, the study delves into the constituent subsystems including smart energy, smart information, and smart communication. Within the smart management system, diverse management objectives such as enhancing energy efficiency, demand profiling, load forecasting, maximizing utility, cost reduction, and emission control, along with corresponding management strategies were analyzed [94][72,82,84,95]. Within the smart protection system, various mechanisms aimed at enhancing SG reliability, as well as delving into the privacy and security concerns inherent in SG operations were reviewed.

SSGs accelerate the liberalization process in the power sector, grow energy efficiency, and save money on electricity consumption, benefiting economic development and energy security in Europe [96]. SSG and SG allow electricity buying and selling (exchange) generated by large-scale concentrated solar power plants and can reduce climate policy costs by up to 34%, and 24%, for Western Europe and Eastern Europe respectively [97], calculated through the WITCH model.

The Dual-Primal Distributed Algorithm (DPDA) effectively manages energy in smart grids with a network-independent step-size, achieving faster convergence and reducing gradient information exchange [98]. The challenge of ensuring transaction security in decentralized SG energy trading was explored in [99], without relying on trusted third parties. By leveraging blockchain technology, multi-signatures, and anonymous encrypted messaging streams, it presents a proof-of-concept for a decentralized power transaction system. This approach enables stakeholders to anonymously negotiate power prices and securely execute energy exchange, addressing concerns related to the security and privacy of load consumption and energy trading data.

Utilizing mean-variance portfolio optimization, [100] investigate optimal scenarios for allocating new renewable capacity nationally to guide energy decision-makers. The findings reveal that the current capacity of distributed generation in Europe is suboptimal, suggesting a potential increase of approximately 31% in mean power supply or a reduction of about 37.5% in daily variability with a more efficient spatial distribution. Strategic planning at the European level could significantly improve this distribution imbalance. However, the optimal deployment of resources depends on the objective; maximizing average output favors countries with abundant resources.

The primary barriers to grid expansion in the European Union are neither financial nor technical, rather lack of appropriate regulatory frameworks and public acceptance, requiring major changes in the overall regulatory process [13]. This study examines excess power generation and the residual load across 30 European countries with 100% variable renewable energy penetration, assessing the benefit of power transactions between them. Using extensive weather data, hourly mismatches between demand and distributed generation are modeled. While separated countries require balancing for approximately 24% of their total yearly electricity consumption, networking all countries with unconstrained interconnectors reduces this to 15%, representing the maximum achievable transmission benefit. Constrained interconnector capacities, just 5.7 times more than current values, provide 98% of this maximum benefit, prompting further investigation into various constrained transmission capacity layouts for a fully renewable energy-based European electricity system [50] [23,101].

SSGs rely on smart grid technologies, which are rapidly progressing in both the U.S. and

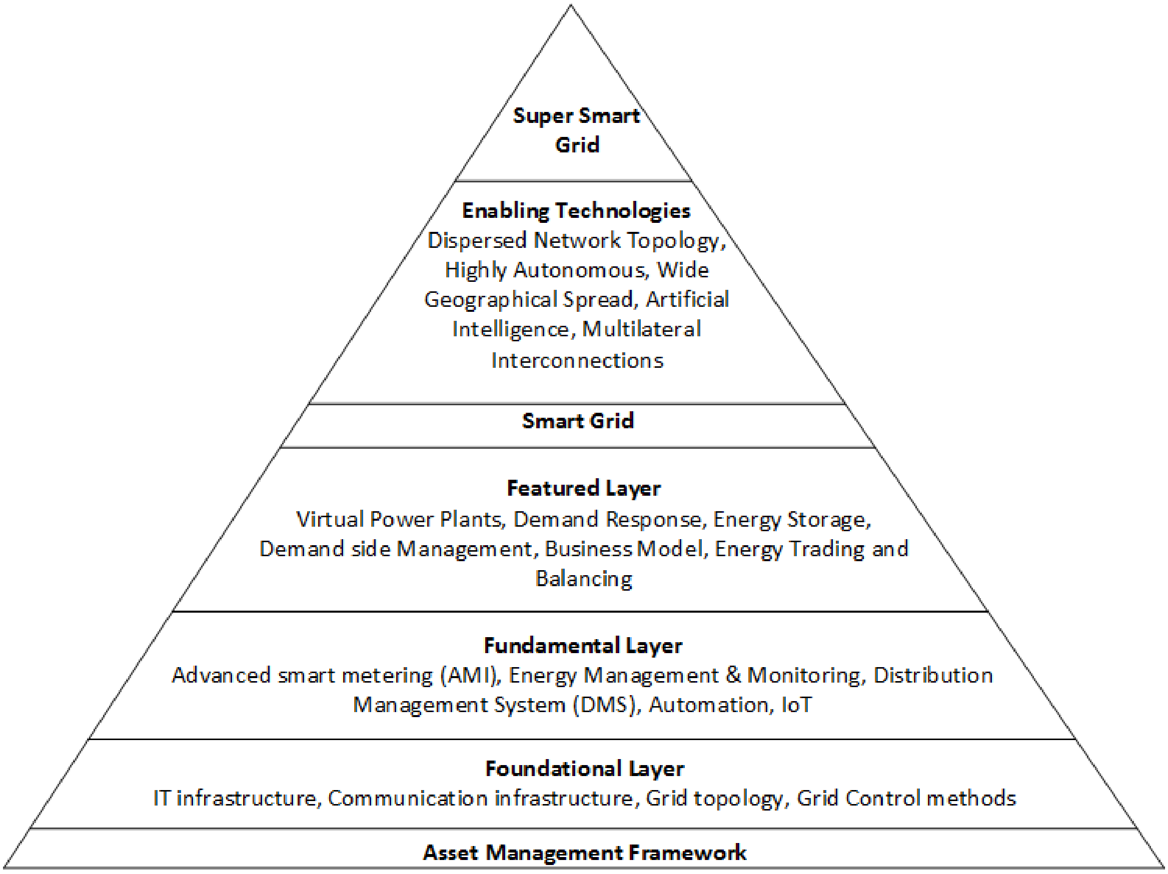

Figure 4. Multi-layered Super Smart Grid Architecture

Europe, with the U.S. smart grid initiative focusing on timely consumer information and control, while Europe is unified in research and development. The Smart Grid Architecture Model (SGAM) [102,103] effectively aids in designing, developing, and validating complex power and energy systems, with potential for future adaptations and extensions. A multi-layered SSG architecture is devised in this paper after reviewing all the attributes of SSG mentioned in the available literature body in **Figure 4**.

3.3. Innovative Ways for Energy Transactions

Energy Transaction or Energy Exchange are terms used interchangeably in the literature. Transactive Energy (TE) is a system where coordinated accomplices utilize automation tools to communicate and exchange energy, adhering to grid reliability indexes and constraints. The growing number of prosumers highlights the necessity of establishing an electricity trading mechanism to facilitate peer-to-peer energy exchange. Within an electric power system, it employs market-based financial transactions and control functionalities to facilitate energy exchange (trading and sharing) among prosumers, conventional and renewable power producers, storage systems, and active consumers. Transactive Energy Systems (TES) transform energy into a tradable commodity, allowing customers to trade surplus energy either in real-time or on a deferred basis [104–106].

