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A review of the development of Smart Grid technologies

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ABSTRACT

Energy sustainability and environmental preservation have become worldwide concerns with the many manifestations of climate change and the continually increasing demand for energy. As cities and nations become more technologically advanced, electricity consumption rises to levels that may no longer be manageable if left unattended. The Smart Grid offers an answer to the shift to more sustainable technologies such as distributed generation and microgrids. A general public awareness and adequate attention from potential researchers and policy makers is crucial. This paper presents an overview of the Smart Grid with its general features, functionalities and characteristics. It presents the Smart Grid fundamental and related technologies and have identified the research activities, challenges and issues. It demonstrates how these technologies have shaped the modern electricity grid and continued to evolve and strengthen its role in the better alignment of energy demand and supply. Smart Grid implementation and practices in various locations are also unveiled. Concrete energy policies facilitate Smart Grid initiatives across the nations. Interestingly, Smart Grid practices in different regions barely indicate competition but rather an unbordered community of similar aspirations and shared lessons.

Contents

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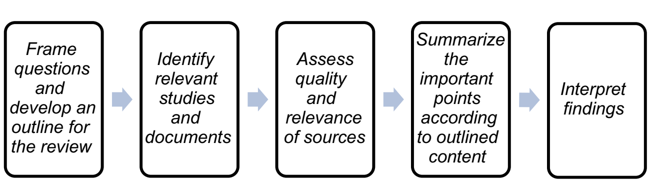
1. Introduction

Smart Grids did not emerge from nowhere. They came about as an answer to a need to modernize the electricity grid, make it greener and improve the delivery of power. As Smart Grids are more autonomous and enhance the effectiveness and efficiency of power delivery, utilities can use the existing infrastructure and minimize the need to build more power plants and substations. Smart Grids allow renewable energy resources to be safely plugged into the grid to supplement the power supply with power from customers' distributed generation and storage.

This paper aims to present an overview of the Smart Grid with its features, functionalities and characteristics. It aims to demonstrate how Smart Grid technologies have shaped the modern electricity grid. It discusses policies, pilots and projects from different countries to provide the extent to which Smart Grid technologies have flourished. It also intends to identify research activities, trends, issues and challenges. The more people know about the Smart Grid, the better they will understand its value, and the less resistant they will be to compromises that might be necessary. More knowledge on the successes and issues revolving around Smart Grids encourages strong participation to improve their capabilities and lessen their setbacks.

1.1. Methodology

The approach of this paper is summarized below.



As of July 14, 2015, there are 10,938 journal articles and 144 books associated with Smart Grid technologies from 2000–2016 at ScienceDirect alone using a general search. The search contents though contain repetitions and less relevant inclusions. At the IEEE Xplore Digital Library, 6877 conference publications and journal and magazine articles come out in a search for Smart Grid technologies from 1991–2015. Access to full texts is very limited and search yields repetitions and papers that are less relevant. Other database sources such as Google Scholar, ISI Proceedings, Scopus, and Web of Science are not included.

The paper starts with Smart Grid definitions and a discussion of the basic infrastructure. It then moves to an elaboration of the Smart Grid functionalities. To trace the beginnings and see the progress of the technologies associated with Smart Grids refers to a bit of history. This opens Section 3. Smart Grid policies in several countries are presented before the discussion on technologies and research activities: control and communication, sensing and measurement, EVs, PHEVs and V2G, security, simulators and information systems, integration of renewables, and microgrids, pilots and projects. Related Smart Grid technologies are included in Section 3.3.8. Section 3.4 centers on future research while Section 4 highlights the issues and challenges. Conclusion is disclosed in Section 5.

1.2. Materials and analysis

This review looks at publications from 2008–2015 mostly from ScienceDirect with very few exemptions. An advanced search filtering for Smart Grid technologies in the Abstract, Title, Keywords fields from 2008-Present renders 502 results, 431 of which are journal articles, 70 are books and one is a Reference Work. Search results had three publications in 2008, six in 2009, eight in 2010, 38 in 2011, 84 and 67 in 2012 and 2013, respectively, 130 in 2014 and 166 in 2015; an increasing amount of research in the area is seen in Fig. 1.

Smart Grid technologies based on the advanced search filtering shown in Fig. 2 indicates a major percentage on *Others* – a category that includes materials like policy papers, introductory Smart Grid papers, book chapters with general topics, railways, social acceptance of the technologies, profitability, lessons learned, barriers, assessments and the like. *Non-relevant* involves water management, robotics and those that are not related to power systems. One paper may also mention more than one technology. In that case, the abstract and the conclusion dictate under what category it goes to.

Only journal articles and proceedings whose abstracts contain possible answers to the research questions are stored in a repository. The use of government publications and other sources was necessary to capture some definitions and fundamentals. The repository contains 468 sources: 400 are journal articles, 25 are conference proceedings, 28 are government and organizational documents, 12 are websites and three are books. A total of 248 of these sources are used as actual references for this study. Some articles were only scanned for relevant contents in terms of technologies discussed and did not make it into the final reference list. While it is aimed to produce a comprehensive review of all the technologies associated with the Smart Grid, it is difficult to have them on one paper.

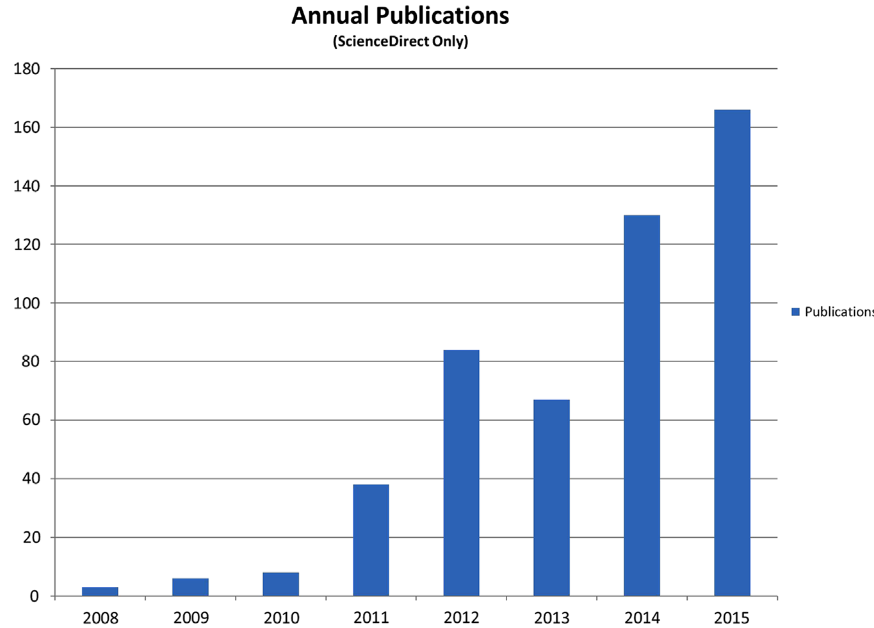


Fig. 1. Annual publications in advanced search for Smart Grid technologies.

