A Comparison of Smart Grid Technologies and Progresses in Europe and the U.S.

Marcelo Godoy Simões, *Senior Member, IEEE*, Robin Roche, *Student Member, IEEE*, Elias Kyriakides, *Senior Member, IEEE*, Sid Suryanarayanan, *Senior Member, IEEE*, Benjamin Blunier, *Member, IEEE*, Kerry D. McBee, Phuong H. Nguyen, *Member, IEEE*, Paulo F. Ribeiro, *Fellow, IEEE*, and Abdellatif Miraoui, *Senior Member, IEEE*

***Abstract*—This paper discusses historical and technical events in the U.S. and Europe over the last few years that are aimed at modernizing the electric power grid. The U.S. federal government has ratified the "smart grid initiative" as the official policy for modernizing the electricity grid including unprecedented provisions for timely information and control options to consumers and deployment of "smart" technologies. European countries are unified in researching and developing related technologies through various structures supported by the European Union. This paper presents the development of smart grids and an analysis of the methodologies, milestones, and expected evolutions of grid technologies that will transform society in the near future.**

***Index Terms*—Control, distributed generation (DG), power electronics, power systems, smart grid, smart metering, storage.**

I. Introduction

THE PRESENT-DAY electric grid was built about a century ago in most industrialized countries and has been growing in size and capacity ever since. Transmission lines connect large centralized power sources to the grid and have been technologically updated with automation and human monitoring over the last few decades. The electrification of our society has empowered countless advances in other fields such that the U.S. National Academy of Engineering ranked it as the greatest engineering achievement of the last century [1]. However, this transformation was mostly in the transmission realm and not in the distribution milieu since the latter has traditionally been considered as user end points of service, where power was delivered to traditional loads. The last two decades saw a steady growth of distributed generation (DG), with plans for higher penetration of renewable energy sources, and the policies on electricity distribution have been supporting needs for a "smart grid" for many reasons that will be discussed in this paper. Centralized power plants have enormous economic constraints and benefits, and utilities have been trying to use their assets more efficiently. As an example, typically, 20% of the U.S. generation capacity is used only for 5% of a year to meet peak demand and is based on coal and gas power plants, which cause environmental concerns and greenhouse gas (GHG) emissions. A paradigm shift in distribution engineering is viewed as the next frontier of advancement in electric power systems, and the smart grid is expected to introduce unprecedented changes in the distribution systems worldwide. Both the U.S. and European economies have taken the lead in establishing some early concepts and policies for realizing the smart grid. In this paper, a comparison of the various smart grid technologies and the paths of progress in the U.S. and in Europe is presented.

Manuscript received November 25, 2011; accepted January 23, 2012. Date of publication May 16, 2012; date of current version July 13, 2012. Paper 2011-ESC-567, presented at the 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, September 17–22, and approved for publication in the IEEE Transactions on Industry Applications by the Energy Systems Committee of the IEEE Industry Applications Society.

M. G. Simões and K. D. McBee are with the Colorado School of Mines, Golden, CO 80401 USA (e-mail: msimoes@mines.edu; kerry.d.mcbee@xcelenergy.com).

R. Roche is with IRTES-SET, Université de Technologie de Belfort–Montbéliard, 90010 Belfort, France (e-mail: robin.roche@utbm.fr).

E. Kyriakides is with the University of Cyprus, 1678 Nicosia, Cyprus (e-mail: elias@ucy.ac.cy).

S. Suryanarayanan is with Colorado State University, Fort Collins, CO 80523 USA (e-mail: ssuryana@mail.colostate.edu).

B. Blunier, deceased, was with IRTES-SET, Université de Technologie de Belfort–Montbéliard, 90010 Belfort, France.

P. H. Nguyen and P. F. Ribeiro are with the Technische Universiteit Eindhoven, 5600 MB Eindhoven, The Netherlands (e-mail: P.Nguyen.Hong@tue.nl; pfribeiro@ieee.org).

A. Miraoui is with IRTES-SET, Université de Technologie de Belfort–Montbéliard, 90010 Belfort, France, and also with Cadi Ayyad University, Marrakesh 40000, Morocco (e-mail: abdellatif.miraoui@utbm.fr).

