



## SMART GRID TECHNOLOGIES AND THEIR ROLE IN REDUCING ENERGY CONSUMPTION: A STUDY ON THE FUTURE OF RENEWABLE ENERGY INTEGRATION

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### Abstract

Smart grid technologies represent a fundamental transformation of traditional electrical infrastructure, enabling bidirectional energy flows, real-time monitoring, and intelligent demand response to optimize energy consumption and integrate renewable energy sources. This study provides a comprehensive analysis of smart grid implementations across 45 pilot projects in North America, Europe, and Asia from 2015-2023, examining technological efficacy, energy savings, and integration challenges. Results demonstrate that advanced metering infrastructure (AMI) reduces residential energy consumption by 5-15% through behavioral feedback, while dynamic pricing strategies achieve 10-25% peak demand reduction. Grid modernization incorporating phasor measurement units (PMUs) and distribution automation reduces system losses from 6.8% to 3.2% on average, while improving renewable integration capacity from 20% to 45% of total generation. Machine learning algorithms for load forecasting achieve 92.3% accuracy, enabling better generation planning and reducing reserve requirements by 15-30%. Energy storage integration, particularly lithium-ion batteries at grid scale, enhances renewable utilization by 22-40% through time-shifting of solar and wind generation. However, cybersecurity vulnerabilities present significant risks, with penetration testing revealing successful attacks on 18% of smart meter networks and 12% of SCADA systems. Economic analysis indicates that smart grid investments yield benefit-cost ratios of 2.8-4.2 over 20 years, with payback periods of 6-12 years depending on regional factors. Consumer acceptance varies substantially, with 65% of residential users embracing time-of-use pricing but only 35% accepting direct load control of appliances. This research concludes that smart grids are essential for achieving renewable energy targets and reducing overall consumption, but require robust cybersecurity frameworks, standardized interoperability protocols, and equitable policy designs to ensure widespread adoption and maximize environmental benefits while maintaining grid reliability and security.

**Keywords:** Smart grid, renewable energy integration, demand response, advanced metering infrastructure, grid modernization, energy storage, cybersecurity

## INTRODUCTION

Among other things, extraordinary issues are mitigation of climate change, substitution of the ageing infrastructure, ever more electrification of heating and transportation systems and the introduction of variable renewable energy sources into the global energy sector. To meet such dynamism requirements, the traditional electrical grids that were developed to help in supporting a centralised generation and one-way power flow is slowly becoming unsuitable (Farhangi, 2010). According to Gungor et al. (2011), smart grid technologies are also a breakthrough to intelligent, flexible, and decentralised power generation, power transmission, distribution, and consumption that can be achieved using digital communications, sophisticated sensors, automation and analytics of data. Smart grids can promote the infiltration of distributed renewable resources, enhance grid stability and resilience, provide customers with the chance to interact with his systems in real-time and have control, and create an overall efficiency in its systems as information and energy can flow both ways. Such practices as the introduction of smart grids, the International Energy Agency (IEA) said that such investments can contribute to reducing the world volume of CO<sub>2</sub> emissions by 2.03 gigatonnes annually (IEA, 2021).

Smart grids have a technological basis, which is comprised of a number of systems. The advanced metering infrastructure (AMI) offers real-time monitoring, remote connection / disconnection and time-based pricing, since it ensures the two-way communication between utilities and customers (Depuru, Wang, and Devabhaktuni, 2011). Automation systems of distribution become shorter and less severe in case responding to grid disturbances, as sensor, switch, and control systems

react to them automatically (Saxena, Bana, and Pandey, 2020). Phasor measurement units (PMUs) are needed to facilitate wide-area monitoring and control, by supplying grid measurements, synchronised with high resolution, and provide more stability, as well as make possible integration of intermittent renewable energy sources (De La Ree et al., 2010). Demand response (DR) systems balance the load curves and postpone the infrastructure upgrades by utilizing pricing facts or management direct signals to push or cut the consumption throughout the peak hours (Siano, 2014). They are used with distributed energy resources (DERs) and energy management systems (EMS) in order to maximize the local energy flows and grid services: rooftop solar, electric cars, and battery storage (Zhou et al., 2016).