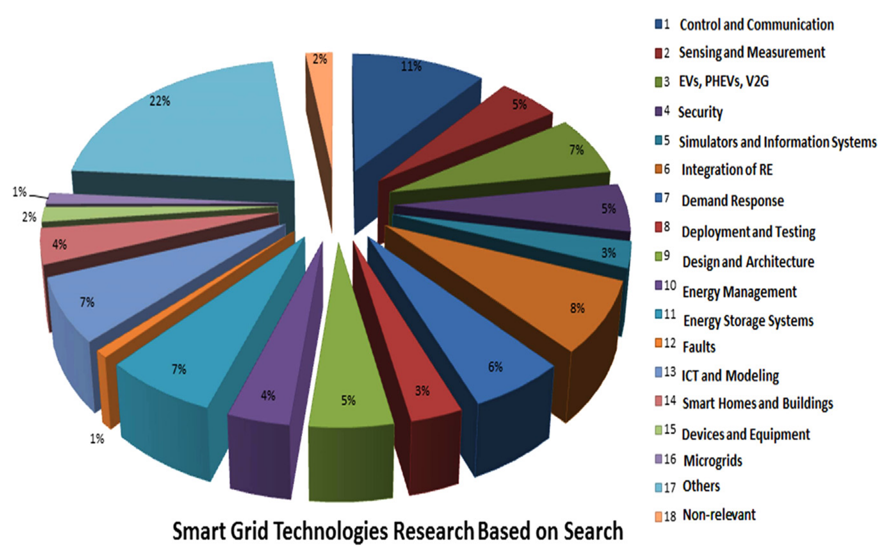


Fig. 2. Smart Grid technologies research based on search.

2. What the Smart Grid is

2.1. Definitions

Smart means intelligent, neat, trim, stylish, or operating in automation; a *grid* is a network of electrical conductors that deliver electricity to certain points. In a way, one can have an idea of what the Smart Grid is. The Smart Grid does not have one definition that is universally accepted. It can be described both in simple terms and in ways that are more complex. It used to be a dream and just an idea but now it is one of the most talked about topics in modern electrical system. Simply put, the Smart Grid is an intelligent grid. The traditional grid can only transmit or distribute electric power. This modern grid is able to store, communicate and make decisions. The Smart Grid transforms the current grid to one that functions more cooperatively, responsively and organically [1]. According to the Strategic Deployment Document for Europe's Electricity Networks of the Future, a Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies [2]. The Korean Smart Grid Roadmap 2030 states that, a Smart Grid refers to a next-generation network that integrates information technology into the existing power grid to optimize energy efficiency through a two-way exchange of electricity information between suppliers and consumers in real time [3]. According to the National Institute of Standards and Technology (NIST), the Smart Grid is a grid system that integrates many varieties of digital computing and communication technologies and services into the power system infrastructure. It goes beyond smart meters for homes and businesses as the bidirectional flows of energy and the two-way communication and control capabilities can bring in new functionalities [4]. In other words, the possibilities of the Smart Grid are vast in the advent of modern technology and increasing interdependence among the grid players. There are tremendous opportunities for experimentations, tests and trials.

The Smart Grid can provide a “platform to maximize reliability, availability, efficiency, economic performance, and higher security from attack and naturally occuring power disruptions” [5]. The Smart Grid may be understood better when viewed alongside the traditional grid. Yu et al. [6] made a good comparison between the two structures. A general summary of the characteristics of the two grids are presented in Table 1.

2.2. Infrastructure

The infrastructure or design of a Smart Grid system is always in relation to set objectives and capabilities. The implementation of a Smart Grid can improve the robustness, self-healing capability and integrability of the grid [25]. The National Institute of Standards and Technology (NIST) presents a conceptual model that supports planning, requirements development, documentation, and organization of the of interconnected networks and equipment that will compose the Smart Grid [4]. NIST has divided the Smart Grid into seven domains (with sub-domains) that encompass Smart Grid *actors* and *applications*. This is shown in Table 2. Furthermore, it classifies as *actors* devices (such as smart meters and solar energy generators), systems (such as control systems), programs, and stakeholders that make decisions and exchange information necessary for performing applications; *applications* as tasks performed by one or more actors within a domain (such as home automation, solar energy generation and energy storage and energy management). Actors in the same domain have similar objectives.

Table 1
The Traditional Electric Grid versus the Smart Grid.

Traditional Grid	Smart Grid
Mechanization	Digitization [7]
One-way communication	Two-way real-time communication [8]
Centralized power generation	Distributed power generation [9,10]
Radial Network	Dispersed Network [11]
Less data involved	Large volumes of data involved [12]
Small number of sensors	Many sensors and monitors [13,14]
Less or no automatic monitoring	Great automatic monitoring [15,16]
Manual control and recovery	Automatic control and recovery [17]
Less security and privacy concerns	Prone to security and privacy issues [18]
Human attention to system disruptions	Adaptive protection [19]
Simultaneous production and consumption of energy/electricity	Use of storage systems [20]
Limited control	Extensive control system [21–24]
Slow response to emergencies	Fast response to emergencies
Fewer user choices	Vast user choices

Fig. 3 shows that actors in a particular domain interact with actors in other domains and particular domains may contain components of other domains. A distribution utility for instance will contain actors in the Operations domain, such as a distribution management system, and in the Customer domain, such as electric meters.

2.3. Smart Grid functionalities

The Smart Grid proposes responses and solutions to the electricity supply adequacy concerns. The Energy Independence and Security Act of 2007 (EISA) sets the stage for the modernization of the electricity grid. The Smart Grid section lists the following characteristics [26]:

2.3.1. Reliability, security, and efficiency of the electric grid

Reliable power supply is crucial to any power system. It determines the success of the grid in providing the needed service to the end users. Smart Grids improve fault detection [27] and allow self-healing [28]. As grids continue to grow in size and complexity, it becomes more difficult to analyze grid reliability but new analytical methods from research efforts have continued to build a stronger reliability foundation for modern networks. A data mining algorithm to discover grid system structure from raw historical system data can estimate grid service reliability by using Bayesian networks [29]. Remote monitoring of hybrid generation and automatic Smart Grid management for instable distribution main contribute to efficiency [30]. The information network in Smart Grids allows for many features, and though prone to attacks, has been countered by promising solutions such as via an intrusion detection system (IDS) [31] or by randomly hiding household sensitive information inside normal readings using wavelet based steganographic technique [32]. Smart Grids systems threats analysis and integrated Systems Security Threat Model (SSTM) that help to better understand the weaknesses exploited by attackers [33], a game theoretic approach to address the issue of cyber-physical security of Wide-Area Monitoring and Protection and Control from a coordinated cyber-attack perspective [34] can enhance security as well. Energy sector partnerships are managing cyber security while keeping critical energy delivery functions to ensure reliability in the modernized grid [35].