It is ideally based on a system of control mechanisms and economics that allows the dynamic balance of demand and supply [107] through the entire grid infrastructure and allows energy give and take at multiple points across the network. This model requires equitable grid access for both demand and supply-side energy resources in both bulk and retail power networks., as well as open and transparent pricing of energy services [108]. The purpose of such a system would be to combine all available resources within a specific geographic footprint to fulfill load at the lowest possible cost. Virtual Power Plants (VPPs) stand as a significant stride towards advancing future Sustainable Smart Grids (SSGs).

In centralized energy exchange, a central authority manages and controls transactions between prosumers, ensuring transparency and imposing penalties for contract violations. However, this central control poses significant risks to the security and privacy of participants and adds time, cost, and computational burdens [1,109–111]. To address these issues, researchers propose using Blockchain-based decentralized energy transactions in Smart Grids (SG) [112], enabling Peer-to-Peer (P2P) trading [113,114] without a central authority. This approach includes models like the SolarCoin-based digital currency for transactions among Prosumers and across Energy Districts, enhancing security, efficiency, and autonomy in energy trading [5,105,115,116].

Decentralized energy markets typically prioritize resilience and safety but often sacrifice privacy. TRANSAX model enables efficient energy futures trading by matching feasible trades, aiding system operators in planning their energy needs. TRANSAX [109] ensures participant privacy through anonymized trading activities using a distributed mixing service while enforcing safety constraints like maintaining energy flow within line capacities [117]. Prosumers and active users interested in energy transactions can be managed through Distributed Ledger Technology (DLT), particularly blockchain, which enables secure smart contracts between prosumers and users, safeguarded by cryptographic hashes [118]. [119] highlights the 3-layer, 5-layer, and 7-layer architecture as well as energy market, control, and network management for a flexible power system.

In a super smart grid environment, the energy transactions would be immense and would require high computation. A possible solution is a study [120], which proposes a transactive energy system of two stages to balance distribution networks, accommodating various participant behaviors. In the first stage, an orchestrator manages the network by purchasing energy, setting dynamic locational marginal prices (DLMPs), or utilizing storage. In the second stage, prosumers make decisions based on DLMPs and preferences, either using grid energy or engaging in peer-to-peer transactions. Results demonstrate reduced import costs and grid energy usage with P2P transactions. The model converges to optimal solutions efficiently as participant numbers increase. **Figure 5** presents the distinct features of the transactive energy network.

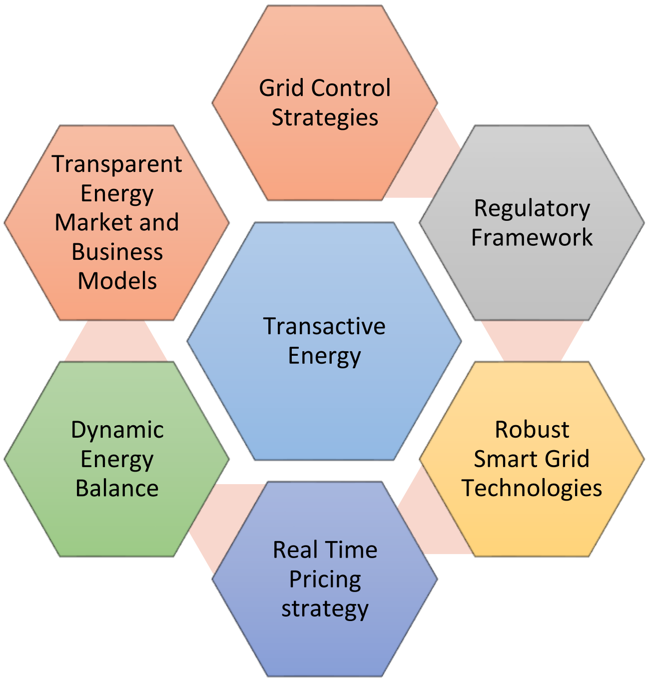

Figure 5. Distinct features of Transactive Energy

4. Regulatory Framework and Policy Interventions

Studies on renewable technologies analyze both transformational and systemic approaches such as [121] studies of systematic problems faced by European countries in developing renewable technologies and diffusing these technologies at a slow rate. Systematic failure is attributed to market structure, where dominant incumbents control the market. Systematic failures as well as markets are reviewed in [122] [13,123]although it lacks to discuss transformational failures.

The development of an SG necessitates a precise regulatory framework having an important aspect of market liberalization. it is an imperative step to keep the energy prices affordable for all stakeholders as well as increase system flexibility by ensuring interoperability between various prosumers. This gives prosumers a choice to opt for a suitable energy provider based on their need and financial situation [124].

For smart grid transition, the case study of the Netherlands can be taken as a reference, which sustains many socio-technological setbacks but continues to evolve. In the Netherlands, the Dutch national government's motivation resulted in the rapid adaptation of smart grid technology. Consequently, it caught the attention of policymakers and attracted investment from firms and scientists for R&D. However, the lack of leadership, learning opportunities, and regulatory frameworks [123] slowed the smart grid diffusion by stakeholders.

The energy system is subject to extensive regulation to ensure a secure electricity supply system. These regulations are continually reviewed and adjusted as needed to address evolving external economic, technical, or social factors. For instance, Germany's electricity system regulation, particularly the EEG (German Renewable Energy Sources Act), has undergone multiple revisions in the past decade. These changes in regulations necessitate careful ex-post evaluations to define their effectiveness and identify any potential unintended consequences. For example, research on electricity market design in Germany indicates that the previous design of the market encouraged participants to systematically under-provide energy, negatively impacting system stability [125–127].

The action plan should have been to involve the corporate sector and relevant stakeholders like energy communities in the policymaking. Also, the upgradation of the grid to incorporate smart technologies should be emphasized in the legislation. Turning smart grids into super smart grids can only be possible with the involvement of innovative entrepreneurs and technological start-ups in the process. They can be supported through legislation, transparent regulations, and robust economic policy instruments [128].

In order to facilitate the innovation [122] by network companies, regulators found it necessary to review their regulatory frameworks. Conventionally, the principal focus of monopoly regulation was cost reduction, achieved in various countries by transitioning from cost plus to regulations based on incentives. However, to efficiently integrate increasing renewables and maximize opportunities presented by digitalization, additional incentives for innovation uptake became essential. Instances of such regulatory mechanisms include output regulation, incentivizing investments with higher returns in innovative networks, and fostering competition for innovation grants [129].

While regulatory experimentation remains relatively underutilized among energy regulators, it serves as a complement rather than a replacement for traditional regulatory methods in fostering innovation. The insights gained from such experiments help bridge the information gap between regulators and innovators, guiding the revision of existing regulations or the formulation of innovative ones.