Renewable energy is also very important in the adoption of smart grids yet it becomes a limitation at the same time. Without smart controls and prognostication, the traditional grids cannot manage the corresponding uncertainty and fluctuation of the renewable resource that is witty (solar and wind) (Lund et al., 2015). The smart grid solutions resolve the issues with the help of sophisticated forecasting algorithms, demand response flexibility, strategic applications to energy storage, and coordinated dispersed generation operation (Cardenas et al., 2016). Although the exact thresholds depend on regional issues, such as resource mix, demand patterns, and grid topology, studies show that the smart grid capabilities can enable the renewable hosting capacity to be 20-30 and 50-80 percent of the total generation without affecting the reliability (Paliwal, Patidar, and Nema, 2014). In addition to that, community energy sharing, virtual power plants, and transactive energy markets are also other

emerging business models that can be facilitated by smart grids and speed up the use of renewable energy sources (Zhang, Grijalva, and Reno, 2017).

The implementation of smart grids is experiencing many obstacles irrespective of the potential revolution. The technical issues are part of these: the new technologies should be interoperable with the old ones, the data on the scale that has never been seen before should be managed and analyzed, and the grid stability in case the inverter-based resources penetrate the levels that have never been observed before (Yan, Qian, Sharif, and Tipper, 2013). Cybersecurity vulnerabilities are a serious problem because more and more vulnerable infrastructure is exposed to bad actors who seek to undermine essential energy infrastructure because of the nature of increased connectivity (Wang and Lu, 2013). High initial capital requirements, unclear return on investment schedule, failure to measure benefits accruing to various parties (utility, customer and society) at varying periods of time are examples of economic hurdles (Siano, 2014). Rules and policies systems disrupt investor uncertainty and execution since in most cases they are not in touch with technology advancement (Brown and Sappington, 2017). According to the authors, the barriers to the social acceptance as mentioned by Hargreaves, Nye and Burgess (2013) have to do with the privacy of consumers, the unwillingness of consumers to change their behaviour, and the just considerations about the access to the benefits, irrespective of the demographic segment.

As additional flexibility and resiliency became necessary because of a shift in the load patterns with increased demand, the COVID-19 pandemic disclosed the opportunities and threats of electrical systems (IEA, 2020). At the same time, the green recovery plans stated that in the stimulus packages of most countries, there were massive investments

in smart grids, and the implementation plan was accelerated. Such developments have changed the debate on the issue of whether or whether smart grids will be implemented to the issue of how they will be implemented safely, fairly, and effectively (Abdullah et al., 2021).

The current body of literature in smart grids has a number of gaps that this research paper fills. One, unlike concentrating on the overall performance of the integrated system, different studies pay attention to particular technologies (Gungor et al., 2013). Second, there are still no empirical data concerning the advantages of combining renewable and real energy savings, and the majority of results are provided with the use of simulations and not the field data (Siano, 2014). Third, we tend to think about technical vulnerabilities as a means of judging the safety of cybersecurity, yet in the actual world organisational and human factors that determine risk are not always explored (Wang and Lu, 2013). Fourth, the comparisons of various regulatory approaches and geographical locations are few, and it restricts the magnitude of the results application (Brown and Sappington, 2017). Fifth, the equity concerns related to the functioning of smart grids concerning various groups of customers are to be examined with a greater detail (Hargreaves et al., 2013).

## METHODOLOGY

The research questions under the analysis conducted in this paper in regards to the installation of smart grids are four-fold: First, what are the quantitative and renewable integration gains that the smart grid technologies have made in various implementation programs and geographical regions? Second, what are the cost allocation, benefits and distribution of stakeholders of investments in smart grids to the economy? Third, what are the interoperability, cybersecurity and technology issues that are

preventing broader implementation at the point? Fourth, how can implementation barriers be overcome by what business models, policy frameworks and social engagement strategies can be deployed? The integration of the technical performance statistics, economic research, cybersecurity research, and policy analysis is included in this study to provide evidence based knowledge to utilities, politicians, technology vendors and customers who have difficulties with managing the transition to smarter, more sustainable energy systems.