2.3.2. Deployment and integration of distributed resources and generation

Distributed energy resources (DER) are small sources of power that can help meet regular power demand. DER such as storage and renewable technologies facilitate the transition to Smart Grids [36]. The coming in of renewable energy sources as distributed generators can help mitigate the problems of depleting fossil reserves and the growing consumer demand. Distributed generation which include wind generators, photovoltaic generators, and

Table 2
Domains in the Smart Grid Conceptual Model by NIST.

Domain	Description
1 Customer	Where electricity is consumed. Sub-domains are homes, commercial and industrial customers. Actors may also generate, store and manage energy use.
2 Markets	Where grid assets are exchanged. Actors are the operator and participants in electricity markets.
3 Service provider	Where support services for producers, distributors and customers are performed. Actors are organizations providing services to electrical customers and to utilities.
4 Operations	Where proper operation of the power system is ensured. Actors are the managers of the movement of electricity.
5 Bulk generation	Where delivery of electricity to customer starts. Actors are the generators of electricity in bulk quantities and may also store energy for later distribution.
6 Transmission	Where bulk transfer of power from generation to distribution is done. Actors are the carriers of electricity over long distances and may also store and generate electricity.
7 Distribution	Where transmission, customer, consumption metering, distributed generation and distributed storage interconnect. Actors are the distributors of electricity to and from customers.

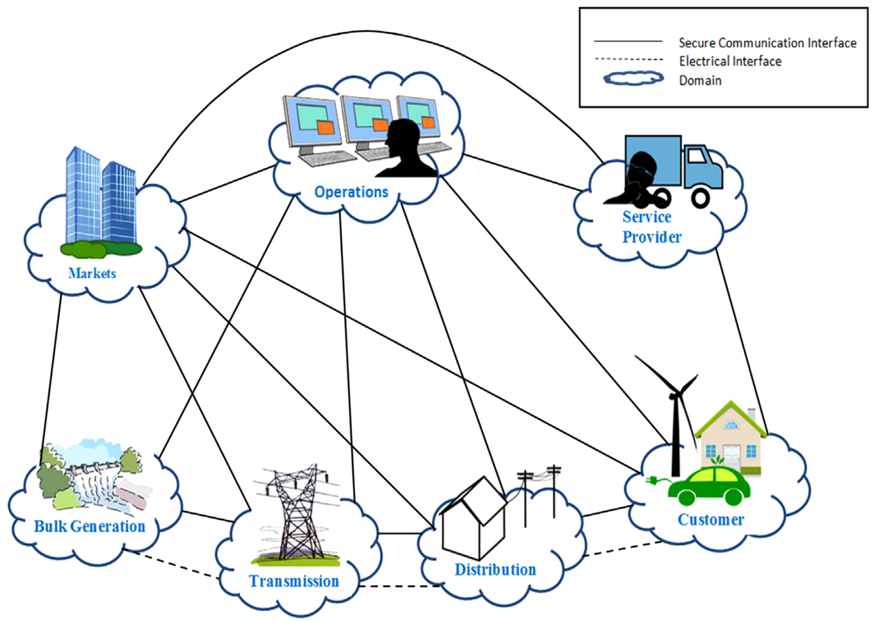


Fig. 3. Interaction of actors in different Smart Grid Domains by NIST.

battery storage systems may incorporate thermal generation and electric vehicles [37]. The aggregation of these sources, however, also means that tremendous amounts of data would need to be handled and processed. The work of Penya et al. [38] presents an architecture that distributes the intelligence all over the grid by means of individual intelligent nodes controlling a number of electric assets, instead of being centralized.

2.3.3. Demand response and demand-side resources

The Federal Energy Regulatory Commission defines demand response as "*Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" [39]. Demand response provides consumers a chance to be involved in grid operations as they can reduce or shift their electricity usage during peak periods and benefit through financial incentives. The development of grid modernization technologies and techniques for demand response is one of the goals of the US Department of Energy [40]. Demand-side resources or energy efficiency and load management programs whose drivers include environmental, economic and reliability concerns have found growing investments [41].

2.3.4. Deployment of "smart" technologies such as for metering and distribution automation

Metering in Smart Grids enables two-way communication between the meters and the utility. The meters ensure more accurate bills and put consumers in control of their energy use. Smart meters, as they are normally called, involve sensors, power outage notification and power quality monitoring. Distribution automation is always associated with smart meters. With advanced metering infrastructure (AMI), utilities can collect consumer information faster and can provide a system-wide communications network to utility service points and link devices across the grid. The AMI and distribution automation opens the door for huge grid modernization though transformer and feeder monitoring, outage management, integration of electric vehicles and effectual fault isolation [42]. One way to achieve distribution automation is through the implementation of Substation Automation System (SAS) that defines locally control actions to solve congestion with minimal renewable energy sources curtailment [43].

2.3.5. Integration of "smart" appliances and consumer devices

Smart appliances and devices are pieces of equipment that can communicate with electrical grids, turn off during peak hours and are able to shift energy use intelligently on their own. In a Great Britain study, the demand response in households with a 20% penetration of smart appliances can provide up to 54% of the operating reserve requirements depending on time of the day [44]. Smart appliances and their larger counterparts, smart buildings, are capable of acting as operating reserves for the system operator [44,45]. Smart appliances shift household electricity demand. A study on households using automation of the smart washing machine has seen that demand automatically shifted to time periods where electricity supply is abundantly available [46]. A wireless sensor home area network using ZigBee protocol, employed for relaying messages among different entities in a home energy management scheme based on appliances coordination, can provide optimized solutions for energy management issues [47].

2.3.6. Advanced electricity storage and peak-shaving technologies, including plug-in electric hybrid electric vehicles (PHEVs), and thermal-storage air conditioning

Electricity storage and technologies that attempt to moderate and reduce peaks is an essential functionality of the Smart Grid. Energy storage is indispensable because electricity generation from renewable energy fluctuates. Storage devices store the surplus electricity when renewable energy generation is abundant so the system is able to use this energy as demand increases. Electric vehicles (EVs) can serve the electric grid as independent energy source. They can remain connected to the grid once they are parked, thus deliver the energy from their batteries in a technology known as vehicle-to-grid (V2G) [48]. Various studies in storage and electric vehicles [49–56] have been undertaken in support to this very important Smart Grid functionality.

2.3.7. Timely information and control option

Timely information over the electrical grid is achieved when grids get smarter. Generation, transmission, distribution and consumers need to make informed decisions at the most appropriate time. Time synchronization and intelligent end-point devices enable the collection of essential data for faster detection of illegal consumers, branch overload detection, and power-quality verification [57]. Intelligent control in Smart Grids on the other hand is necessary for the optimal scheduling of energy sources, to maximize power transport, for transient stability and for real and reactive power control. It optimizes power generation by perfectly tracking the load demand fluctuations [58] and can be used for autonomous fault detection and reconfiguration [59], optimal reactive power control for distributed generation [60], and in SAS for electric utilities [61]. Reddy et al. [62] highlight the different methods for Smart Grid important features, Integration, Control, Communication and Metering (ICCM). Providing accurate timestamping of network events, of key importance in any time synchronization protocol, is a primary concern. Low-cost and low-complexity timestamping techniques that maintain full compatibility with already existing communication standard for wireless nodes used in smart grids offers a solution [63].