In only a few Member States, regulatory frameworks for network companies include specific compensation for innovation activities, which can incentivize innovation by reducing financial risk for Distribution System Operators (DSOs). DSOs, subject to economic regulation, face the risk of not recovering costs if innovation projects fail, particularly with large-scale demonstrations that entail high risks and costs [78]. To accelerate smart grid development, it's essential to fund such projects through special mechanisms rather than relying solely on the regular regulatory framework.

To encourage the emergence of new market players and activities, regulators often utilize waivers as a key regulatory instrument. These waivers provide narrowly defined exemptions for specific actions or types of stakeholders, automatically applying to all concerned parties. They are explicitly granted by regulatory decisions and may be revisited once the innovation has matured sufficiently. Additionally, waivers can also be implicitly granted when regulators choose to overlook new activities or actors. For instance, in the case of wind and solar generators, some European Union Member States waived financial obligations for balancing in 2013, as reported by the European Commission [130,131]. **Figure 6** demonstrates the key action points for the uptake of SSG from the regulatory perspective.

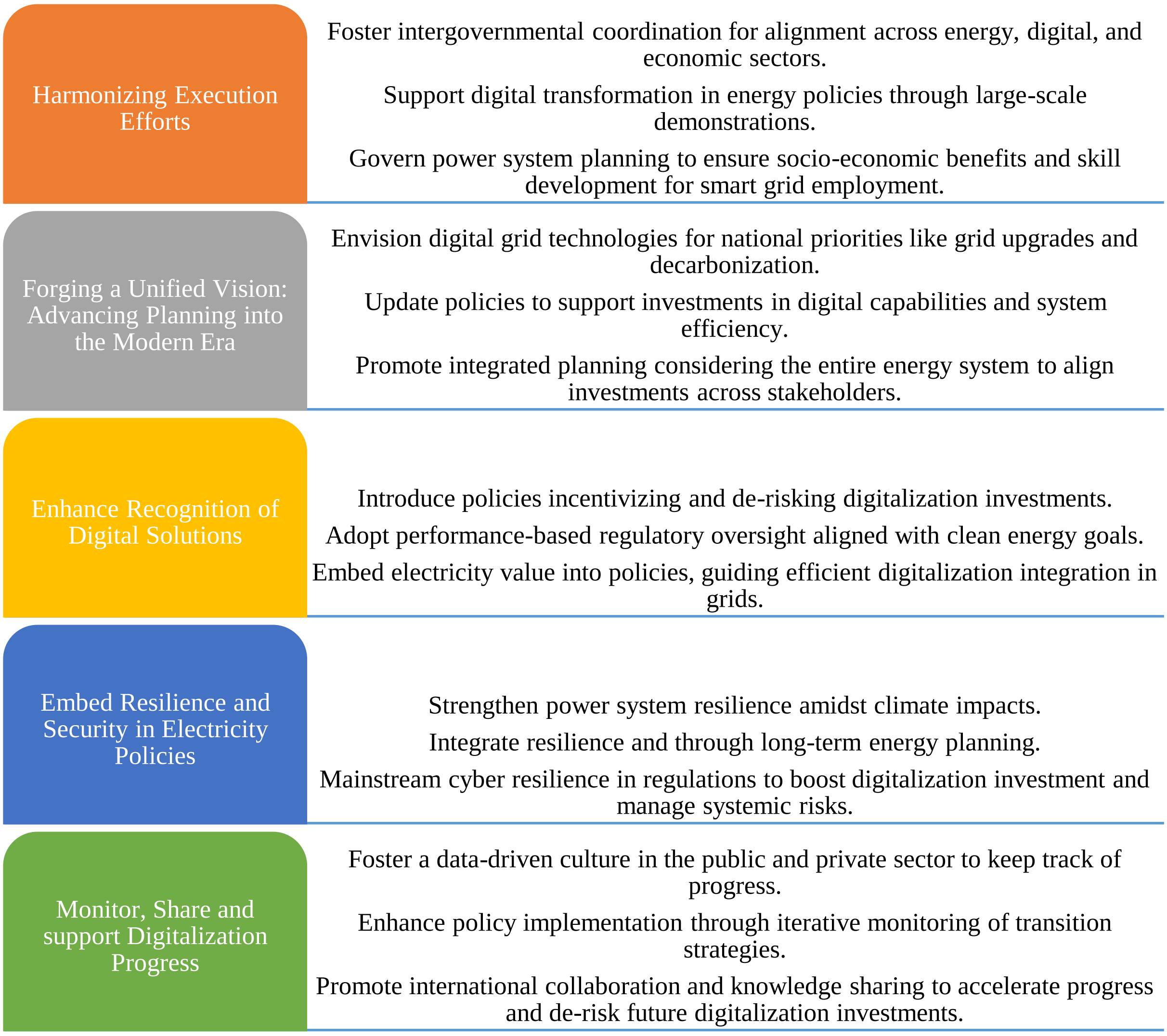

Figure 6. key regulatory actions for the fast-track uplifting of super smart grids

5. Enabling Technologies in Super Smart Grid

This section discusses leveraging the key enabling technologies to transform smart grids into super smart grids through innovation and improvements. In the modern world, cities generate nearly 80% of greenhouse gases and consume 75% of the total energy [132], leading to severe environmental impacts. Experts from both industry and academia recognize smart cities as the ultimate solution to the challenges posed by population growth, rapid urbanization, energy resource depletion, and environmental pollution. The foundation of smart cities is the Internet of Things (IoT) [133–135], which has evolved from conventional networks to connect billions of devices. Technological progressions in wireless sensor networks (WSN), ubiquitous computing (UC), and machine-to-machine (M2M) communication have further enhanced the IoT, supporting the development of smart cities and SG [136].

Employing the latest technologies has multifaceted advantages for the energy industry; enhances the communication protocol for smart grids, provides a virtual experience to customers, and ensures supplier support. These cutting-edge technologies facilitate real-time system monitoring, remote monitoring and maintenance of assets, virtual site visits, and accurate energy accounting [25]. Furthermore, it also has social benefits as it can provide a virtual environment for training field engineers to manage power plants, thereby saving time and reducing risk [137]. The methods and techniques used by these technologies in super smart grids can support optimizing resource allocation, evaluating strategic interactions, extracting patterns from large volumes of data, and modeling network/communication infrastructure. Moreover, it can enhance the functionality of the grid by realizing it in the virtual environment, which results in an immersive and real-time experience [138–140] [141,142]. **Figure 7** shows the role of enabling technologies in SSG.