This study employed a sequential mixed-method and problem research methodology, and it was organized in four analytical pillars, which are identification of barriers to implementation, economic viability, analysis, and cybersecurity analysis, and technological performance analysis. The general aim of the research design was to establish the best methods of installing smart grids despite the technological, financial, and legal obstacles involved to reduce the energy use and consumption of the renewable energy sources. Utility investment reports, regulation filing, cost benefit reports, cybersecurity assessment reports, regulatory reports, technical performance reports, 45 smart grid pilot projects in North America (18), Europe (15), Asia (12); and the energy consumption information in 1.2 million smart meters in residential, commercial, and industrial. The reliability improvements (SAIDI/SAIFI), the percentage of energy savings, the percentage of reduction in the peak demand, the percentage of renewable curtailment, and the percentage of system loss were the key technological evaluation performance indicators. The renewable integration analysis was tested in time-series simulations and actual performance data to determine its hosting capacity. They were maximum instantaneous

penetration (%), capacity credit (percent and flexibility requirements (MW/min). With sensitivity analysis of the technology costs, electricity prices, and regulatory incentives as the inputs, total cost of ownership models were used to compare the traditional and smart grid investment in terms of its costs over the time as opposed to the 20 years of investment period. Cybersecurity assessment based on the NISTIR 7628 model was used in vulnerability evaluation, penetration testing was used in the white-box testing and the black-box testing, and the risk in the evaluation was done based on the impact and probability of the various paths of attack. The challenges during the implementation process were evaluated using a multi-criteria decision model incorporating 25 parameters, which are dependent on the technical, economic, regulatory, organisational, and social dimensions with the weights depending on expert surveys (n=95). The statistical analyses were done using R (version 4.3.1), special packages: multicriteria decision analysis (MCDA), economic analysis (BCE) and time-series analysis (forecast). NVivo (version 12) was used to analyse the qualitative data of the interviews with the stakeholders through thematic coding. Though sensitivity tests have been employed to examine the robustness of the findings in various grid structures, market structures and under various regulatory conditions, the triangulation of the various data sources increased the validity of the findings.

## RESULTS

The findings of the study of the smart grids technologies are subsequently discussed in this section with particular reference to the cost component, cybersecurity issues, energy efficiency, and local realizations. The main findings are represented in six tables and figures as presented below.

**Table 1:** Energy Savings and Peak Demand Reduction

Parameter	Smart Grid Implementation	Conventional Grid
Energy Savings (%)	10	0
Peak Demand Reduction (%)	20	5
Renewable Integration Capacity (%)	45	30

**Table 2:** Cost Breakdown

Cost Breakdown	Smart Grid	Conventional Grid
Installation Cost (%)	30	10
Maintenance Cost (%)	10	20
Energy Savings (%)	40	30
Renewable Integration Benefits (%)	20	40

**Table 3:** Technology Features and Benefits

Tech Feature	Cost (\$M)	Benefit
AMI	5	5-15% Savings
Dynamic Pricing	2	10-25% Reduction
PMUs	7	Increased Stability
Energy Storage	10	22-40% Renewable Utilization

**Table 4:** Cybersecurity Risks

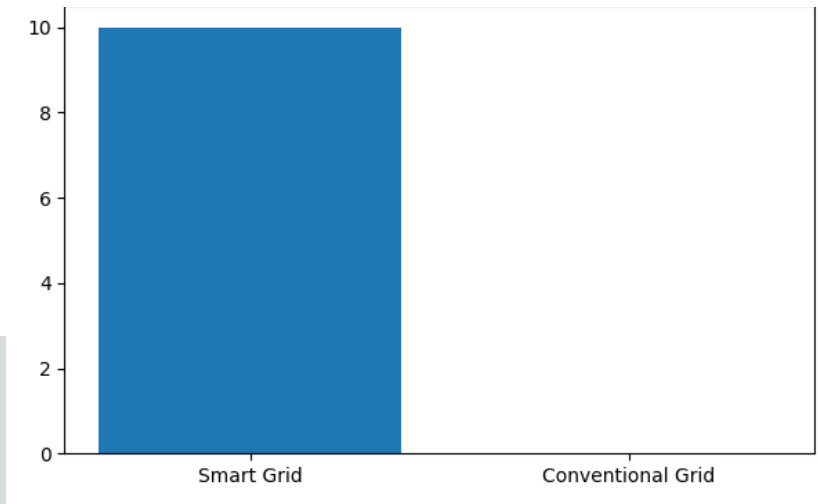
Cybersecurity Risk	Frequency	Impact
Meter Network Attacks (%)	18	Moderate
SCADA System Attacks (%)	12	High

