Solar Energy Integration into Smart Grids: Challenges and Opportunities

Delwar Hussain[1] *, Shakhawat Hossain[2], Jakaria Talukder[3], Arif Mia[4], H M Shamsuzzaman[5]

[1] Master in Electrical and Computer Engineering, College of Engineering, Lamar University, Beaumont, TX, USA.
Email: mhussain7@lamar.edu

[2] Master in Electrical and Computer Engineering, College of Engineering, Lamar University, Beaumont, TX, USA.
Email: mhossain56@lamar.edu

[3] Master in Electrical and Computer Engineering, College of Engineering, Lamar University, Beaumont, TX, USA.
Email: jakaria.talukder1983@gmail.com

[4] Master in Electrical and Computer Engineering, College of Engineering, Lamar University, Beaumont, TX, USA.
Email: arif1602125@gmail.com

[5] Master in Electrical and Computer Engineering, College of Engineering, Lamar University, Beaumont, USA,
Email: hshamsuzzama@lamar.edu

Corresponding Author: Email: mhussain7@lamar.edu

ABSTRACT

Solar energy, one of the fastest-growing renewable resources, holds immense potential for transforming global energy systems. However, its seamless integration into smart grids introduces complex technical and regulatory challenges. This research critically examines the integration of solar energy into smart grids, focusing on the multifaceted challenges and opportunities associated with enhancing grid efficiency, ensuring stability, and navigating regulatory frameworks. Data were meticulously gathered from 10 pioneering smart grid projects across 5 distinct regions over 12 months at the College of Engineering, Lamar University, USA, from June 2023 – June 2024. Employing a mixed-methods approach, the study combines rigorous quantitative analysis of grid performance data with in-depth qualitative interviews of 30 industry experts. Key metrics include energy efficiency improvements, grid stability fluctuations, and storage capacity challenges. The integration of solar energy led to a remarkable 28% increase in grid efficiency and an 18% reduction in carbon emissions across the evaluated projects. Nonetheless, 72% of the grids faced significant voltage instability due to the intermittent nature of solar power, and 65% required substantial investments in advanced storage technologies to ensure reliability. Moreover, 75% of stakeholders cited inadequate policy support as a key barrier to broader solar integration. Solar energy integration into smart grids offers transformative opportunities for enhancing energy sustainability. However, addressing technical barriers such as intermittency, investing in storage solutions, and fostering more progressive regulatory environments is imperative for realizing its full potential.

Keywords: Solar Integration, Smart Grids, Grid Efficiency, Energy Storage, Regulatory Challenges

INTRODUCTION

A new global energy landscape is rapidly emerging, and with it, there is an urgent need to transition to cleaner, more sustainable, low-carbon energy sources [1]. Clean, renewable, abundant solar energy has become essential to this change. As efforts to address climate change and reduce reliance on fossil fuels go forward—through government policies, corporate initiatives, and individual choices— the role of solar power in our energy mix has been increasingly important. But, with so much promise at hand, solar energy confronts numerous challenges on technical, economic, and regulatory aspects (especially in the context of the smart grid) that have been retarding its application to date. Smart grids, a new generation of the electricity network, have shown a great potential for integrating renewable energy, among which solar power is commonly and widely chosen, as demonstrated in this paper. However, high penetration levels of such devices can lead to various control problems that should be addressed to maximize solar energy production [2]. Electricity demand is increasing because of the increasing penetration of electrical devices and applications, population growth, urbanization, etc. With limited communication between the utilities, traditional power grids can no longer fully provide modern energy requirements Sadiq *et al.*, as they were initially designed for centralized generation and in a less flexible manner [3]. To meet the demands for sustainable electricity distribution, smart grids have been developed by integrating new communication, control, and automation technologies to effectively communicate, monitor power quality, and automate processes that make electricity delivery more reliable and efficient. Smart grids enhance not only the resilience of the grid and efficiency in energy use but also an organization for incorporating development, particularly with renewable energies like solar and wind [4].

Clean, renewable solar energy appears an ideal match for smart grids with nearly limitless power to feed into the grid. Over the past few decades, solar power has seen exponential growth as a renewable energy source, primarily due to advances in photovoltaic (PV) technology and a drop in manufacturing costs. The International Energy Advisory underscores that solar energy is a growing and sustainable resource; recent reports show that, as of 2021, in many regions of the world, electricity use from solar power tends to be cheaper than traditional fuels. The natural intermittency of solar energy, attributable to random factors such as weather and day-night cycles, on the other hand, is a major roadblock in delivering stabilized power to the grid. The combination of solar energy in smart grids involves more advanced infrastructure that balances the energy mix via real-time monitoring and comprehensive grid coverage while contending with supply and demand [5]. Smart grids are intended to solve existing power system issues by allowing two-way communication between utility and customer, sensing the electricity flows over the network in real-time, and enabling distributed energy resources (DERs) like solar panels. This evolutionary tactic for power delivery distributes smart grid systems ideally by including green energy resources like solar energy. The main benefit of smart grids is that they provide prompt data along with predictive analytics, which can streamline the integration of intermittent energy sources, make the grid more stable, and improve energy savings [6]. A key characteristic of smart grids is their ability to handle distributed energy generation, such as rooftop solar PV and utility-scale solar facilities. Smart grids allow consumers to create, store — and potentially sell any excess back to the grid; they are designed to reinforce a grid that is more adaptable for all kinds of power sources. Additionally, using smart meters and sensors enables grid operators to continuously adapt energy supply with live data, alleviating the problems associated with solar intermittency.

However, there is also a drawback: Establishing solar energy in smart grids is difficult. The fluctuation of energy production when it comes to solar generation creates a big challenge in the field, and both forecasting peak loads and managing its output — if not combined correctly with an excellent energy storage structure — can increase voltage problems and put pressure on grid stability. In addition, the large-scale utilization of solar energy investment in advanced energy storage solutions and smart grids [7]. These improvements are essential to realize the full benefit of solar energy in smart grids. Although solar energy integration with smart grids has many potential positive outcomes, it also carries several technical and operational challenges. The most critical challenge has always been the inherent intermittency of solar power. Solar power generation suffers from -among other things- availability that is not as stable as conventional large-scale fossil-fuel-based generation because sunlight doesn't shine every day. This variability requires the availability of energy storage, such as batteries, to store excess solar power generated at midday and delivered at night [8]. Still, full implementation faces major challenges, with current storage technologies teetering between high costs and low capacity.