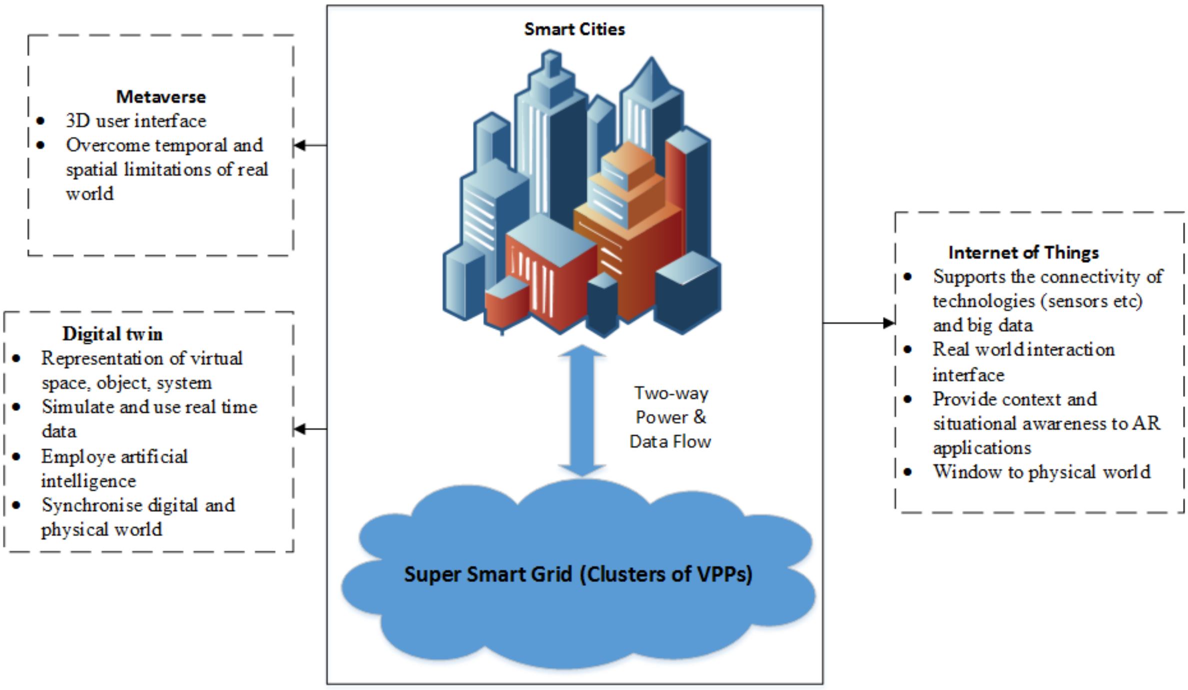

Figure 7. Role of Enabling Technologies in Super Smart Grid

5.1. Metaverse and Digital Twin

The metaverse is a prime example of Human-Computer Interaction (HCI) and is widely explored by researchers globally. It is a virtual environment, that consists of immersive and intertwined digital spaces, providing users a platform to interact with computer [143][144]. Applying metaverse in SG can revolutionize and transform the grid into a super smart grid. It has the potential to enhance the features of smart grids like reliability, better infrastructure, prosumer service, accessibility, and economics [145]. The European Parliament expects that the metaverse market will reach 597.3 billion euros by 2030 [146]. Metaverse has huge applications in smart cities as it can help smooth the integration of electric vehicles, ease of connectivity for the Internet of Things [144,147], prevent cyber-physical attacks [148,149], lowers carbon emissions by reducing the commute, and efficient energy management. It would be the next generation of Geographic Information Systems (GIS) [144], in which super-smart grids would be perfectly laid out in 3D.

Digital twins as a fundamental building block of the metaverse [150] are expected to reach an 86.09 billion dollar market by 2028. In the case of a super smart grid, it acts as a virtual representation of the whole electric network in the digital space of the metaverse and uses simulation, real-time data, and artificial intelligence methods to help reach a decision. This technology replicates reality and instantaneously synchronizes the sensor-collected real-time data between digital space and the physical world [151]. Like metaverse applications in smart cities[152], employing it in a smart grid can help in optimal resource allocation, analyzing strategic interactions between elements of the grid, extracting trends from data, predicting future energy supply demand, and modeling system components. In a metaverse environment, grid-forming components like generation sources, transmission, and distribution networks can be virtually modeled and analyzed. Modeling the contingency situation of the grid is also an added advantage of the metaverse. **Figure 8.** Metaverse and Digital Twin representation in SSG

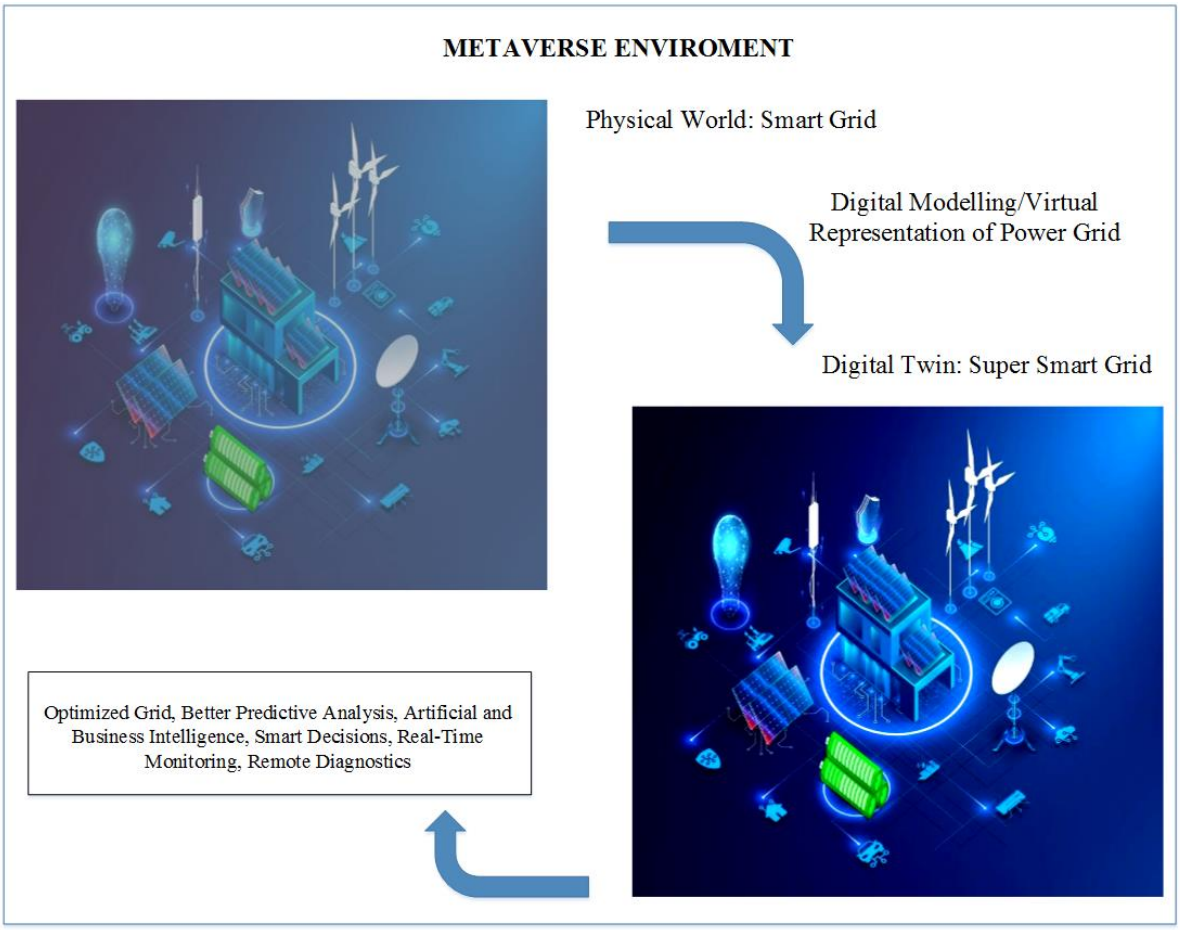

Figure 8. Metaverse and Digital Twin representation in SSG

The creation of a digital twin of energy infrastructure makes system testing more robust, reduces cost and errors, and improves the estimation of carbon emissions. The metaverse provides the environment for optimizing and simulation of renewable energy resources for virtual power plants and battery storage systems. Implementation of such technologies would greatly enhance energy efficiency and management throughout the network and help prosumers as well as energy companies to make informed decisions.