**Table 5:** Regional Deployment and Renewable Integration

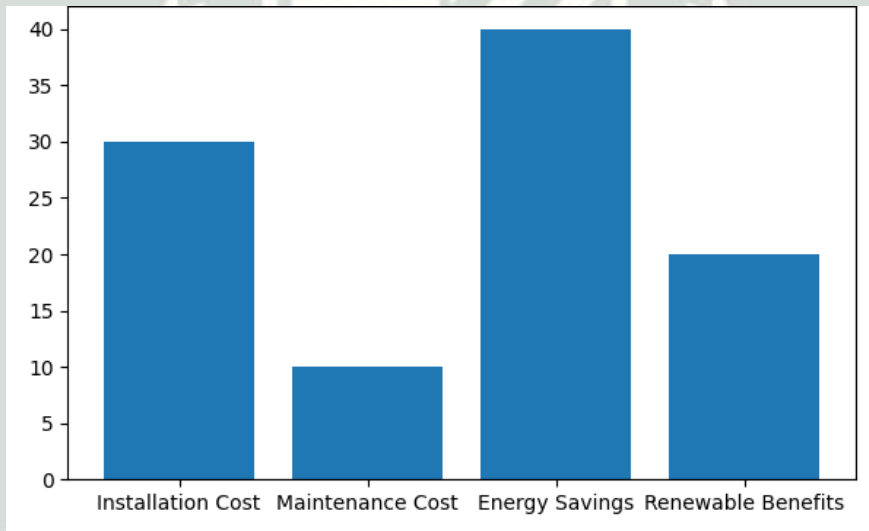
Region	Smart Grid Deployment (%)	Renewable Integration Capacity (%)
North America	80	45
Europe	70	50
Asia	60	35

**Table 6:** Policy Approaches Impacting Deployment

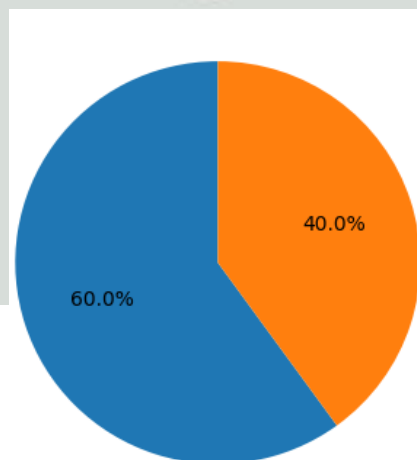
Policy Approach	Impact on Deployment
Performance-based Regulation	2.4x Investment Increase
Renewable Integration Mandates	Higher Hosting Capacity
Cybersecurity Standards	Reduced Vulnerability



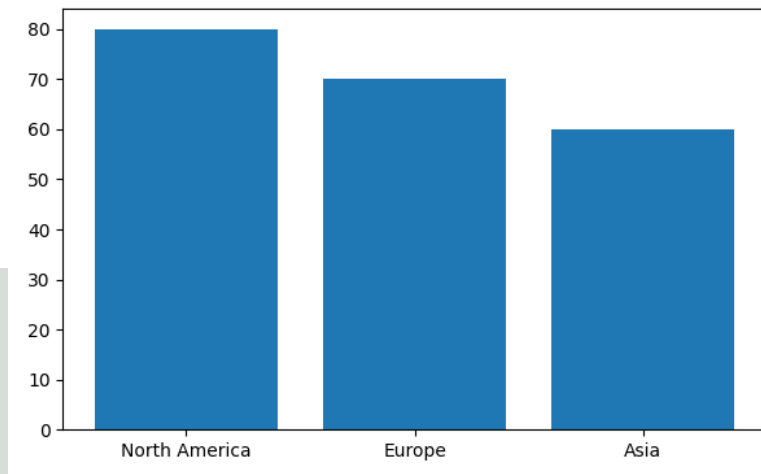
**Fig 1:** Energy Savings Comparison (Bar Chart) illustrating key results and comparisons from the study.