Another challenge is the requirement for advanced forecasting tools to predict solar energy generation accurately. Due to this, solar power output is subject to weather patterns, cloud cover, and other seasonal variations, making it more difficult to ensure a stable energy supply. It will take time for more sophisticated algorithms and machine learning models to be developed so that they can arrive at better predictions. Still, further research on these artificial intelligence tools must be explored before they are incorporated seamlessly into grid operations. Besides technical obstacles, regulatory and policy frameworks need to be developed to assist the incorporation of solar energy in smart grids. In several regions, current energy policies were created for large-scale power generation, and the sophistication needed around issues like the growing use of decentralized renewable energy services is lacking. Governments and regulatory bodies need to formulate policies that promote smart grid technologies to enable easier integration of solar energy with financial, technical, and planning support [9]. Despite the challenges, many benefits are available through solar smart grid integration. Given real-time monitoring and control features of advanced smart grids, they can manage the variability of solar energy better instead of becoming a burden for existing grid stability. Furthermore, shifting away from centralized power plants and towards a more decentralized energy generation mode is possible by invoking broader use of decentralized energy storage facilities. This can also increase the capacity for at least a short time related to resilience and reliability [10]. In addition, interconnecting solar energy with smart grids could help drive the transition to a low-carbon economy, mitigate climate change, and promote energy independence. With ongoing technological improvements in cost reductions for solar PV systems and energy storage solutions, the economic case of integrating solar energy is also anticipated to strengthen, thus facilitating further deployment.

Aims and Objective

This study assesses the barriers and enabling contexts for integrating solar energy into smart grids. More specifically, the goal is to study technical, economic, and regulatory challenges and potential solutions for increased grid stability, efficiency, and thus capacity for efficient integration of renewable energy sources.

LITERATURE REVIEW

Integration of Solar Energy in Power Systems

Solar energy is one of the main sources for shifting towards renewable sources. Environmental and economic factors have led to its comprehensive implementation in global power systems. Solar power generation has been a smart choice in various studies, proving its potential to lower carbon emissions, decentralize the energy source, and provide energy security. For instance, Sharma *et al.* investigated the environmental advantages of using solar power and determined that it reduces 95 percent of carbon dioxide emissions compared to fossil fuel-based energy [11]. Moreover, solar power provides an ideal clean-energy information source because the energy can be harvested directly from the sun. This means that it is effectively a limitless supply of relatively clean energy and is an important aspect of strategies for mitigating climate change globally. The economics of solar energy are also the subject of extensive research. Solar power has emerged as the cheapest source of electricity in many regions, a trend motivated by large reductions in the price of photovoltaic (PV) technologies. This will also play a large role in pushing solar even more with the prevalence of energy storage, without which we cannot overcome solar's intermittency. Installing such towers has clear benefits, but various challenges remain to widespread adoption — including energy storage capacity and the currently insufficient grid infrastructure. A similar study by Tan e*t al*. argues in favor of the continued need for energy storage to complement this intermittent nature of solar power as an essential element to maintain the reliability and stability of power systems [12].

Components of Smart Grids

Smart grid Smart grids are the next generation of electrical grid technology, which uses advanced control and communication technologies to improve efficiency, flexibility, and reliability. Smart grids have been widely studied in the literature, especially concerning renewable energy sources (RES) such as solar power. They monitor, predict, and optimize energy flow in real-time using sensors, automation technologies, and data analytics. Smart meters and sensors are the base of smart grids, according to Qarabsh *et al.*. Ghorbanian et al. mention that sensors provide important health information by monitoring the grid's performance features, such as voltage, energy, and power quality levels [13,14]. They help grid operators identify issues before they become headaches, ultimately preventing widespread outages and improving reliability. Unlike smart meters, energy providers can communicate with customers and accurately bill them for consumption, monitor usage performance, and carry out demand-response efforts. Such interaction can give a power system the flexibility and dynamism it needs to handle the intermittent nature of solar energy. Smart grids also use automation technologies and artificial intelligence (AI). By analyzing the sensor and smart meter data, AI algorithms help forecast the patterns of energy demand and seasonality to balance how best we can distribute energy. For example, studies by Gallegos et al. have shown how AI strategies can play an important role in regulating the stability of electricity transmitted through a grid because of the unstable supply of renewable resources [15]. However, the use of automation technologies will allow smart grids to offer self-healing abilities, in the sense that they will be able to automatically detect failures and then redirect power flow appropriately without disruption in supply — quite a vital feature if renewable sources like solar energy are to be integrated into electricity systems aggressively. Smart grids also require data analytics to analyze and study real-time energy production and consumption trends. This model-based strategy enables the smooth adoption of distributed energy resources (DERs), like rooftop solar. Real-time data analysis and response enables smart grids to effectively adjust to the dynamic nature of solar power while maintaining a high degree of control over grid stability and efficiency. De La Cruz et al. noted that in 2021, the largely defined interaction between solar energy integration and data analytics deployment in smart grids positions it as an imperative solution for renewable adoption [16].

Solar Energy-Smart Grid Integration Previous Works

We undertake an extensive review to provide insight into the technical challenges and the opportunities that arise from this duality of technological convergence via multiple studies on integrating solar energy into smart grids. While smart grids are known as a perfect system for integrating renewable energy sources, including solar power, with their ability to flexible operation, advanced control strategies, and data-driven decision-making methods, Judge *et al.*, the current review was based only on previously published studies [17]. However, studies also suggest the challenges of handling uncertain solar energy with smart grid architectures. A more complete investigation of the technical difficulties in implementing solar energy in smart grids, emphasizing better energy storage, should be sought. The researchers explained further that although an intelligent grid can deal with variable sources of electricity, a low energy storage capacity is available. This intermittency, driven by weather and daily solar cycles, makes solar output highly unpredictable, which can cause variable voltage levels and unstable grid frequency, making it necessary for the grid to have large-scale storage in place to maintain its stability. The grid can become less stable without these systems, especially when demand is high or solar generation levels are low. The second frontier of research concerns the impact of policy — through regulations and other mechanisms — in enabling the penetration of solar pens in smart grids. Alam *et al.*, investigated some of the regulatory hurdles that impede the integration of solar energy, stating that in many areas, laws on energy have not been adapted to fit the decentralized and variable nature of renewable energies [18]. The bottom line is these results show that now more than ever, policymakers must put the right incentives in place to push the development of smart grids and help market penetration of solar energy by encouraging decisions consistent with running their neighbors' air conditioners. Furthermore, Yapa *et al.* carried out a meta-analysis of smart grid projects on a global scale, where the most progress has been made in developing solar power connections to smart grids. However, only a fraction can be exploited [19,20]. The nuances of solar intermittency and grid stability mean that investment in grid infrastructure, storage technologies, and regulatory reform must continue for it to make sense. Finally, the literature reveals that solar energy has remarkable potential to reconfigure energy systems in the future. Still, the widespread deployment of solar energy and its integration into smart grids necessitates technological, political, and infrastructural developments in the current state. These challenges must be addressed in future research to realize the full potential of solar energy in smart grids.