Digital Object Identifier 10.1109/TIA.2012.2199730

II. Evolution of the Smart Grid in the U.S. and Europe

Conceptualization of techniques to improve the intelligent interaction of distributed assets for smart grids emerged in the 1980s as a call to modernize the grid, allowing deeper penetration of alternative and renewable energy sources. The first references to the term *smart grid* were provided around 2004 by Amin and Wollenberg [2], [3]. While some common characteristics of a smart grid exist, Europe and the U.S. have been following different paths to make their respective grids smarter.

A. Trajectory in the U.S.

The electric grid in the U.S. is composed of approximately 15 000 generators operating in 10 000 power plants, accounting for approximately 3.95 million MWh (as of 2009), with approximately 160 000 miles of high-voltage transmission lines (at voltages typically above 280 kV) [4], [5]. The electric grid in the U.S. evolved from small-rated centralized power stations, such as the historical Pearl Street Station in Manhattan, NY (such power stations supplied dc electricity to relatively smaller rated loads in the late 19th century), to the interconnected ac

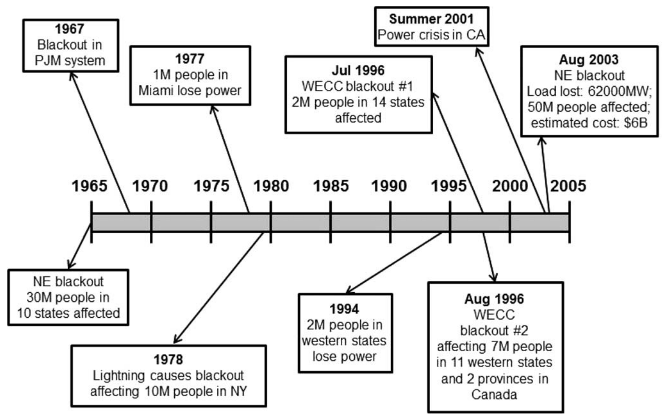

Fig. 1. Timeline of major events in the U.S. electric grid.

system of present day that crisscrosses North America [6]. The present-day massive North American grid consists of three large asynchronous interconnections, namely, the Western Electricity Coordinating Council system, the Eastern Interconnection, and the Electric Reliability Council of Texas, and has been referred to as the "most complex man-made machine" [7]. The evolution of the smart grid in the U.S. may be traced to several innovations in the transmission grid, such as the wide-area measurement and fast controls, and the installation of power system stabilizers, phase shifting transformers, flexible ac transmission system devices, and phasor measurement units (PMUs). Additionally, the advent of advanced control room visualization has heralded the template for the smart grid. Public awareness and concomitant push for more renewable energy sources in the grid have also provided some impetus to the integration of newer technologies in the grid.

However, the modernization of the electricity grid has been largely restricted to the transmission systems and did not penetrate the distribution system level as much. This may be attributed to factors such as higher variability in system scenarios at the latter level and a relatively low economy of scale when compared to the transmission systems. Several legislative mandates have provided various opportunities for the modernization of the electric grid in the U.S. Fig. 1 shows a timeline of some events related to the electricity grid in the U.S. that have served as harbingers to important changes via mandates and legislations.

B. Trajectory in Europe

The unification of the European grid was achieved in parallel to the economical unification of European countries. This process has been slow, due to the high cost of building new infrastructures and historical events such as the two world wars and the political separation of Eastern and Western Europe for more than four decades.