2.3.8. *Interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid*

Grid components must be able to work together to enable the reliable transport of electricity from generation to consumption. Interoperability is crucial in planning and implementing grid architecture. The complexity and the number and scale of systems and devices involved in Smart Grids make interoperability indispensable. The Smart Grid Interoperability Panel (SGIP), initiated by NIST is tasked to coordinate standards development for Smart Grids and assure that the components can seamlessly operate and communicate with each other; all integrated domains of the power system, customers, markets, service providers, operations, bulk generation, transmission and distribution work together to build a modern and efficient grid [64]. Some of the studies on this area have looked into interoperability issues in heterogeneous wireless networks for smart cities [65], elaborated on the different ways and levels in which application-level interoperability can be achieved in a distributed infrastructure [66], and reviewed international cloud standardization activities with focus on interoperability [67].

3. Discussion

3.1. *History of Smart Grid systems*

The knowledge of how a system started can provide a better understanding of what it is and why it is significant.

3.1.1. *The Pearl Street Station*

In the early days of electricity, electric systems were small and highly localized. Today's power grid has evolved to become a large interconnected networks that connects thousands of generating stations, transmission lines, distribution networks and load centers.

The Pearl Street Station in New York City was the first electric system, connecting a 100 V generator that burned coal to power a few hundred lamps. It began operation in 1882, initially serving 85 customers. It was then the modern electric utility industry, featuring a central power generation, distribution, and end use. The Pearl Street Station also had several obstacles to overcome [68]. For one, Edison wanted to generate enough power but no dynamos that were powerful enough were present in those times. In addition, the large network of wires and conduits that span distances were expensive and politicians initially rejected his plan of digging up the streets for the underground conduits. Tracking energy consumption so that customers could be charged for their consumption was also an obstacle during the initial run. It is quite a similar scenario these days. Costs, policies, suitable electric meters and other challenges abound in the quest for better and more reliable electric networks.

The Pearl Street Station paved the way for many similar self-contained, isolated systems built across the country, and eventually around the world. Thomas Edison designed and built the Pearl Street Station with no model to guide him through but it became the foundation for the intricate electrical grid more than a hundred years later. It was clearly an original work, a supplement to the electric bulb that he discovered a couple of years prior. Edison wanted to get electricity to his bulb, so he came up with the station and its distribution system. Investors that saw promise in the system funded his project [69]. Just like today, the infrastructure and implementation of grid projects are collaborations between several industries and partners.

3.1.2. *The birth of the intelligent grid*

The actual birth of the Smart Grid is unspecified. It is a case of an evolution that started almost as soon as grids started electrical distribution. With the transmission and distribution of power comes a need to monitor consumption, prices and services. Reliability and energy efficiency are fundamental requisites of the electric power grid. In addition, nations around the world are transitioning to renewable energy to reduce greenhouse emissions, mitigate climate change and ensure sustainable energy in the future. The modernization of the elecric power grid is central to these efforts. Smart Grid projects are usually associated with smart meters. Smart meters that provided information back to the electric utility came into the picture in the 1970s [70] and were widely used in the 1980s. For Pacific Gas and Electric Company, it was then a small one watt radio that permits a two-way communication between customers and, thereby enabling customers to review their consumption [71]. Prof. Gómez-Expósito of Universidad de Sevilla listed five oldest works on the Smart Grid published in journals (IIEE Xplore) [72]. He found one on "Grids get smart protection and control" as early as 1997, another paper in 2003, two in 2005 and another one in 2008. Another association of the Smart Grid is with sensor and control technologies. Although sensors and controls were already introduced in the 1930s, the first wireless network that bore any real resemblance to a modern Wireless Sensor Network (WSN) was the Sound Surveillance System developed by the United States Military in the 1950s. The Distributed Sensor Network (DSN) program of the United States Defense Advanced Research Projects Agency in 1980 brought the WSN into the academia and non-military researches. *A DSN is a set of spatially scattered intelligent sensors that can obtain measurements from the environment, to abstract relevant information from data gathered, and to derive appropriate inferences from the data gathered* [73]. That paved the way for the use of WSN in specialized factory automation, wastewater treatment and power distribution applications [74]. Enel's Telegestore Project in Italy is regarded as the first commercial scale use of Smart Grid technology to the home. Enel is Italy's largest power company and Europe's second listed utility by installed capacity. The Telegestore Project is the frontrunner smart metering application in the international context. It is a system made of 32 million electronic meters, more than 350,000 data concentrators and thousands of meters in secondary substations [75].

3.2. *Policies*

Smart Grid policies worldwide show the increasing trend in providing a dependable framework to facilitate the development and deployment of Smart Grids.

3.2.1. *United States*

The US government energy policy aims for a secure supply of energy, keep energy costs low, and protect the environment by reducing consumption through increased energy efficiency, increasing domestic production of conventional energy sources, and developing new sources of energy, particularly renewable energy and renewable fuels [76]. The US has invested in renewable energy resources and initiated modernization of its energy infrastructure. While the US is not a member of the Kyoto Protocol, it does have a carbon reduction target. The Global Smart Grid Federation Report of 2012 mentions that the US has a non-binding target of around 17% below 2005 levels by year 2020 under the Copenhagen Accord. It has also noted that in 2010, 663 US electric utilities had installed 20,334,525 smart metering infrastructure and that the national penetration rate for smart meters was already 14% a year hence. Moreover, much of the cost of the deployment of these meters is recovered back through the consumers, which is one of the reasons why some consumers reacted negatively. Consumers also repelled because of health and privacy concerns [77]. With the formation of the Smart Grid Consumer Collaborative, a nonprofit organization facilitating cooperation among consumers, advocates, utilities, and technology providers, the sustainable benefits of the Smart Grid can be appropriately managed.

The US Department of Energy formed the Office of Electricity Delivery and Energy Reliability for electric grid modernization and resiliency in the energy infrastructure. The office has produced “GRID 2030” which articulates a national vision for electricity's second 100 years.

3.2.2. South Korea

South Korea, driven by national security and economic growth, developed an energy policy tied to sustainable development. Wanting to improve the country's self-sufficiency and diversify energy supply mix, South Korea has passed laws that promote low carbon growth and green energy initiatives. It has committed to a voluntary emissions reduction target of 30% by 2020 and plans to install smart meters in half of Korean households by 2016 and replace all old meters by 2020 [78].The 2010 Basic Law on Low Carbon Growth and Green Growth reserves 2% of the country's gross domestic product for green business and projects and lowering greenhouse gas emissions. Under the renewable portfolio standard for South Korea, effective 2012, 2% of total generation will come from renewable energy for larger generators, rising to 10% in 2022 [79].