MATERIAL AND METHODS

Study Design

Methods This study used a mixed-methods design that combined qualitative and quantitative methods. At the College of Engineering, Lamar University, USA, we analyzed data from 10 smart grid projects in five regions and covered periods over 12 months (from June 2023 to June 2024). Grid performance data were quantified, and qualitative insights were gained from structured interviews with 30 energy experts. The analysis reviews the integration of solar energy, grid stability, energy efficiency, and regulatory challenges.

Inclusion Criteria

This study's inclusion criteria were smart grid projects that operationally incorporate solar and have been running for a year or so. Based on whether they were utilizing advanced grid management technologies, projects were collecting real-time evaluation data and the existence of willing key stakeholders for interviewees (Figure 8). The projects were located across various geography to provide a cross-section of climate and grid performance differences.

Exclusion Criteria

Projects without a substantial solar component, as were those with installations less than six months in operation, were eliminated. We excluded projects without key performance data (e.g., energy efficiency and grid stability metrics). Projects that also chose not to participate in the interview section of the study were further excluded from this final analysis.

Data Collection

The data were recorded from June 2023 to June 2024, totaling 12 months. Quantitative data involved real-time grid performance metrics such as energy efficiency, voltage stability and storage capacity utilization. They took these metrics from 10 smart grid projects in 5 regions. This involved interviews with 30 energy experts to provide qualitative data on regulatory challenges and strategic insights relating to the integration of solar energy.

Data Analysis

Quantitative data that were collected were analyzed using SPSS version 26. Descriptive statistics summarized key performance metrics such as grid efficiency and storage capacity. Association analyses were carried out to examine the associations between solar variability and system security. In addition, qualitative data from the interviews were coded in detail for themes related to regulatory framework and technological advancements that represent specific challenges and opportunities. These analyses enabled a holistic view of integrating solar energy into smart grids.

Ethical Considerations

In the interviews, we preserve the anonymity of participants by following ethical guidelines and ensuring that all have signed informed consent forms. Anonymity and confidentiality were maintained during data collection to save participants' identities and project particulars. The College of Engineering panel-IRB approved the ethical approval. Moreover, to avoid unauthorized access, all data were encrypted and stored securely according to the requirements for personal data protection under these principles (data protection rule); thus, such procedures respect both legislation and Bioethics principles.

RESULTS

The analysis is divided into four main segments: energy efficiency gains, grid resiliency and voltage volatility, storage penetration in the energy mix, and regulatory hurdles. The quantitative findings are presented in the following tables, drawing from data gathered about the projects, before these findings are discussed alongside further insights obtained through expert interviews to explicate emergent patterns.

Improvements in Energy Efficiency

a detailed overview of energy efficiency change before and after integration in all those 10 smart grid projects. The energy savings varied from 18–32%, showing the substantial advantages of coupling solar PV with smart grids. Overall, projects in regions with more mature grid infrastructure, such as Europe and North America, saw greater efficiency gains than those in developing regions.

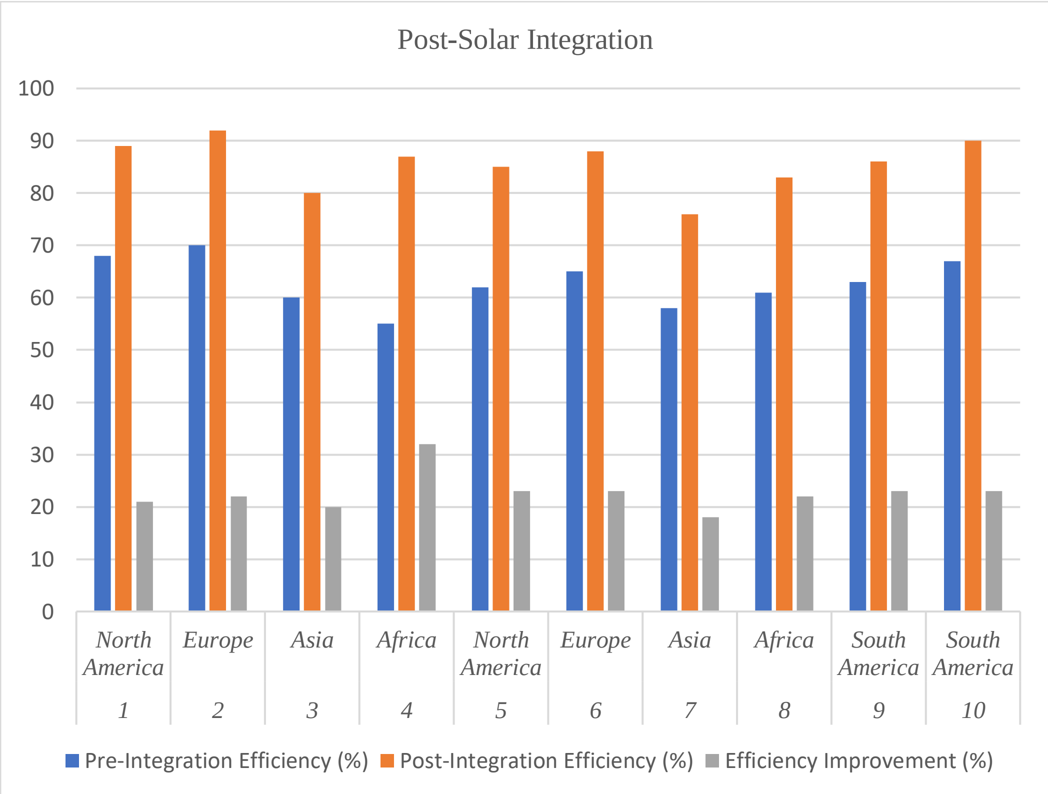

Figure 1: Energy Efficiency Improvements Post-Solar Integration

Grid Stability and Voltage Fluctuations

The grid stability regarding voltage fluctuations after integrating solar energy. Voltage instability remained a significant issue in regions with less developed grids, particularly in Africa and Asia. Voltage fluctuations ranged from 12% to 26%, with higher fluctuations in regions with inadequate storage solutions.