5.2. Artificial Intelligence (AI)

AI founds its application in the metaverse as a combination of computer vision, natural language processing (NLP) [153,154], and machine learning. The metaverse has roots in AI to generate 3D animations, images, speech, and smart contracts and to carry out virtual transactions [155]. In smart grids, AI can help generate virtual assists; a prime example is virtual power plants (VPPs). Through machine learning and deep learning using artificial neural networks (ANN), AI empowers the system to make informed decisions based on pattern recognition and predictions. This assists in stimulating novel scenarios which results in diverse, more accurate, and adaptive solutions. Moreover, AI also facilitates prosumer interaction, data, and grid network protection. For instance, in a study [156], authors proposed an energy management technique known as collaborative multi-agent deep reinforcement learning and modeled the problem of energy optimization, which finds its application in transmission power control.

Contemporary machine learning (ML) tools offer powerful capabilities for predicting market dynamics using publicly available data. ML techniques have been employed to forecast and balance the electricity market prices [157]. While these models excel at capturing non-linear effects and interactions for accurate predictions, they often lack interpretability, making them unsuitable for analyzing regulatory changes post hoc [158,159]. As a result, econometric analyses typically resort to linear models. However, explainable artificial intelligence (XAI) in energy systems is rapidly advancing, with diverse applications spanning from ensuring power grid stability to analyzing price trends. XAI models effectively differentiate between regulatory settings and enhance comprehension of their impacts on changes in the grid [124,125,160,161].

Federated Learning (FL) techniques facilitate collaborative model training across distributed devices ensuring data privacy without the necessity to transmit data to a centralized server. In Smart Grids (SG), FL mechanisms maintain data privacy [162] by conducting local training at individual stations, with only the results shared with the cloud server. Consumers receive suitable incentives based on the data obtained by the cloud server. Edge-cloud collaboration was proposed by [163,164] for privacy-preserving energy data sharing. **Figure 9** shows the application of artificial intelligence and machine learning algorithms with asset and ICT layers in an SG environment [23]. These enabling technologies in SG constitute the basis of a super smart grid. **Table 4.** Summary of research papers within the domain of enabling technologies, SG, and SSG

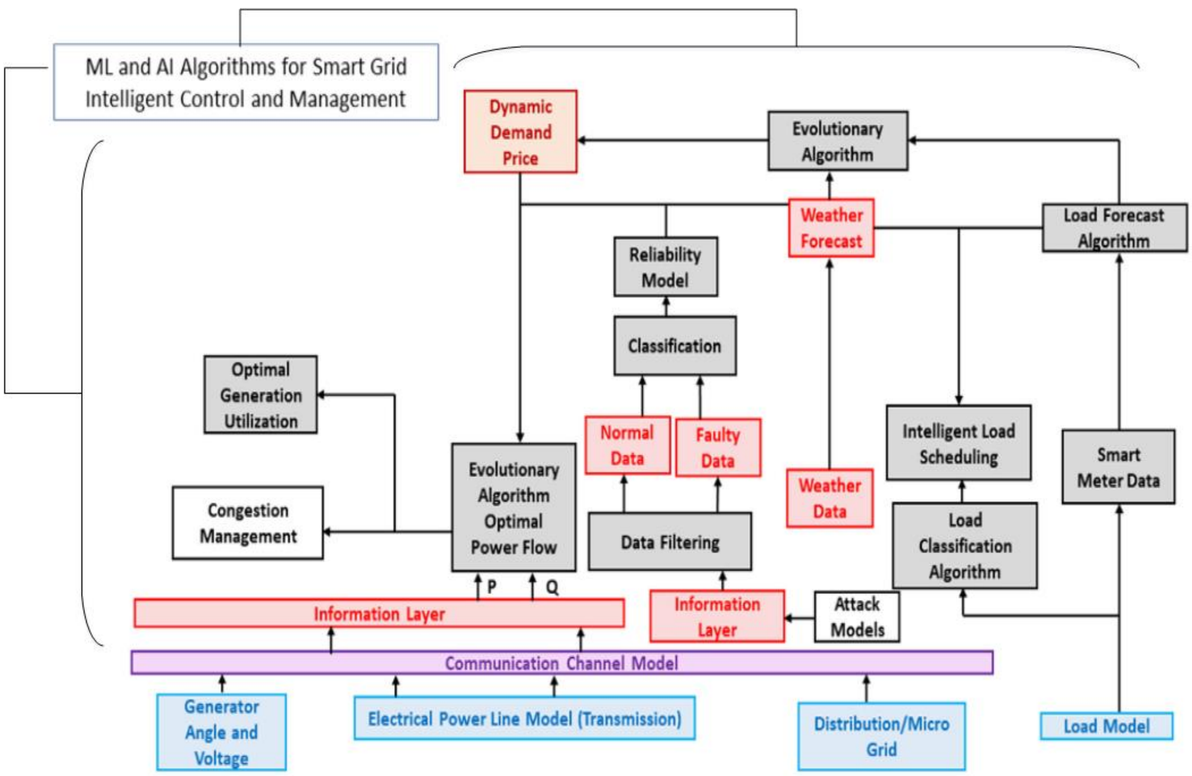

Figure 9. Artificial intelligence applications in SG [23].
Grey: Artificial intelligence , Purple: communication layer, Blue: Asset layer, Red: information layer

5.3. Big Data

With resources becoming scarce and affluent, it is crucial to implement solutions for improved and controlled utilization. Integrating technological systems like Geographic Information Systems (GIS) and Enterprise Resource Planning (ERP)can help [165]. These monitoring systems enable the identification of waste points, improve resource distribution, control costs, and reduce energy and natural resource consumption. Enhancing grid reliability and efficiency through self-monitoring and feedback loops involves deploying smart meters and sensors across production, transmission, distribution systems, and consumer access points [166]. These devices provide granular, near-real-time data on power generation, consumption, and faults. Implementing dynamic pricing models can smooth out peaks by charging higher rates during peak times and lower rates during off-peak periods, helping to prevent outages from high demand. Consumers receive near real-time information about their load demand, enabling them to manage consumption based on needs and cost [167]. This approach requires extensive data collection from all stages of the power system and real-time big data analytics to process this data and send control information, thereby enhancing the overall performance of the electric power system [168].