As South Korea attempts to improve its energy self-sufficiency, it exports green technology and offer development assistance in exchange for energy resources. The South Korean Smart Grid Promotion Act provides a framework for sustainable Smart Grid projects, their development, deployment and commercialization. South Korea is a leader in Smart Grid and its Jeju Smart Grid Demonstration project shows just that. The level of coordination between government and industry in achieving Korea's green innovation objective is remarkable, add to that the presence of Korea Smart Grid Association mediating between the parties and helping in the Smart Grid development, standardization and valuable research and development.

3.2.3. Europe

The European Union (EU) is an economic, scientific, and political organization consisting of Belgium, France, Italy, Luxembourg, Netherlands, Germany, Denmark, Greece, Ireland, United Kingdom, Spain, Portugal, Austria, Finland, Sweden, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia, Bulgaria, Romania and Croatia [80]. It operates through supranational institutions and intergovernmental agreements. The EU aims to get 20% of its energy from renewable sources by 2020 and cut down greenhouse emissions, and rely less on imported energy [81]. In 2007, the European Council adopted the 20:20:20 objective, reducing greenhouse gas emissions by 20%, increasing renewable energy to 20% and making 20% energy efficiency improvement by 2020.

Electricity Directive 2009/752/EC, requires EU members to implement smart metering in 80% of households by 2020. This however is subject to a positive cost-benefit analysis. The electricity sectors of the member states vary, so the roll out and their costs have to be individually dealt with. The European Commission also established the European Electricity Grid Initiative, a nine-year research and development program for Smart Grid technology and market innovations [82].

3.2.4. Australia

Australia targets to integrate 20% renewable energy by 2020. Since Australia is a federal parliamentary democracy with states and territories, policies, though coordinated nationally are under state jurisdiction. The Council of Australian Governments (COAG) establishes the framework for their energy policy. It committed to smart meter roll out after the energy shortages in 2006 and 2007 despite being a costly move. New South Wales and the State of Victoria proceeded with smart meter deployment. Australia's interest in the Smart Grid is manifested via Smart Grid Australia, a non-partisan organization taking the lead in modernizing the electrical system and assisting the government in the Smart Grid initiatives, one of which is the Smart Grid Smart City program. Australia is also working at improving incentives for Smart Grid investments and developing measures to address demand-side regulation and time-of-use tariffs. Demand management, energy security and energy efficiency are top priorities.

3.2.5. Canada

Although Canada has withdrawn from the Kyoto Protocol in 2011, it is a party to the Copenhagen Accord. As such, it aims a greenhouse gas reduction of 17% below 2005 levels by 2020. This however is not an obligation. The federal government funds green initiatives, such as the Clean Energy Fund and the ecoEnergy Innovation Initiative. It has been embracing green energy and some provinces have carbon taxes. There are Smart Grid pilots in the Provinces of Quebec, Ontario and in other provinces. Utilities are also undertaking grid modernization projects. SmartGrid Canada, an association of different stakeholders and academia, was formed to promote Smart Grid awareness and enable research and development of new energy technologies and recommend policies that support Smart Grid Development [78].

The Canadian government supports the development of Smart Grid through these entities: Natural Resources Canada, the ministry overseeing the energy sector; National Energy Board, an independent federal agency established to regulate international and interprovincial aspects of the oil, gas and electric utility industries; and National Smart Grid Technology and Standards Task Force, an entity created to coordinate all aspects of Smart Grid development. The provincial governments are also involved in supporting Smart Grid developments [83].

3.2.6. Japan

Japan's 2010 Strategic Energy Plan emphasizes energy security, environmental protection, efficient supply, economic growth and reform of the energy industrial structure. Among its ambitious targets in 2030 are: raising its energy independence ratio to 70%, raising the zero-emission power source ratio to about 70%, halving CO_2 emissions from the residential sector, maintaining and enhancing energy efficiency in the industrial sector at the highest level in the world and maintaining or obtaining top-class shares of global markets for energy-related products and systems [84].

The Japanese government has adopted smart metering after the Fukushima nuclear disaster as an aid to demand side management. Tokyo Electric Power Co. (TEPCO), Japan's largest utility, prompted by the government, has announced installation of about 27 million residential smart meters for customers in 2014. Services using smart meters will be rolled out in July 2015 to enable remote metering and to provide users with detailed data on power use [85].

The Ministry of Economy, Trade and Industry (METI), responsible for establishing energy policy in Japan, promotes the construction of Smart Grid and its deployment overseas to support Japan's efforts to become a worldwide energy power. Japan has promoted “Eco-Model Cities” which are next generation energy and social systems using low carbon technology. The Kansai City for instance focuses on electric vehicles (EVs) and photovoltaic in homes. Yokohama integrates photovoltaic installations and electric vehicles, along with real-time energy management systems for homes and buildings. Toyota City also integrates electric vehicles and centers on demand response as well [78].

3.2.7. China

The basic contents of China's energy policies are "giving priority to conservation, relying on domestic resources, encouraging diverse development, protecting the environment, promoting scientific and technological innovation, deepening reform, expanding international cooperation, and improving the people's livelihood [86]."

The development of Smart Grids in China is incorporated in China's energy priorities. These include improving energy efficiency, increasing renewable energy mix and reducing carbon intensity. The Chinese government has tasked agencies like the *National Development and Reform Commission* (NDRC) – to oversee Smart Grid development plans, control electricity pricing and hold the authorization of review and approval of Smart Grid projects, the *National Energy Agency* (NEA) – to formulate and implement national energy policy and development plans, the *State Electricity Regulatory Commission* (SERC) – to supervise the daily operation of power generation companies and power utility companies, the *China Electricity Council* (CEC) – to assist in the formulation of power policies and lobby national Smart Grid plans, and the *Ministry of Science and Technology* (MOST) – to take charge of research and development, with Smart Grid technologies being one of the priorities in its 12th Five-Year Plan on National Scientific and Technological Development [87]. China has given substantial attention to the development and emergence of Smart Grids.

3.3. Technologies and research activities

This section conveys the Smart Grid technologies and researches, along with their concentration. Due to the magnitude of papers available, it is hard to include everything. More or less, this section gives the picture of what is being done. Smart Grid functionalities in the previous section have mentioned some valuable investigations as well.