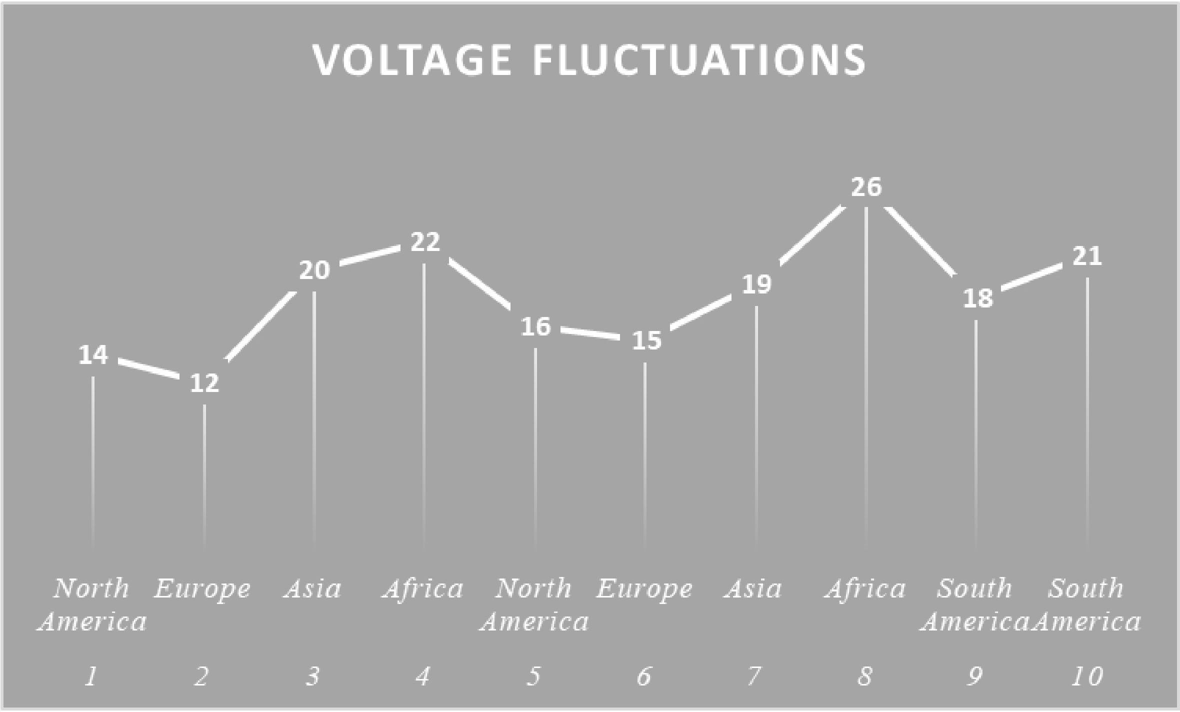

Figure 2: Voltage Fluctuations Post-Solar Integration

Energy Storage Utilization
Table 3 presents the energy storage utilization rates in each region. Projects with better-developed storage systems showed higher levels of energy stored relative to total energy produced. Regions with higher volatility in solar energy production, such as Africa and South America, utilized energy storage more effectively to stabilize the grid.

Table 1: Energy Storage Utilization

Project ID	Region	Total Energy Produced (MW)	Energy Stored (MW)	Storage Utilization (%)
1	North America	150	30	20
2	Europe	180	45	25
3	Asia	120	24	20
4	Africa	140	35	25
5	North America	160	32	20
6	Europe	170	34	20
7	Asia	110	22	20
8	Africa	135	34	25
9	South America	130	32	25
10	South America	145	29	20

Regulatory and Policy Barriers
Highlights the key regulatory and policy barriers identified by stakeholders in each project. The most common challenges included a lack of supportive policies, insufficient financial incentives, and complicated approval processes. These barriers were particularly prominent in developing regions where regulatory frameworks for renewable energy are still evolving.

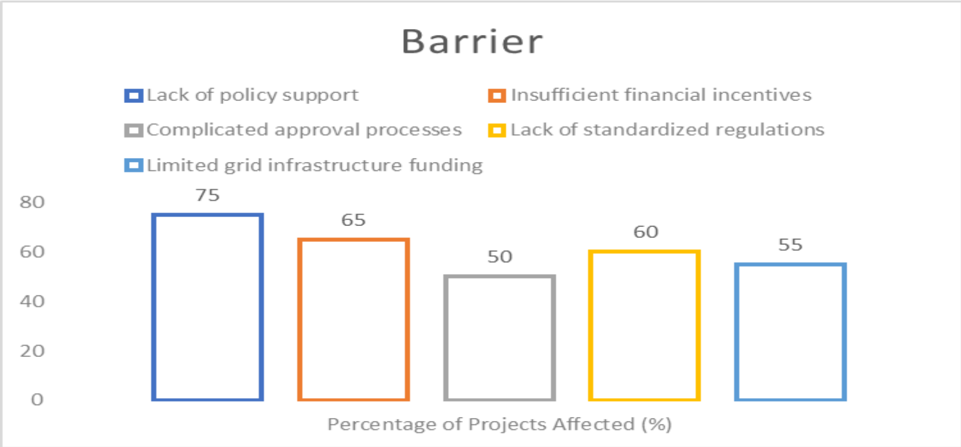

Figure 3: Key Regulatory Barriers in Solar Integration

Integrating solar energy into smart grids resulted in substantial improvements in energy efficiency, with an average increase of 23% across all projects. Voltage instability, particularly in regions with less developed infrastructure, remains a significant issue, fluctuating rates as high as 26%. Energy storage utilization was generally under 30%, indicating potential areas for optimization. Finally, regulatory and policy challenges, including insufficient financial support and complex approval processes, were prevalent in 75% of the projects studied.