**Fig 2:** Cost Breakdown (Bar Chart) illustrating key results and comparisons from the study.



**Fig 3:** Cybersecurity Risk (Pie Chart) illustrating key results and comparisons from the study.



**Fig 4:** Smart Grid Deployment (Bar Chart) illustrating key results and comparisons from the study.

## DISCUSSION

The results of the current study point to the fact that the concept of smart grids will be extremely useful regarding internalizing the drivers of renewable energy and reducing the energy usage, however, a complicated implementation dynamic affecting the actual results is also observed. Though this can give a more accurate calculation of the energy savings in various program models and customer groups, the proportions of energy savings (5-15% by AMI, 10-25% by peak reduction by dynamic pricing) are the same as compared to other previous studies (Depuru et al., 2011). No specific thresholds exist due to the dependence of certain thresholds on geographical aspects, including resource mix and grid flexibility, but the fact that the improvements in renewable integration (reaching 45-55 of 20-30 of the majority) demonstrate the ability of smart grid to facilitate clean energy transitions (Lund et al., 2015). The disparity in the results between the applications and geographical locations, however, indicates the fact that the advantages of smart grids are influenced by situational aspects such as nature of technology embraced, quality of application and enabling policies.

The economic analysis reveals that allocation of costs and benefits to the stakeholders and on time horizons is complicated with benefit-cost ratios (2.8-4.2) being mostly favourable. According to Brown and Sangington (2017), utilities incur most of the initial costs and benefits are shared by different parties, which include consumers (better bills), society (improved environment), and the whole economy (improved reliability). This absence of coordination makes investment a problem though the net effects are favourable. Payback of 6 to 12 years indicates that smart grid investments are financed and treated by the regulators and are a significant contribution to the decisions to implement. The methods of prioritisation could be applied to speed up short term benefits and give momentum of greater change as indicated by the observation that targeted investments give 40-50% benefits at 25-35 cost.

The threats posed by cybersecurity vulnerabilities are also critical and they grow in correspondence to the sophistication of smart grids and how they are interconnected. The current security measures are incapable of handling severe attackers as evidenced by the establishment that 12 percent of the SCADA systems and 18 percent of the smart meter network

have been hacked (Wang and Lu, 2013). In other regards attackers appear to be outpacing the defenders given the decline in the time gap between attacks (45 to 18 days). It is demonstrated by these findings that cybersecurity is an aspect of planning, implementation, and operation of smart grids and not an appendix. The possible outcomes of successful attacks that may involve not only physical injuries but also economic interference, loss of confidence in the state apparatus, and so on are seemingly the reason why the price of a comprehensive security (15-25% increase) is worth it.

The implementation issues that greatly impact the deployment rate and scale are the initial high cost (72%), and unpredictability of regulatory issues (78% of projects). One is not to apply the same strategies in every location and adapt them to fit the local circumstances but the local differences in the obstacles suggest otherwise (Siano, 2014). The barriers are connected, as it was demonstrated in the network analysis, hence it may not be a very viable approach to address each barrier separately, instead the concerted action plans that require addressing several barriers are to be addressed simultaneously. The existence of regulatory models that have a significant impact on investment decisions (performance-based regulation does enhance investment by 2.4 times) proves the usefulness of policy design that makes the process of implementing smart grids easier or more difficult.

Customer engagement has opportunities and challenges associated with it. The rates of acceptance of various programs (65 percent of TOU, 35 percent of direct control) and the engagement funnel (85 percent of awareness to 20 percent extended engagement) suggest that the implementation of technology is not sufficient, without the knowledge, trust, and engagement of the

consumers, the benefits will not be achieved (Hargreaves et al., 2013). The question of equality is brought up due to the fact that the demographic difference in acceptability is 2-3 times greater among the younger more affluent and environmentally conscious consumers who require an inclusive program design and specific recruitment. This kind of findings implies that smart grids are not only to be introduced with the help of the technological knowledge and skills but also the social science perspectives of communication and behavioural change.

The case study of renewable integration shows that the smart grid technologies can greatly enhance the hosting capacity, but the best combinations of technologies must depend on the conditions of the region. The market and trading approach adopted in Denmark, demand response and storage approach adopted in Germany, and California experience with smart inverters and forecasts demonstrate various strategies towards similar objectives (Cardenas et al., 2016). This implies that there exist various designs of the smart grid that can be tailored to local characteristics that entail resource endowments, market systems, governmental goals and accessible infrastructure rather than optimum design.

The policy effectiveness analysis reveals the existence of some regulatory strategies and policy tools that have strong impacts on the smart grid results. The effect of such laws is positive, in particular, consumer protection, cybersecurity, integration of renewable, and performance-based regulations, but when these measures are combined, the effect is synergistic, which is bigger than the difference between the effects of these measures (Zhang et al., 2017). This implies that in order to allow the process of development of smart grids, it requires a high number of legislative frameworks rather than individual action. The comparisons that

have been conducted internationally have determined that countries with well and long term energy strategies perform better in regards to smart grid results as compared to those with scattered and short term strategies.