5.4. IoT, 5G, and Edge Computing

The emergence of the metaverse hinges on its capacity to derive valuable insights from real-world data while prioritizing prosumer safety and inclusivity. This necessitates a robust IoT infrastructure due to its role in linking the physical and digital realms. IoT facilitates the interconnection of devices, enabling seamless data exchange and integration [136], which is crucial for the metaverse's functionality and complexity. IoT not only underpins the technological foundations of the metaverse but also shapes its user experience and potential for innovation [80]. The integration of AI and IoT tools along with virtual reality helps in better understanding the energy efficiency and consumption of a system.

5G technology plays a pivotal role in facilitating the functionalities and applications of the metaverse. Its capabilities in ensuring latency, reliability, and throughput, address the fundamental requirements of the metaverse environment. Notably, 5G technology significantly lessens power consumption and enhances data rates, outperforming conventional wired broadband connections by nearly 90%. Moreover, it substantially diminishes latency by approximately 20 times and improves reliability by about 95% [134,169,170]. These enhancements are instrumental in enhancing user experiences and meeting the specific demands of metaverse applications. Additionally, edge computing emerges as another crucial enabling technology for the metaverse, offering users swift response times that contribute to a heightened sense of immersion and engagement within the virtual environment.

The vast amount of data requires a capable communication network for supporting the metaverse and should be highly responsive, with high bandwidth connectivity [171] and latency. The Internet of Things (IoT) [172] plays a crucial role in smart grids by enabling efficient data transfer and interaction among utilities and smart devices. IoT devices, such as smart energy meters, help identify power shortages and collect load patterns, improving fault detection, grid restoration, and overall efficiency. This data collection leads to better customer load management, reduced energy outages, and lower consumer bills. IoT also enhances the resilience of power transmission systems against natural disasters and reduces losses through effective sensing and advanced communication technologies. However, IoT-enabled smart grids face significant security challenges, including impersonation, unauthorized access, data tempering, eavesdropping, data tampering, malicious code, cyber-attacks, and privacy issues [173–175].

5.5. Block-chain

Block-chain technology has profound application in super smart grids as it simplifies the complex multi-level system [176][177]. It is a secure, decentralized, trustworthy, and traceable digital ledger for keeping transactions that can ensure the safeguarding of digital assets in a virtual space [178][179,180]. Blockchain works in a synchronized virtual space in a decentralized environment and allows independent nodes in synchronization. Just like monetary trading, blockchain can also work in energy trading like real-time trading with cryptocurrency as a means of virtual purchase [181,182]. Similarly, Non-fungible tokens (NFTs) can create a system of digital economy within this realm [182]. Blockchain technology has proven effective in optimizing big data applications, data sharing, and data circulation. **Figure 10** shows the blockchain working [24] in a potential SSG.

Given that the future Metaverse will generate vast amounts of data, the current centralized data storage mechanisms are inadequate to manage these challenges. Blockchain offers promising solutions for data storage and processing in the Metaverse. Its features of non-tampering and non-traceability ensure data authenticity and high quality, providing a foundation for the Metaverse's development, including its unique virtual economic systems [177,183]. Distributed Ledger Technology (DLT), such as blockchain, enables decentralized data management. DLT ensures the security of digital assets, verifies user identities, and establishes a trustworthy environment for transactions [184]. DLT is extensively cited in the smart grid literature as an efficient and suitable blockchain. A comprehensive comparison between various blockchain algorithms is given in [108].

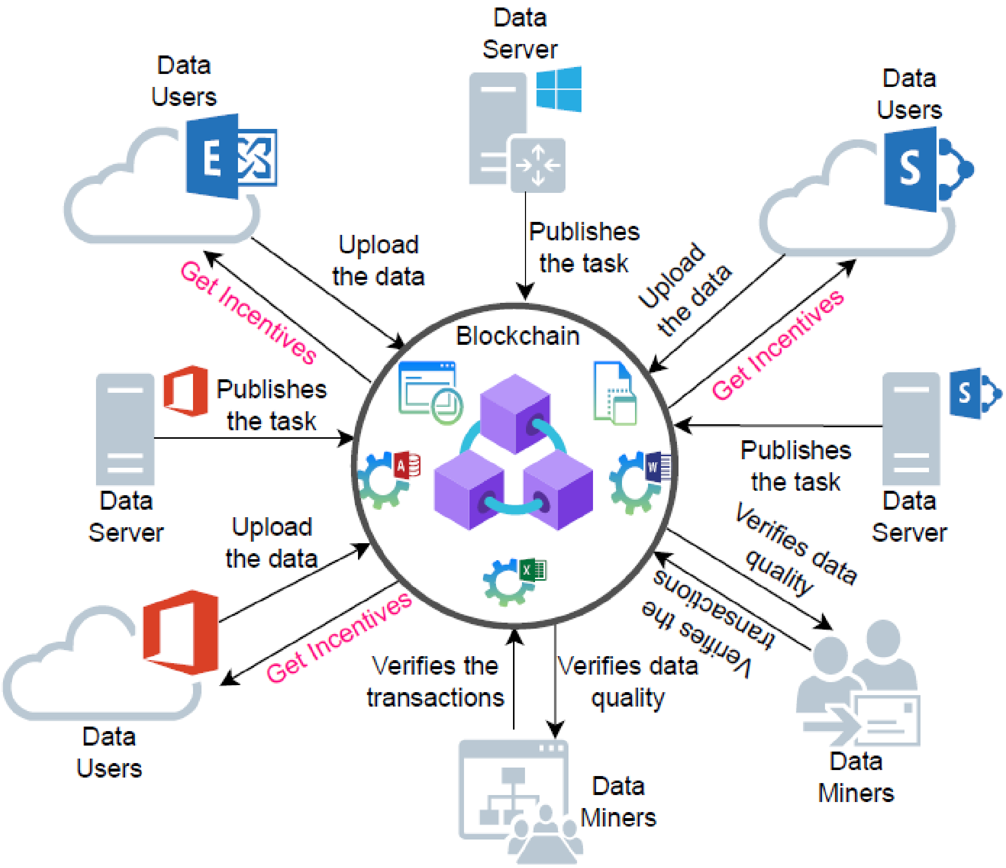

Figure 10. Role of Blockchain in Super Smart Grid [24]

To manage a crowdsourced energy system, an optimized blockchain architecture is presented in [185] for seamless peer-to-peer energy transferring as well as to operate islanded microgrids. This operation algorithm is prototyped through IBM Hyperledger Fabric, an efficient blockchain implementation. Blockchain technology plays a crucial role in virtual power plants (VPPs) by facilitating real-time energy trading through smart contracts. These contracts enable secure, transparent transactions and reflect supply and demand information, allowing for efficient two-way selection under information symmetry. Blockchain helps set fair electricity prices, reduces trust costs, improves trading efficiency, enhances the and scheduling of distributed energy resources and their coordinated control within VPPs [116,186,187].