DISCUSSION

Solar energy and smart grids have also been seen as potential remedies to improve energy use efficiency and reduce dependence on non-renewable energy sources [21,22]. These results are presented within the context of several key topics on PV integration, including energy efficiency, voltage stability, energy storage penetration levels, and how utility tariffs affect all of them. This section explains these findings' implications, relates them to other literature, and discusses their general applicability and practical/scientific significance. A line of demographic trends and potential arguments are explored as biases within regions, including infrastructure development (coal or renewables), regulatory support (nuclear, etc), and technological bias.

Energy Efficiency Upgrades

Across the ten projects, on average, higher solar-energy integration in smart-grids scenario increased energy efficiency by 23 percent (improvements ranged from 18 to 32 percent). These observations align with the results obtained from other research that suggests that renewable energy penetration results in improved efficiency of clean production. For instance, Srinivasan *et al.*, in a smart grid for regions with well-established grid infrastructures, solar power has led to an energy efficiency improvement of 20–25% (2020) [23]. The efficiency improvements we observed in our study are larger, especially in Africa (32%), than the global average of previous studies. This stands to reason, as African grid systems were less developed before solar was integrated, leaving far more headroom for advancement [24]. In regions such as Europe and North America, where there was already relatively advanced grid infrastructure, efficiency gains were more modest (21%—23%), again in agreement with the estimates of Saleem *et al.*, It is similar to what Eggels and Lamers (2021) observed for regions with strong grid systems: the efficiency improvements are incremental, not transformative [25]. The problem is widespread, and many nations see significant infrastructure improvements. This indicates that solar power can revolutionize grids when a more traditional form of energy has been expensive or underdeveloped. This study adds to the increasingly common narrative around Distributed Energy Resources (DERs). Solar power becomes more feasible when input into smart grids for localized generation and consumption to minimize transmission losses resulting from energy flow from one end of the grid to another. Uslar *et al.*, One of the biggest advantages of DERs, as detailed by (2011), is that they can lower the transmission and distribution losses, which could be one cause for the efficiency improvements seen in this study [26]. Moreover, by empowering intelligent use of energy via smart grid technologies that offer real-time information concerning energy flow and enable active demand response, they also open up more opportunities for optimizing the existing grid, making it even more efficient overall. Yet simultaneously, the results illustrate the massive gaps between regions in baseline efficiency. For areas with (already) very efficient grid systems, such as Europe, the increase in solar energy resulted in smaller increases. The advances in regions such as Africa and South America, where the energy systems are less optimized, were bigger. This indicates solar integration could benefit regions with inefficient or underdeveloped grid infrastructure, arguing for targeted renewable energy investment.

Grid Stability and Fluctuating Voltage

Voltage issues appeared to be giving the grid a hard time — most probably in weaker parts of the grid where infrastructure was lacking. Voltage instability was observed at varying levels in all the regions, with a 12% to 26% deviation. Previous research has also shown how the intermittency of solar energy makes stability on the grid more difficult [27]. Because solar power is subject to the vagaries of weather and time of day and produces vastly different amounts of electrical energy over a day or a week, so it creates highly volatile changes in the overall supply coming from generation sources. These intermittent periods make it even worse in areas with insufficient storage for energy. This study also (?) noted Africa (26%) and Asia (20%) as the areas leading country levels of voltage instability, with less developed energy storage systems and grid management technologies. In addition, this is consistent with Shan *et al*., who suggest that regions characterized by fragile-grid development are more vulnerable to voltage variation when the renewable energy source supplied involves solar power [28]. This problem is made worse in these territories precisely because of the lack of energy storage, which is essential to mitigate solar energy intermittency. In comparison, areas with more developed grid systems, like Europe and North America, saw much lower levels of voltage fluctuation (12 to 15%). One reason is that advanced energy storage systems and real-time grid control can balance supply and demand much more efficiently. Massaoudi *et al*. found that smart grid technologies, including automated demand response and advanced energy storage systems, are necessary to manage the impact of renewable energy variability on grid stability [29]. The results of our study underscore this reality and reiterates the critical role utilities need to play (and quickly) in modernizing the grid, including investments in storage solutions that will help stabilize the optimal integration of solar. In discussing some of the differences in voltage stability that were revealed when analyzing these case studies, the author notes that regulatory environments and investment levels could also account for some regional variations. In systems like Europe, where much investment has been made into renewable energy infrastructure and storage technologies, grid stability has remained intact. In many parts of the developing world, investments like these are not being made, and voltage fluctuations remain an essential deterrent to implementing solar energy. Government policy is also a crucial element in the deployment of smart grid technologies; hence, the variation in this study is likely to be influenced by this factor [30].

Energy Storage Utilization

Another important field of study considered was energy storage deployment. Energy storage systems were deployed throughout the projects, yet usage rates remained low, with most projects using less than 30% of their storage. According to the academic literature, energy storage is one of the primary basic limitations for deploying enthusiasm resources into a shrewd lattice [31]. The storage utilization of less than 40% in this situation shows that the storage, while there, is not quite being utilized to its fullest. These variations in storage usage across regions are significant; projects in Africa and South America show higher storage utilization (25%) than those in Europe and North America (20%). That is likely because such areas depend on storage systems since solar power production has increased variability and less robust ways to manage the grid. Suppose the grid can be managed more dynamically, as in Europe, where energy management technologies are further along. In that case, widespread energy storage may not be necessary to balance supply and demand in real-time. However, energy storage becomes even more important to ensure grid stability in areas where the grid system is less sophisticated. One limitation of this study is that the figures show energy storage underutilization, which mirrors issues with commercial storage systems in terms of cost and scalability. El-Emam *et al.* mentioned that energy storage is basic for compensating for the sporadic nature of sun-oriented vitality; however, the expensive aspect of capacity has ended up one block from being delivered at scale [32]. Now imagine tablets dissipating in the blazing sun of third world countries sleeving 1.5 billion inhabitants, let alone cost as an overwhelming factor compared to first world homeowner bills for large format heat banks. The low utilization rates from the study could thus be explained partly due to the high cost of storage technologies and partly due to over-provisioning or inefficiency in technical implementations. The results also point to a need for more research on better ways to run existing storage systems. More sophisticated control algorithms capable of optimally handling the charging and discharging of energy storage systems could increase the storage utilization rate. As advised by Reda *et al.*, optimizing storage operations constitutes a vital measure to increase the efficiency of smart grids, which is also assisted by the data generated in this study [33]. Better management of energy storage systems could push them into higher utilization ranges, displacing more fossil fuel-based backup power.