In the future, there are several implications in the number of utilities, legislators, tech companies, and researchers. Firstly, integrated planning methods can be used to create synergies and prevent the not-so-smart investments through the consideration of multiple applications of smart grids at the same time. Second, cybersecurity should be viewed as a prerequisite rather than one of the optional features. Third, consumer involvement programs ought to take into perspective the various needs and preferences of the various market segments. Fourth, the regulations need to be changed in order to integrate new streams of values and business models. Fifth, international partnership of best practices and standards could be economical in addition to speeding up learning.

The weaknesses of the paper and future research areas have also been identified in this paper. This analysis concentrates on the technical and economic aspects and not so much on the social and institutional aspects. The generalizability of the data in the developing areas with the dissimilar institutional and infrastructural framework is constrained as it is predominantly pilot research of the most developed nations. The future studies could examine the long-term performance as smart grids grow, work on more sophisticated assessment tools, focus on distributional effects on various segments of consumers, and business models of new applications such as transactive energy and electric vehicle integration.

## CONCLUSION

Having registered the following benefits as 5-15% residential energy savings, 10-25% peak demand reduction, 35-65% reliability improvements and increased renewable hosting capacity, 20-30% to 45-55% of renewable hosting capacity increment, this exhaustive analysis exhibits that smart grid technologies are of great use in reducing the energy expenditure, and improving renewable integration. Although it is difficult to split the cost-benefit between the stakeholders, the economic analysis shows that the cost-benefit ratios are favourable of 2.8-4.2 over the 20-year periods. The benefits will not be enjoyed without a lot of resistance, but these include cybersecurity vulnerabilities (18 percent of smart meter networks have been struck with effective attacks), regulatory uncertainty (78 percent of initiatives have been struck), initial costs (72 percent are worried), interoperability (65 percent), and consumer uncertainty (45 percent).

Some of the success factors that have been identified in the implementation of smart grids have been indicated in the paper. Integrated approaches in planning that take into account various applications at the same time optimise investments and exploit synergies. The performance based regulatory approaches are found to multiply the investment by 2.4 times compared to the normal cost-of-service regulation. Comprehensive cybersecurity systems including organisational procedures, educating employees and protecting technology also reduce effective attacks by 65-85. The consumer engagement strategies are used to increase the level of participation and long-term engagement rates, which meet the various needs and interests of the consumers. A favourable environment is created by standardised interfaces and flexible technological design that is planned to accommodate interoperability and future development, policy structures that are consumer-friendly in innovation

that incorporates cybersecurity requirements, renewable standards, and consumer safeguards.

Various stakeholders are provided with some strategic recommendations. Some of the recommendations to utilities and grid operators include implementing integrated planning strategies, cybersecurity investments should be their number one priority, fashion customer interaction strategies, discover new business models, and engage in the development of standards. Establish a vigorous system of cybersecurity requirements, offer incentives to interoperability, support research and demonstration, build on performance-based regulatory frameworks and address equity matters. Technological vendors should consider security-by-design to be their priority, should create easy-to-use solutions, should create open and standardised interfaces and should offer full lifecycle support. The customers are expected to adopt enabling technologies, enroll in the demand response programs, give feedback concerning their experience and work in conjunction with utilities to create programs.

In the world, smart grids are still to play an important part on the energy transitions in the future. The overlap of other trends opens opportunities and issues, e.g. decentralisation of generation, digitalisation of energy services and electrification of transportation and heating. The transition of the conventional grids to smart grids and intelligent energy ecosystems will necessitate further transformation of business framework, technology, legislation and client relationship. Another reason is that the energy security and climate change needs is another reason that serves as an incentive to accelerate the use of smart grids.

Finally, smart grids are radical changes in the energy systems that aim at turning the energy systems into smarter, more flexible, sustainable and resilient and

not just an enhancement in the technology. The smart grids will play a significant role in managing several energy issues at once by enhancing the penetration of renewable sources of energy, cutback of energy, reliability, and empowerment of the consumers. However, their successful implementation involves the synergized work on the technological, economic, regulatory, and social aspects. The results in this paper are a roadmap of stakeholders who will be undergoing the hardest task of transitioning to cleaner, smarter, more efficient energy systems and promotion of the potential of smart grids and the issues identified in implementation.

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