Table 4. Summary of research papers within the domain of enabling technologies, SG, and SSG

Reference	Year	Scope of research
[188]	2018	Survey privacy preserving schemes, leaking privacy attack, countermeasures, and game theory approach. Also reviewed SG communications, standards, applications, and security.
[189]	2019	Presented a review of game theory-based incentive mechanisms in telecommunication within blockchain networks designed to motivate participants using consensus mechanisms.
[190]	2019	Presented a review on the application of big data analytics and machine learning in the next generation of SG along with their application to load forecasting
[191]	2019	Explores blockchain applications in the SG, detailing its use in peer-to-peer energy trading, data privacy and security, energy distribution control, and equipment maintenance, while discussing commercial implementations and integration challenges.
[192]	2020	Examines smart grid communication needs, evaluates IoT protocols, identifies their shortcomings, and proposes cost-effective, high-penetration solutions while emphasizing security and reliability.
[193]	2021	Reviews cyber-physical security in SG, categorizing attacks, presenting defense strategies, and discussing future security challenges and opportunities.
[194]	2021	Explores the role of business intelligence and data analytics in managing smart grid networks with RE, highlighting their importance in operational and strategic decisions for energy companies.
[141]	2022	Surveys the fundamentals, security, and privacy of the Metaverse, exploring its architecture, key characteristics, threats, challenges, and current countermeasures, while highlighting future research directions.
[195]	2022	Explores the sociotechnical drivers and barriers to the development of a global Super-grid, a vision for a renewable-based electricity system with a vast, advanced transmission network.
[138]	2022	Explores the edge-enabled Metaverse, addressing communication, networking, and computation challenges, and examines blockchain solutions to enhance interoperability, economic transactions, and resource management.
[196]	2023	An overview of the Metaverse, its technologies, applications, challenges, and ethical and social implications, with a focus on its transformative impact on e-commerce and other sectors.
[197]	2024	Outlines the framework of the electric digital twin grid and its applications in serving producers, prosumers, consumers, and national development.
[198]	2024	presents strategies for integrating Green Cloud Computing techniques into metaverse platforms, aiming to create sustainable and energy-efficient cloud architectures to support immersive virtual worlds.

6. Challenges in Super Smart Grid

The escalation of super smart grid technologies necessitates enhanced sensing, communication, and control strategies with increased microgrid integration. However, this integration also amplifies the susceptibility of grids to cyber-attacks. Such attacks can manipulate crucial data utilized for grid operations, potentially leading to significant malfunctions. Injecting incorrect data into the system can induce grid instability and provide financial incentives for attackers [23,199–202].

SSGs are prone to cyber-physical attacks. The study delineates three key security levels for smart grids: confidentiality, availability, and integrity. Various attack classification strategies have been explored, elucidating their impacts across different communication layers such as the physical, MAC, network, transport, and application layers. Detailed examinations of cyber-attacks on data integrity and confidentiality are also provided in [48,203].

Security mechanisms outlined in [204] offer protection for numerous information objects within the SG. Vulnerabilities of these objects are simulated, demonstrating their effects using defined performance metrics. Additionally, the deployment framework for sensors and actuators, crucial for Industry 4.0 services and management, is discussed in [205], enhancing system robustness and reliability.

Cyber-attacks on the generation side can manipulate automatic voltage regulator (AVR) set-points, and governor settings impacting frequency and active power control. Transmission control-side attacks can disrupt FACTS device operations, state estimation algorithms, and wide area monitoring systems (WAMS). Similarly, attacks on distribution systems can influence load-shedding and demand-side management strategies. Once these effects are understood, supporting methodologies are implemented to detect and mitigate cyber-attacks. Emerging research challenges in smart grid cybersecurity, as discussed in [206] encompass risk modeling, mitigation algorithms, coordinated attack defense, AMI security, trust management, attack attribution, and validation of incoming data.

Managing data in the metaverse involves addressing multiple challenges [196] due to the diversity of data formats, including structured data, location information, and multimedia each requiring distinct management and storage methods. Current methods, such as data compression, streaming, and cloud storage, are limited by processing power, data size, interoperability issues, and network bandwidth [25,207].

To understand the metaverse potential, new requirements must be met: scalable infrastructure, enhanced compression algorithms, efficient data management, and seamless integration of various data types. Technical challenges like user experience optimization, real-time rendering, and data synchronization also need resolution. Additionally, decisions regarding the treatment of physical and virtual data—whether separate or unified—impact data organization and performance [178]. Integrating diverse data sources and developing innovative solutions beyond conventional heterogeneous databases is crucial. For context-aware scenarios, the development of context-aware algorithms, novel operators, and new approximation operators is essential [208]. Table 5. Super Smart Grid challenges and solutions.

Table 5. Super Smart Grid challenges and solutions

Parameters	Grid Challenges	Solution via Enabling Technologies
System Monitoring	Remote monitoring and maintenance of assets	Immersive and real-time monitoring and maintenance using metaverse
Energy management solution (EMS)	High computation	Through virtual power plants, simulation and optimization help in EMS
Contingency	Ability to detect gaps and loopholes in the event of contingency	Virtual visualization of the system helps in pre-planning and detecting loopholes
Interoperability [209][210]	Variety of software, hardware, and network protocols as well as user inputs	Maintain standards and regulations, pre-testing system virtually
Network and communication requirements [171,211]	High-bandwidth connectivity requirements and responsiveness	Upgradation of network infrastructure with automation
Security and Privacy [212,213]	Grid and user data require high-security measures and protection	Creation of a doable privacy policy for metaverse that ensures user-to-user privacy. Employing enhanced multi-factor authentication method [214].
Data Management [215]	Large volumes of data need to be processed and integrated. Also, heterogeneous storage needs increased	Design algorithms that are context-aware and novel approximation operators. Use pf AI, IoT, and fast computing methods.
Governance and Law [216]	Traditional institutions and physical premises are required for resolving conflicts. Well-crafted Energy and Power policies require that address every problem.	A decentralized governance system for virtual space having a transparent conflict resolution system. Policies are crafted with the support of generative AI.
Monetarily Transactions	Traceable transactions with high-security measures	Blockchain ensures the immutability of transactions and storage. Transactions would be virtual, encrypted, and anonymous.

Enforcing laws in the metaverse presents significant challenges due to its virtual nature and the use of anonymous, encrypted cryptocurrency transactions [145,182]. This anonymity complicates accountability for data theft. Metaverse lacks consumer protection and traditional regulation, as physical institutions for handling complaints are absent. New legislation is needed to address virtual crimes, but determining jurisdiction and enforcing these laws is challenging. This is due to the intangible nature of virtual assets and conflicts arising from differing legal frameworks. Additionally, the metaverse introduces specific challenges for smart cities, including privacy breaches, unauthorized access to virtual infrastructure, especially data manipulation, and the need for comprehensive security measures to safeguard both physical and virtual modules. Addressing these issues is essential for ensuring user safety in the metaverse.