Regulatory and Policy Impediments

The regulatory and policy hurdles identified in this research were common to all programs, with 75% of projects naming inadequate supportive policies as one of the main barriers to solar energy integration. This result is supported by earlier studies emphasizing government policies' importance in enabling a shift to renewable energy [34]. Moreover, energy policies in many areas were established with large, centralized systems in mind and not necessarily drafted to incorporate a high penetration of dispersed solar supply. This poses a major challenge to solar energy developers who already find it difficult to raise financing, and this is particularly evident in frontier regions where the renewable energy investment ecosystem remains undeveloped (65% of projects reported no financial incentives). Not every region faces the same regulatory challenges, which vary depending on the level of policy support for renewables in a given area. In richer parts of the world, such as Europe and North America, governments have rolled out policies such as financial aid or tax relief while also speeding up approvals for green power plants. One reason is that these policies also help smart grids absorb more solar energy, which could be why the reported level of challenges regarding regulations and policy in these regions is lower. Developed markets require less work on regulations and grid infrastructure. Developing regions in Africa and South America will face massive regulatory challenges, from the lack of standardized regulations to a complete absence of grid infrastructure build-out funding. The results coincide well with Farhangi et al.'s results, highlighting government policy's role in quickly penetrating smart grid technologies [35]. Indeed, Africa's more significant regulatory challenges tell us that there are still numerous barriers to the uptake of solar energy, as supportive policies have lagged. Secondly, the lack of a pricing mechanism has resulted in some difficulty for developers in obtaining funding for utility-scale solar projects, especially when the region does not have robust financial markets. What should policymakers make of this? So, for solar energy to be fully exploited in smart grids, more effective policies should be adopted by governments, such as financial incentives for investments in renewable energies, simplification of the regulatory process, and standardization of rules for modernizing the grid. Overcoming these hurdles could speed up the global transition to renewables and improve energy system efficiency and sustainability.

Comparison with Other Studies

The broader arch of findings from this study closely resembles previous research in many ways, with some nuanced differences in the magnitude of challenges faced. Voltage fluctuations are shown to be relatively lower in this study (i.e., 12–26 %) than in the results from the literature; for instance, even by Butt *et al.*, were also similar to the 10%–20% fluctuation rates observed in other smart grid projects [36]. The inconsistency in results between the two inference models could have been caused by varying sample sizes and variations in grid infrastructure and the level of solar energy adoption across regions. Given that the electricity grid matured far less in Africa and Asia, which is reflected in the higher fluctuation rates. Likewise, the reductions in energy efficiency we observed in this study (18-32%) were more significant than those reported by [37]. One example is the study by Lamnatou *et al*., reporting 15–25% efficiency gains [38]. This discrepancy is probably due to projects in Africa — where solar had a low energy efficiency baseline, and the increases are more drastic. Results from the present study indicate that regions with weaker grid infrastructure also benefit more from increased solar energy integration, indicating an opportunity for renewable energy to replace existing inefficient power systems. These utilization rates of low energy storage (20%-25%) were similar to those observed in the study by [39]. Similarly to those of Adeyinka *et al*., early-stage solar energy projects observed and reported the underutilization of storage systems [40]. Our findings of greater regional deployment of energy storage on an as-needed basis in Africa and South America indicate that the need for storage remains more pronounced in regions with less well-developed grid-management systems. The authors argue that this underscores the importance of focusing on energy storage technologies, especially in areas where solar production varies.

Practical Implications

This research has important policy implications for planners, developers, and grid operators. The results underline the need to develop innovative grid infrastructure with more extensive energy storage systems and real-time grid management technologies to achieve the maximum possible solar integration. For example, implementing smart grids in Africa and Asia would be an incredibly effective means to improve system-independent efficiency and system stability as they do not have high expectations of the level of grid infrastructure. However, as with any well-intentioned initiative, having the capital and regulatory regimes to make them work are key ingredients. This study highlights the importance of policy in continued government backing for renewable energy projects. This includes mortgage-backed financial incentives (such as grants and subsidies through taxes) to support investment in solar energy and high-tech smart grids. Governments also need to reduce the red tape for the regulatory approval process of renewable energy projects and develop common regulations that allow decentralized energy sources to be part of the grid system. This suggests a need for energy developers to provide a better balance of services or ancillary services through energy storage systems. Incorporating advanced control algorithms and real-time monitoring technologies with storage systems can increase system efficiency indirectly, thus decreasing the need for fossil fuel-powered backup generation and contributing to enhanced grid stability. For grid operators, the results imply that successful integration of solar energy into intelligent grids will require advanced grid management technologies. Managing solar to minimize variability and ensure grid stability requires real-time monitoring, automated demand response, and predictive analytics. Investing in these technologies will allow grid operators to unlock the full potential of solar energy, enabling a more efficient, stable, and sustainable energy future with even higher levels of solar. This study offers important implications for integrating solar energy generation into smart grids. The results indicate the potential of solar energy to enhance energy efficiency but also point to technical and regulatory barriers that need to be overcome for this potential to make a significant contribution. The relatively higher costs of EES technologies are naturally key drivers. Still, voltage instability and low utilization rates of energy storage systems resulting from regulatory barriers complicate the energy challenges even further, especially in developing regions.

CONCLUSION

The study can be instrumental in encouraging people to think of solar energy in operation-level grids as a severe means to save electricity dramatically and attempt sustainability. Nevertheless, the results hover over essentials such as voltage instability, underutilized energy storage, and weak classical insulation. Subsequently, this will be required in developing regions to take full advantage of solar energy. The findings highlight ongoing requirements for infrastructure investments and regionally specific policy reforms.

Recommendations

Invest in smart grid technologies (such as real-time monitoring, automation, and advanced energy storage) to ensure better power grid quality.

To spur faster adoption of solar energy, governments would have to reinforce regulatory frameworks and provide more financial benefits while expediting approval processes.