3.3.1. Control and communication

In the aspect of control for Smart Grids, clean energy grid-connected control methods and techniques are being utilized. These methods are power electronics-based control method, multi-agent system based control method, advanced fault management control method and the virtual power plant (VPP) control technology [88]. VPPs are systems composed of small-sized distributed generating units that form single virtual generating units. These units can be managed individually [89]. With the advent of power electronics devices and modern control strategies for inverters, conventional large power plants can be integrated into the grid system using thousands of small energy conversion systems (ECS). These conversion systems are able to operate autonomously, grid connected or isolated [90,91]. Various configurations of small and medium power conversion topologies, including their control (mainly for PV-systems), are available and wind turbine configuration and their control have been set [91]. Multi-agent based control technologies have been dealt with in previous studies. Existing centralized control systems cannot handle the large number of renewable components in clean energy power systems, but a decentralized control scheme called Multi-Agent System (MAS) can manage these components [92]. The use of multi-agent systems to control a distributed Smart Grid demonstrated that a multi-agent system enables a seamless transition from grid connected to an island mode in case upstream outages are detected. Thus, a multi-agent system is a useful technology for managing microgrids [93]. Advanced fault management is possible through full coordination of local automation, locally controlled switchgear and relay protection. Islanding operation can be used to protect important consumers from outages [94]. Diagnostic techniques are important in microgrids as they should be fault-tolerant [95]. A real-time control strategy for the virtual power plant could cover fluctuating non-controllable distributed generation output and mutational load without the need of measurement [96].

Other researches in the area of control are: Optimal management of the automatic generation control service in smart user grids including electric vehicles and distributed resources, Dynamic Load Control Scheme for Smart Grid Systems, Islanding Control Architecture in future Smart Grid with both demand and wind turbine control, Smart control of operational threats in control substations, A wind energy generator for Smart Grid applications using wireless-coded neuro-fuzzy power control and Communication effects on frequency control [97–102]. Communication-related studies include: Communication network requirements for major Smart Grid applications in HAN, NAN and WAN, Resilient communication for Smart Grid ubiquitous sensor network, Two new multi-path routing algorithms for fault-tolerant communications in Smart Grid, Learning automata-based multi-constrained fault-tolerance approach for effective energy management in Smart Grid communication network, Strategies for power line communications smart metering network deployment, Blind processing framework to facilitate openness in Smart Grid communications, Impact of scalable routing on lifetime of Smart Grid communication networks and Evolution of Communication Technologies [103–110].

3.3.2. Sensing and measurement

Sensors are essential Smart Grid components. These small nodes serve as detection stations and enable remote monitoring of equipment and energy sources. High speed sensors called synchrophasors or phasor measurement units (PMUs) are devices that provide synchronized measurements of real-time phasors of voltages and currents. These phasor measurements are used in advanced power systems monitoring, protection and control applications [111]. PMUs are 100 times faster than Supervisory Control And Data Acquisition (SCADA) and are able to record grid conditions with great accuracy [112].

Other studies involving sensors are: Resilient communication for Smart Grid ubiquitous sensor network, Secure and reliable surveillance over cognitive radio sensor networks in Smart Grid, Quality-of-service differentiation in single-path and multi-path routing for wireless sensor network-based Smart Grid applications, and Cognitive radio sensor networks: smart communication for Smart Grids—a case study of Pakistan [113–116].

Smart Grids use digital meters that can record usage in real-time, provide dynamic pricing, aid in demand response and remotely connect or disconnect power. In a technology called AMI, communication between generation plants all the way to the homes and businesses is enabled. Smart meters are the next-generation in power measurement. There are eight basic measurement blocks in smart meters: microcontroller unit, analog-to-digital converter, analog-front end, interface unit, liquid crystal display, real-time clock, security scheme and communication protocol stack [117] and each of these blocks contribute to the capabilities of the meter. Moreover, the use of electric meter replacement programs can help reduce peak demand and improve energy consumption [118].

3.3.3. EVs, PHEVs and V2G

EVs and V2G offer many benefits. V2G is a technology in which electric vehicles, PHEVs or fuel cell electric vehicles communicate with the power grid in order to provide peak power and spinning reserve, renewable energy storage and backup [119]. V2G scheduling can dramatically smooth out the fluctuation in power load profiles [120]. The V2G concept can improve the efficiency, stability, and reliability of the grid [121]. Vehicle owner costs are roughly halved with the use of EVs and in terms of distribution system losses and voltage regulation, EVs have only a minor impact on the network [122]. Real-time communication, smart metering and home area networks (HANs) can enhance the V2G capability for coordinated charging and discharging of the EV fleet in a distribution feeder [123]. Ota el al. [124] proposed a scheme that considers charging request for the next drive and battery condition. A case study in Portugal shows a good correspondence between EV smart charging and PV production profiles [125]. Charging is an essential part in V2G technology and works related to charging and discharging have been dynamic [126–135] and there is a huge number of papers and proceedings.

Other researches involving this set of technologies are: Plug-in hybrid electric vehicles and Smart Grids: Investigations based on a microsimulation, Grid harmonic impact of multiple electric vehicle fast charging, Electric vehicles interacting with renewable energy, Adaptive intelligent energy management system of plug-in hybrid electric vehicle, Integration of plug-in hybrid electric vehicles into existing power system structures, Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks, Through-life Management of Electric Vehicles, Optimal scheduling of electric vehicles in an intelligent parking lot, Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles and Life cycle analysis of energy supply infrastructure for conventional and electric vehicles [136–145].

3.3.4. Security

Smart Grid security is an offshoot of the complex networks in Smart Grids composed of millions of devices and entities that connect with each other. Vulnerabilities in Smart Grids are most common in smart meters, intelligent devices in electricity supply and demand, components in insecure physical locations, outdated equipment that may be incompatible with current devices, device-to-device communication, unorganized communication among teams involved, IP-based components that are prone to attacks and the fact that there are many stakeholders [146]. IEC SmartGrid Standardization, IEEE Power & Energy Society (PES), National Institute of Standards and Technology (NIST) and National Standard of People's Republic of China Smart Grid help develop the security standards for Smart Grid [147]. A methodology for assessing Smart Grid security [148] is prime. Chakib Bekara [149] investigated the security issues and challenges on the IoT-based Smart Grids and defined the major security services that should be considered. Internet of Things (IoT) is the next step evolution of today's Internet where physical objects are equipped with computation and communication capabilities. Initial simulation results in a study on cross-layer security framework [150] illustrate the feasibility and effectiveness of physical security layer developed using a conceptual layering model.

Other security researches include: Location Based Security for Smart Grid Applications, Integrated Smart Grid systems security threat model, Privacy-preserving smart metering with multiple data consumers, and Ortho code privacy mechanism in Smart Grid using ring communication architecture [151–154].

3.3.5. Simulators and information systems

With a great amount of data to be processed and decisions to be made, tools to effectively and efficiently operate Smart Grids help operators, managers and other players achieve easily understandable formats from large complex data. Software systems and solutions offer strategies to enable planning, coordination and safe performance of grid operations. A co-simulator framework for wide-area Smart Grid monitoring systems based on PMUs is presented in a paper by Bhor et al. [155].