Super smart grids comprising extensive energy internet of things (EIOT) have to face critical challenges like data security, privacy as well as latency issues [217] due to high computation volume. For this purpose, authentication schemes were employed with the help of two-factor authentication (2FA), ID-based single-factor authentication schemes, and Public Key Infrastructure (PKI) [218,219] [220,221]. Realizing super smart grids in the metaverse, high latency will create problems with the validity of data such as payment information. One way to manage the unbalanced computational capability (between client and server) is to use low-latency authentication and key exchange protocol LLAKEP [222].

Data uncertainty is a significant concern in designing super smart grids. It encompasses issues such as consistency, completeness, and accuracy. However, challenges arise due to missing or inconsistent values, noise, unsynchronised data, cyber-attacks, physical damage to devices, sensor inaccuracies, and other factors, leading to erroneous real-time decisions [24]. Ensuring data availability and public trust are significant challenges in the adoption of incentive-based smart grids [223–225]. Data analytics and data mining can be the foremost options to resolve such data uncertainties. Other challenges include data security, privacy [201,225,226], integrity, authenticity, latency, throughput, anomaly issues, and real-time pricing [227–231][63].

Efficient energy management in the Metaverse requires overcoming the challenges of integrating virtual and real spaces while optimizing the energy utilization in the network [232]. Key issues include managing energy transmission between these domains, calculating consumption accurately, and optimizing energy use. Addressing these challenges such as Green Metaverse Networking [233], is essential for the power system to effectively support the demands of artificial intelligence and the Metaverse. However, significant work needs to be done in exploring and developing solutions for future power grid challenges.

7. Future Research Direction

The challenges associated with transitioning to a grid focused on transactive demand signals are substantial, particularly in terms of retail tariffs. Retail tariffs currently comprise various components, including energy generation costs, transmission and distribution costs, market operation costs, and retailer operational expenses. Moreover, they often encompass the costs of complying with federal regulations, such as those related to environmental and social initiatives like green energy incentives and efficiency programs. Implementing a system based on transactive demand signals would require reconfiguring these tariffs to accurately reflect the dynamic nature of energy consumption and production, which could pose significant logistical and regulatory challenges. The literature is void of optimal grid operation in the event of energy trading in an SSG environment when multiple nodes are involved. Also, the evolution of energy markets in SSG should be studied in detail for real-time price signaling, energy volatility, and consumer behavior.

SSGs are largely interconnected and even slight load variability could make a huge impact on system stability. This load variability creates voltage fluctuations and frequency in the system. Moreover, the incorporation of abundant inverter-fed RER reduces the inertia of the system in the event of load fluctuations. Hence, the need is to devise a decoupled control strategy inclusive of the inertial dynamics of the system for both voltage and frequency deviations. A study should be done on the inclusion of non-linear devices in sophisticated inertial systems in super smart grids. Addressing reliability concerns associated with Renewable Energy Resources (RERs) and the unpredictable discrepancies between demand and generation responses presents challenges in Sustainable Smart Grids (SSGs). Achieving load flow equilibrium and transient stability becomes particularly complex, especially in scenarios of unexpected outages such as three-phase faults (L-L-L), which induce power quality disturbances [28].

The emergence of the metaverse raises legal concerns regarding the enforcement of laws across different jurisdictions, the absence of regulations, and the need for consumer protection within virtual businesses. Addressing these challenges is crucial for governments to oversee commercial transactions and determine jurisdiction for resolving disputes involving intangible assets in virtual realms. It is imperative for all stakeholders to carefully deliberate on these issues moving forward.

As SSGs rely on the integration of various technologies such as HVAC, FACTS devices HVDC, etc. [234], interoperability emerges as a significant research challenge. Ensuring the seamless operation of SSGs' power infrastructure necessitates addressing the coexistence of diverse components amidst the interconnection of numerous heterogeneous standards and technologies.

Engaging various societies and organizations in the development of future Sustainable Smart Grids (SSGs), and power grid infrastructure will render the interdisciplinary research. This entails integrating wireless sensor networks, communication networking technologies, and actuators with power systems infrastructure. Additionally, attention is focused on implementing cooperative control strategies and security protocols within the SSG's power infrastructure.

Considerable research is currently underway to advance smart grid technologies. However, numerous opportunities exist for future exploration across various domains within the smart grid field. These areas encompass forecasting, power flow optimization, communication protocols, integration of micro-grids, development of demand and energy management systems, standardization for interoperability, economic considerations, scalability, data security measures, and notably, the automation of electricity production, transmission, and distribution processes.

To effectively implement, operate, and regulate SSG transactive energy systems a robust legal framework is necessary. This framework should encompass privacy standards and data integrity, mechanisms for energy transactions, customer participation contracts, and transparent rules for market price clearing. The analysis of transactive energy systems should extend beyond real-time balancing to include day-ahead management and ancillary services such as frequency stability and voltage regulation. Simulation and emulation tools are essential for identifying and addressing practical challenges before implementation. Optimal deployment of information and communication infrastructure, considering investment and maintenance costs, bandwidth, and coverage, is crucial for efficient energy transactions and data sharing. Additionally, defining interoperability standards for various distributed ledger technologies and enhancing network security with strong cryptographic measures are vital to ensuring customer privacy, data integrity, and protection against cyber attacks. These recommendations will support the transition from conventional power systems to decentralized smart grids and then all the way to super smart grids, improving scalability, resilience, reliability, and sustainability.

Conclusion

This study contributes to the acceleration of the development of super smart grids by employing a new approach and exploratory super smart grid innovation from the perspectives of policy and governance. The study's findings can assist policymakers in developing unified strategies to address previous shortcomings in policies aimed at fostering the transition to super smart grids. Qualitative analysis plays a crucial role in this review, particularly in examining the regulatory frameworks and policy interventions across Europe. This analysis delves into the effects of market liberalization, the impact of blockchain on decentralized energy transactions, and the role of 5G and IoT technologies in supporting super smart grid operations. Furthermore, the study explores the socio-economic impacts of these transitions and emphasizes the importance of stakeholder involvement in the policymaking process.

Energy transactions in super smart grids facilitate dynamic pricing, enabling consumers to respond to real-time price signals and balance energy demand. They support decentralized energy production and peer-to-peer trading, enhance grid efficiency through automated controls, and integrate renewable sources by managing their variability. These transactions also boost energy security with microgrids, aid in decarbonization by optimizing resource use, and incorporate electric vehicles as flexible energy storage solutions.

Finally, the paper conducts a thorough technological assessment, evaluating solutions such as AI for predictive analytics and the application of the metaverse for simulating and optimizing energy systems. This assessment discusses both the potential benefits and the challenges these technologies present in enhancing grid efficiency, security, and resilience. By employing this multi-faceted approach, the study aims to present a widespread understanding of the current state of affairs and prospects of transitioning to super smart grids in Europe, emphasizing the critical interplay between technology, regulation, and economic factors.

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