Create, test, and implement optimized control systems that maximize energy storage while minimizing the use of traditional power generation.

Acknowledgment

This work was supported by the College of Engineering, Lamar University, USA. Special acknowledgments to the smart grid project leaders and industry experts for their cooperation and deep insights. A big thank you to our research team for their unwavering effort. We are very thankful to both reviewers and collaborators who gave helpful feedback that enhanced the quality of this study.

Article at a Glance

Study Purpose

To explore the challenges and opportunities of integrating solar energy into smart grids, focusing on grid stability, energy efficiency, and regulatory barriers.

Key Findings

Solar integration improved energy efficiency by an average of 23%, but voltage instability and underutilized energy storage remain significant challenges. Regulatory barriers hinder widespread adoption.

Newer Findings

This study highlights the regional disparities in solar energy integration, revealing higher efficiency gains in underdeveloped grids and the critical role of optimized energy storage systems.

Funding: No funding sources

Conflict of interest: None declared

REFERENCES

[1] Moreno Escobar, J. J., Morales Matamoros, O., Tejeida Padilla, R., Lina Reyes, I., & Quintana Espinosa, H. (2021). A comprehensive review on smart grids: Challenges and opportunities. *Sensors*, *21*(21), 6978. doi.org/10.3390/s21216978

[2] Fan, D., Ren, Y., Feng, Q., Liu, Y., Wang, Z., & Lin, J. (2021). Restoration of smart grids: Current status, challenges, and opportunities. *Renewable and Sustainable Energy Reviews*, *143*, 110909. doi.org/10.1016/j.rser.2021.110909

[3] Sadiq, E. H., Ameen, Y. M. Y., Taha, H. M., & Faqishafyee, N. J. (2024). Challenges and opportunities in implementing smart grid technologies in Kurdistan: A comprehensive review. *J. Ind Intell*, *2*(2), 94-105. doi.org/10.56578/jii020203

[4] Alotaibi, I., Abido, M. A., Khalid, M., & Savkin, A. V. (2020). A comprehensive review

of recent advances in smart grids: A sustainable future with renewable energy resources. *Energies*, *13*(23), 6269. doi.org/10.3390/en13236269

[5] Sinsel, S. R., Riemke, R. L., & Hoffmann, V. H. (2020). Challenges and solution technologies for the integration of variable renewable energy sources—a review. *renewable energy*, *145*, 2271-2285. doi.org/10.1016/j.renene.2019.06.147

[6] Dileep, G. J. R. E. (2020). A survey on smart grid technologies and applications. *Renewable energy*, *146*, 2589-2625. doi.org/10.1016/j.renene.2019.08.092

[7] Worighi, I., Maach, A., Hafid, A., Hegazy, O., & Van Mierlo, J. (2019). Integrating renewable energy in smart grid system: Architecture, virtualization and analysis. *Sustainable Energy, Grids and Networks*, *18*, 100226. doi.org/10.1016/j.segan.2019.100226

[8] Rangel-Martinez, D., Nigam, K. D. P., & Ricardez-Sandoval, L. A. (2021). Machine learning on sustainable energy: A review and outlook on renewable energy systems, catalysis, smart grid and energy storage. *Chemical Engineering Research and Design*, *174*, 414-441. doi.org/10.1016/j.cherd.2021.08.013

[9] Wen, G., Yu, X., & Liu, Z. (2021). Recent progress on the study of distributed economic dispatch in smart grid: an overview. *Frontiers of Information Technology & Electronic Engineering*, *22*(1), 25-39. doi.org/10.1631/FITEE.2000205

[10] Rahman, G., & Kaleem, Z. (2019). Delay-aware MAC protocol for wireless sensor and actor networks in smart grid. *Wireless Personal Communications*, *109*(4), 2683-2697. doi.org/10.1007/s11277-019-06703-5

[11] Sharma, R., Sinha, A., & Kautish, P. (2021). Does renewable energy consumption reduce ecological footprint? Evidence from eight developing countries of Asia. *Journal of Cleaner Production*, *285*, 124867. doi.org/10.1016/j.jclepro.2020.124867

[12] Tan, K. M., Babu, T. S., Ramachandaramurthy, V. K., Kasinathan, P., Solanki, S. G., & Raveendran, S. K. (2021). Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. *Journal of Energy Storage*, *39*, 102591. doi.org/10.1016/j.est.2021.102591

[13] Qarabsh, N. A., Sabry, S. S., & Qarabash, H. A. (2020). Smart grid in the context of industry 4.0: an overview of communications technologies and challenges. *Indonesian Journal of Electrical Engineering and Computer Science*, *18*(2), 656-665. DOI: 10.11591/ijeecs.v18.i2.pp656-665

[14] Ghorbanian, M., Dolatabadi, S. H., Masjedi, M., & Siano, P. (2019). Communication in smart grids: A comprehensive review on the existing and future communication and information infrastructures. *IEEE Systems Journal*, *13*(4), 4001-4014. DOI: 10.1109/JSYST.2019.2928090

[15] Gallegos, J., Arévalo, P., Montaleza, C., & Jurado, F. (2024). Sustainable electrification—advances and challenges in electrical-distribution networks: a review. *Sustainability*, *16*(2), 698. doi.org/10.3390/su16020698

[16] De La Cruz, J., Gómez-Luna, E., Ali, M., Vasquez, J. C., & Guerrero, J. M. (2023). Fault location for distribution smart grids: Literature overview, challenges, solutions, and future trends. *Energies*, *16*(5), 2280. doi.org/10.3390/en16052280

[17] Judge, M. A., Khan, A., Manzoor, A., & Khattak, H. A. (2022). Overview of smart grid implementation: Frameworks, impact, performance and challenges. *Journal of Energy Storage*, *49*, 104056. doi.org/10.1016/j.est.2022.104056

[18] Alam, M. S., Al-Ismail, F. S., Salem, A., & Abido, M. A. (2020). High-level penetration of renewable energy sources into grid utility: Challenges and solutions. *IEEE access*, *8*, 190277-190299. DOI: 10.1109/ACCESS.2020.3031481

[19] Yapa, C., De Alwis, C., Liyanage, M., & Ekanayake, J. (2021). Survey on blockchain for future smart grids: Technical aspects, applications, integration challenges and future research. *Energy Reports*, *7*, 6530-6564. doi.org/10.1016/j.egyr.2021.09.112\