Simulating the Smart Grid is an essential tool in their design and implementation. Simulations allow a variety of scenarios and configurations. Real-time simulation platforms can simulate complex Smart Grids with many switching devices and these are effective in testing communication and distributed control [156]. Simulation also helps prevent costly failures. Pochacker et al. compared ten free power system simulators, wherein four were quantitatively compared as well. Agent based modeling functions or information and payments flow were not supported in six of the simulators while the other four newer ones come with information and payment features [157]. SGSim, a unified simulator for Smart Grids provides a distribution side virtual environment that combines power flow and communication [158]. Essentially, the simulator choice depends on the research that needs to be done.

3.3.6. Integration of renewables

While many renewable energy studies have been conducted to explore additional sources of clean energy, integrating renewable energy sources into the power system is one of the challenges in the modernization of the electric grid and making the grid smart. Some grids are already highly congested and moving power from wind farms into the grid for consumption can be difficult. Renewable energy sources are intermittent and inherently variable. Traditionally, electricity has flowed one way, from a power station to a customer. With additional sources coming from alternative sources, electricity has to enter the grid from multiple locations. Grid automation, two-way power flow and modern controls are needed to bring wind, solar and other alternative sources into the distribution grid and move it to its destinations. Coordinated efforts are needed to adapt solar photovoltaic and wind energies and new devices in Smart Grid systems must be able to integrate with existing equipment [159]. Computer tools for analyzing the integration of renewable energy into energy systems are also available. These energy tools are diverse in terms of applications, corresponding technologies and objectives they realize [160].

Feasibility and viability studies around the world are common. These can be used as inputs to the development of various grid-connected renewable energy systems for specific localities. An investigation of 80 kW solar PV-grid connected system, using HOMER energy optimization software, proved the feasibility of the system in Jos, Nigeria [161]. An operation strategy applied in El Hierro Island confirms that a reliable and efficient electrical system is achievable using a combination of wind and hydro units; a model for transient stability analysis was developed for a small isolated grid supplied mainly by renewable sources was used [162]. Optimization of seven remote villages of the Almora District, State of Uttarakhand, India, found the most reliable and cost effective scenario (mix of renewable sources) for the area .

In addition, general renewable energy researches are fundamental to the Smart Grid concept. A study based in Senegal produced a rural electrification kit that formed the basis in the installation of microgrids in some non-electrified villages [163]. This study concluded that hybrid microgrids with high renewable content are promising options for rural electrification in developing countries. Trends in the growth of renewables in India are used to set their targets and point to a need to for capacity building, system sizing and the proper installation, operation and maintenance of these renewable systems [164].

3.3.7. Microgrids, pilots and projects

Smart microgrids, pilots and related projects are being undertaken in many countries and sharing of knowledge and experiences have paved the way for better planning and execution of Smart Grid projects. In countries like the Australia, Canada, Great

Britain, United States, South Korea, Ireland, and Japan, the Smart Grid already forms a vital part of goverment strategy to achieve energy security and low carbon emissions. The Global Smart Grid Federation Report of 2012 [78] has noted the following:

- The intelligent Networks Communities project in Australia is testing network fault detection, isolation and restoration, power quality monitoring and distribution automation with a commercial distribution management system.
- Canada has Transmission Dynamic Line Rating which can optimize the transfer capability of transmission, Wide-Area Control System that improved voltage stability, and the Ontario Smart Metering Initiative which achieved a peak shaving of 5–8%.
- Low Carbon London integrated a number of low carbon technologies like photovoltaic installations, smart meters, electric vehicles, charging stations and heat pumps into the distribution network. In Reading, Berkshire, Slough Heat & Power has integrated into the national grid the world's first cryogenic (low temperature liquid) energy storage solution, thus the name Cryogenic Energy Storage Pilot.
- In the United States, the Pacific Northwest Smart Grid Demonstration Project, showcases a pilot project that spans five states (Montana, Washington, Idaho, Oregon and Wyoming) and includes 22 utilities, to demonstrate continuous coordination of Smart Grid assets. Houston's Smart Grid implements a fully integrated metering system, customer web portal and automatic outage notification. In addition, Smart Texas implements a massive smart meter deployment and distribution automation.
- Korea has the famous Jeju Smart Grid Demonstration Complex incorporating wind and solar, electric vehicles, AMI, energy storage, distributed automation, network monitoring and telemetry. Smart Transportation implements an electric vehicle infrastructure that relies on wireless communication. Renewable Energy Source Operating System is a microgrid demonstration that incorporates large-volume wind generation and battery technologies. Consumer-Participating Smart Place introduces real-time electricity rates, renewable energy sources, smart appliances and storage solutionswith in-home displays.
- In Ireland, the Commission on Energy Regulation (CER) Smart Meter Trial completed a trial of smart meters in around 9000 homes and businesses. A project call Ecar Ireland pilots an electric vehicle charging infrastructure, wherein drivers pay the electricity supplier and not the charging station.
- In Japan, Kit Carson Electric Cooperative builds a network of smart meters at approximately 30% less than the current market costs with the help of Fujitsu's wireless technology solution. A project in Aomori, Hachinohe Microgrid Demonstration Project, tested the performance of a demand-supply control system in the management of renewable energy impact on a commercial power grid. Other significant projects and pilots in Japan are: Total Energy Solutions Test Bed Project where rooftop photovoltaic systems and litium-ion batteries are used to create and store energy, Distribution Stabilizing Solution that verified the efffective voltage regulation of photovoltaics and provided fast voltage control in intermittent conditons, Yokohama Smart City Project that features a Massive Introduction of EVs and Energy Management Using EVs and Miyako-Island Mega-Solar Demonstration Research Facility, a testbed for the study of the impact of photovoltaic generation facilities and rechargeable batteries on power system stability.

An actual large-scale Advanced Metering Infrastructure (AMI) deployment in Spain, discussed in detail in terms of operation, will be used in the European R&D project IGREENGrid (IntegratinG Renewables in the European Electricity Grid) [165]. The project deploys over 200,000 smart meters in the area of Madrid. Field data needed in order to prepare the regulation that should promote distribution system innovation for Smart Grids are identified for Italian Smart Grid pilot projects [166]. As these Smart Grid projects are still in progress and field data are not yet disposable, numerical simulations were developed on a reference network. Gouveia et al. [167] presents the major implementations of Smart Grid projects in Portugal. The entire development process is presented with the real implementation of the developed concepts. Portugal deployed management and control schemes both in a pilot test site and in a laboratory. Indonesia adopted smart meters, although this was received with skepticism due to limited consumer awareness [168]. In addition, a realistic cost benefit analysis metholody for Smart Grid implementation was proposed in a work done in the Czech Republic [169].

Other researches in this category are on: Practical implementation of Smart Grids in the urban area of Milan, Smart Grids in China, Mathematical model for the optimal operation of the University of Genoa Smart Polygeneration Microgrid, Paving the road toward Smart Grids through large-scale advanced metering infrastructures, Smart Grid on field application in the Italian framework, Smart Grid opportunities and applications in Turkey, Criteria for Smart Grid deployment in Brazil by applying the Delphi method, Experimental and data collection methods for a large-scale Smart Grid deployment, The Italian Smart Grid pilot projects: Selection and assessment of the test beds for the regulation of smart electricity distribution, and Stimulating the deployment of Smart Grids with effective regulatory instruments [170–179].

3.3.8. Related technologies

This subsection lists related technologies and researches that are also very relevant to the development of Smart Grids.

3.3.8.1. Demand response [180–186]. Experimental evaluation of BZ-GW (BACnet-ZigBee Smart Grid gateway) for demand response in buildings, Novel air-conditioning system for proactive power demand response to Smart Grid, Hourly demand response and battery energy storage for imbalance reduction of smart distribution company embedded with electric vehicles and wind farms, Fuzzy Subtractive Clustering Technique Applied to Demand Response, Modeling framework and validation of a Smart Grid and demand response system for wind power integration, Forecasting for demand response in Smart Grids, Visualization Aid for Demand Response Studies, Autonomous demand response program for electricity and natural gas networks.

3.3.8.2. Design and architecture [187–195]. Cloud Computing, Designing dependable and sustainable SMART GRIDs, Wireless Sensor Networking Architecture of Polytropon, Model Based Systems Engineering for Smart Grids, Smarter universities, Smart monitoring infrastructure design for distributed renewable energy systems. Standard-based service-oriented infrastructure to integrate intelligent buildings in distributed generation, Multilevel method to assess and design the renovation and integration of Smart Cities, Designing reliable and resilient smart low-voltage grids.

3.3.8.3. Energy management [196–202]. Multi-commodity network flow models for dynamic energy management, Computational Energy Management in Smart Grids, Heuristic approach to Active Demand Side Management in Off-Grid systems, Distributed demand-side management framework, Interactive building power demand management strategy, Demand side management using artificial neural networks, New Scheme for Demand Side Management, Intelligent energy and thermal comfort management.

3.3.8.4. Energy storage [203–211]. Reactive power control for an energy storage system, New perspective for sizing of distributed generation and energy storage for smart households under demand response, Influence of the heat storage size on the plant performance, EV fast charging stations and energy storage technologies, Energy storage model with gridable vehicles for economic load dispatch, Evaluation of a fast power demand response strategy using active and passive building cold storages, Modeling energy storage systems using Fourier analysis, Cold Storage Devices for Smart Grid Integration, Quantifying economic benefits of second life batteries of gridable vehicles.

3.3.8.5. Faults and transients [212, 213]. Multi-agent approach for enhancing transient stability in Smart Grids, Control and Fault Management of Microgrids.

3.3.8.6. ICT and modeling [214–216]. Integrating GIS databases and ICT applications for the design of energy circulation systems, Modeling Smart Grid neighborhoods with the ENERsip ontology, Simulation of the Smart Grid communications: challenges, techniques, and future trends.

3.3.8.7. Smart homes and buildings [217–223]. Smart Home Information Management Model for Device Interoperability Simulation, Application of multi-agent systems in buildings for improved building operations, performance and Smart Grid interaction, Virtual Retrofit Model for aging commercial buildings in a Smart Grid environment, Cross-country review of Smart Grid adoption in residential buildings, Ground source heat pumps for building space conditioning and for integration in Smart Grids, Smart Grid Gateway and its application to demand response, A room level support system for integrating smart technologies into existing buildings.

3.3.8.8. Others [224–231]. Contributions of power electronics, Comparison between time-constrained and time-unconstrained optimization for power losses minimization, Applications of forecasting based dynamic p-cycle reconfiguration under reliable optical network, Smart Grids, information flows and emerging domestic energy practices, Parallel Dual Tabu Search for Capacitor Placement in Smart Grids, A traffic-aware street lighting scheme for Smart Cities, Reliability assessment in distribution, Smart Grid technologies and applications for the industrial sector, Probabilistic solar power forecasting in Smart Grids.

3.4. Future research

Smart Grid research have gone a long way since it first came out in 1997 [72]. While many technologies, systems, devices, methods and processes that enhance Smart Grids have surfaced, there is an immense potential for future research. Among these are:

- new time series forecasting methods for Smart Grids [232]
- new communications infrastructure for self-healing grids, enhanced reliability and power quality studies [233]
- improvement in power flow optimization [234]
- new EV battery techniques to prolong their useful life [1·37,235]
- more practical methods for large scale RES integration [137]
- cloud based control and management studies [236]
- new and improved battery systems [237]

4. Issues and challenges in Smart Grids

Despite obvious success in the development of Smart Grids and their technologies and systems, issues and challenges surround them and ultimate success is still quite far. The following issues and challenges are also potential research areas:

- V2G: battery wearing, low penetration of the EVs, new battery technologies [235]
- barriers to implementation: cost and benefit, knowledge, institutional inertia [238]
- costs, consumer engagement, data protection, privacy [239,240]
- security issues and challenges in the Iot-based Smart Grid [149,241]
- routing design [242]
- interoperability and conformance to standards [243]
- physical security, cyber security, vulnerabilities in AMI [244]
- Smart Grid simulators and co-simulators: able to simulate simple scenarios only, time synchronization and data exchange [216]
- lack of scalable, interoperable context-aware middleware platforms [245]
- compatibility problem with intelligent devices, technological standards for data logging and communication requirements [246]
- distributed generation in distribution system and distribution system automation [247]
- designing strong data encryption schemes, security solutions vary among domains [248]

5. Conclusions

The Smart Grid concept has evolved from a vision into a goal that is slowly being realized. As technology grew, devices and systems are able to support the formation of a more intelligent grid. Concrete energy policies facilitate Smart Grid initiatives across the nations. Smart Grid practices in different regions barely indicate competition but rather an unbordered community of similar aspirations and shared lessons.

This paper has traced the emergence of the the Smart Grid out of the need to modernize the electric grid. Eventually the traditional grid became limited and needed more features. It has identified the functionalities and characteristics of Smart Grids. The paper has presented the Smart Grid fundamental and related technologies and have identified the research activities, challenges and issues that revolved around them. There are opportunities for research in the areas of time series forecasting in Smart Grids, reliability and power quality studies, power flow optimization, battery systems, cloud computing and practical large scale renewable energy sources integration. Even the identified issues and challenges such as battery wearing in V2G, data protection, physical and cyber security, simulator limitations and distribution system automation can be good starting points for future research.

The basic idea of the Smart Grid is not enough when embarking on this complex system. Even with experiences and technologies that are available for reference, the Smart Grid pursuit is an investment of time, money and continuous investigation and testing. With large efforts put forth for Smart Grid research, the Smart Grid can be more effective in helping attain energy sustainability and environmental conservation and preservation. The exact future of the Smart Grid may be difficult to predict, but recent innovations display a dynamic merging of sectors, mechanics and communities.

Conflicts of interest

The authors declare no conflict of interest.

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