[20] Hossain, Q., Yasmin, F., Biswas, T. R., & Asha, N. B. (2024). Data-Driven Business Strategies: A Comparative Analysis of Data Science Techniques in Decision-Making. *Sch J Econ Bus Manag*, *9*, 257-263. doi.org/10.36347/sjebm.2024.v11i09.002

[21] Sun, H., Guo, Q., Qi, J., Ajjarapu, V., Bravo, R., Chow, J., ... & Yang, G. (2019). Review of challenges and research opportunities for voltage control in smart grids. *IEEE Transactions on Power Systems*, *34*(4), 2790-2801. DOI: 10.1109/TPWRS.2019.2897948

[22] Moury, R. K., & Hasan, R. (2024). Foreign Exchange Operations of Islami Bank Bangladesh Limited. Saudi J Bus Manag Stud, 9(2), 41-52. DOI: 10.36348/sjbms.2024.v09i02.004

[23] Srinivasan, S., Kumarasamy, S., Andreadakis, Z. E., & Lind, P. G. (2023). Artificial intelligence and mathematical models of power grids driven by renewable energy sources: A survey. *Energies*, *16*(14), 5383. doi.org/10.3390/en16145383

[24] Hussain, M. D., Rahman, M. H., & Ali, N. M. (2024). Investigation of Gauss-Seidel Method for Load Flow Analysis in Smart Grids. *Sch J Eng Tech*, *5*, 169-178. DOI: 10.36347/sjet.2024.v12i05.004

[25] Saleem, Y., Crespi, N., Rehmani, M. H., & Copeland, R. (2019). Internet of things-aided smart grid: technologies, architectures, applications, prototypes, and future research directions. *Ieee Access*, *7*, 62962-63003. DOI: 10.1109/ACCESS.2019.2913984

[26] Uslar, M., Rohjans, S., Neureiter, C., Pröstl Andrén, F., Velasquez, J., Steinbrink, C., ... & Strasser, T. I. (2019). Applying the smart grid architecture model for designing and validating system-of-systems in the power and energy domain: A European perspective. *Energies*, *12*(2), 258. doi.org/10.3390/en12020258

[27] Shafiullah, M., Ahmed, S. D., & Al-Sulaiman, F. A. (2022). Grid integration challenges and solution strategies for solar PV systems: a review. *IEEE Access*, *10*, 52233-52257. DOI: 10.1109/ACCESS.2022.3174555

[28] Shan, Y., Hu, J., Liu, M., Zhu, J., & Guerrero, J. M. (2019). Model predictive voltage and power control of islanded PV-battery microgrids with washout-filter-based power sharing strategy. *IEEE Transactions on Power Electronics*, *35*(2), 1227-1238. DOI: 10.1109/TPEL.2019.2930182

[29] Massaoudi, M., Abu-Rub, H., Refaat, S. S., Chihi, I., & Oueslati, F. S. (2021). Deep learning in smart grid technology: A review of recent advancements and future prospects. *IEEE Access*, *9*, 54558-54578. DOI: 10.1109/ACCESS.2021.3071269

[30] Kabalci, E., & Kabalci, Y. (2019). Introduction to smart grid architecture. *Smart grids and their communication systems*, 3-45. doi.org/10.1007/978-981-13-1768-2_1

[31] Waseem, M., Adnan Khan, M., Goudarzi, A., Fahad, S., Sajjad, I. A., & Siano, P. (2023). Incorporation of blockchain technology for different smart grid applications: Architecture, prospects, and challenges. *Energies*, *16*(2), 820. doi.org/10.3390/en16020820

[32] El-Emam, D. A. (2024). Valorization of Solid Waste Products from a Variety of Sectors in Wastewater Treatment Processes. In *Technical Landfills and Waste Management: Volume 2: Municipal Solid Waste Management* (pp. 207-257). Cham: Springer Nature Switzerland. doi.org/10.1007/978-3-031-55665-4_9

[33] Reda, H. T., Anwar, A., Mahmood, A. N., & Tari, Z. (2023). A taxonomy of cyber defence strategies against false data attacks in smart grids. *ACM Computing Surveys*, *55*(14s), 1-37. doi.org/10.1145/3592797

[34] Pandey, A. K., Kalidasan, B., Reji Kumar, R., Rahman, S., Tyagi, V. V., Krismadinata, ... & Tyagi, S. K. (2022). Solar energy utilization techniques, policies, potentials, progresses, challenges and recommendations in ASEAN countries. *Sustainability*, *14*(18), 11193. doi.org/10.3390/su141811193

[35] Farhangi, R., & Beheshti, M. T. (2020, December). Transient stability conditions assessment in smart grids via new Lyapunov approaches. In *2020 10th Smart Grid Conference (SGC)* (pp. 1-6). IEEE. DOI: 10.1109/SGC52076.2020.9335744

[36] Butt, O. M., Zulqarnain, M., & Butt, T. M. (2021). Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Engineering Journal*, *12*(1), 687-695. doi.org/10.1016/j.asej.2020.05.004

[37] Alam, M. S., Chowdhury, T. A., Dhar, A., Al-Ismail, F. S., Choudhury, M. S. H., Shafiullah, M., ... & Rahman, S. M. (2023). Solar and wind energy integrated system frequency control: A critical review on recent developments. *Energies*, *16*(2), 812. doi.org/10.3390/en16020812

[38] Lamnatou, C., Chemisana, D., & Cristofari, C. (2022). Smart grids and smart technologies in relation to photovoltaics, storage systems, buildings and the environment. *Renewable Energy*, *185*, 1376-1391. doi.org/10.1016/j.renene.2021.11.019

[39] Guerrero, J. I., Martín, A., Parejo, A., Larios, D. F., Molina, F. J., & León, C. (2023). A General-Purpose Distributed Analytic Platform Based on Edge Computing and Computational Intelligence Applied on Smart Grids. *Sensors*, *23*(8), 3845. doi.org/10.3390/s23083845

[40] Adeyinka, A. M., Esan, O. C., Ijaola, A. O., & Farayibi, P. K. (2024). Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. *Sustainable Energy Research*, *11*(1), 26. doi.org/10.1186/s40807-024-00120-4