The idea of a pan-European grid was first discussed by the League of Nations in the 1920s. This became a reality only in 1951 with the creation of the Union for the Coordination of Production and Transmission of Electricity [which eventually became the Union for the Coordination of Transmission of Electricity (UCTE)], which was aimed at interconnecting the grids of France, Germany, and Switzerland. Similar associations were created in other regions of Europe, such as NORDEL or SUDEL. However, during the Cold War, a real interconnection of the western and eastern parts of Europe was nearly impossible, and European countries reorganized such interests only after 1990, with the fall of the Iron Curtain. In 2008, the regional associations ETSO, ATSOI/UKTSOA (Ireland, Great Britain), NORDEL (Finland, Sweden, Norway, and Eastern Denmark), UCTE (23 continental European countries), and BALTSO (Baltic countries) merged into the European Network of Transmission System Operators for Electricity (ENTSO-E), which now coordinates 41 Transmission System Operators (TSOs) from 34 countries [8]. Smart grid policies in Europe are relatively new, while at the same time, the European grid is becoming more interconnected and sees that investments decrease. However, the sense of ownership and contribution of each individual country to the whole grid is different from how the U.S. directs initiatives through its Department of Energy. Some recent European Union (EU) initiatives are as follows.

1) The European energy program for recovery (2009), which has some similarities to the U.S. Stimulus Fund. This program was aimed at speeding up and securing investments for projects in the energy sector.
2) An overall energy-efficiency action plan (2007–2012) establishes a firm objective of 20% improvement.
3) The European energy infrastructure package identifies smart grids as the key infrastructure for energy modernization in Europe.
4) The Competitiveness and Innovation Framework Program proposes an intelligent energy for Europe program.
5) The European Energy Research Alliance aims at accelerating the development of new energy technologies by maximizing funding sources, facilities, and complementarities among institutes in participating countries.

III. Governing Bodies in Smart Grid Development

The U.S. Smart Grid Initiative is the official policy of grid modernization in the U.S. as formalized by the 2007 Energy Independence and Security Act (EISA07) [9]. Under the purview of this legislative mandate, the U.S. smart grid is characterized by the following:

1) increased digital information and controls;
2) dynamic optimization of grid operations, including cyber security;
3) deployment of distributed resources, including renewable resources;
4) incorporation of demand-side resources and demand response;
5) deployment of "smart" technologies and integration of "smart" appliances and consumer devices;
6) deployment of storage and peak-shaving technology, including plug-in hybrid electric vehicle (PHEV);
7) provision of timely information and control options to consumers;
8) standard development for communication and interoperability of equipment;

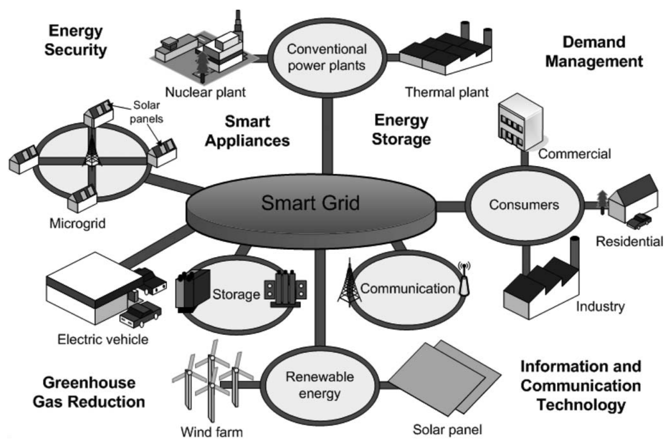

Fig. 2. Future electric smart grid.

9) identification and lowering of unreasonable barriers to adopt smart grid technology, practices, and services [9].

An illustration of an implementation of the smart grid is shown in Fig. 2. The U.S. National Institute of Standards and Technology (NIST) provides a conceptual model that defines seven important domains: bulk generation, transmission, distribution, customers, service providers, operations, and markets [10].

In the EU, the smart grid strategy is motivated by concepts of innovation with regard to social and environmental reforms for an interactive economy. The European energy policy relies on [11] the following: 1) security of supply; 2) sustainability; and 3) market efficiency. In addition, six goals have been set for the EU energy strategy: 1) to achieve the highest levels of safety and security; 2) to achieve an energy-efficient Europe by improving buildings, transportation, and distribution grids; 3) to extend Europe's leadership in energy technology and innovation; 4) to empower consumers; 5) to build a European integrated energy market; and 6) to strengthen the external dimension of the EU energy market. The European Strategic Energy Technology Plan includes eight European Industrial Initiatives (EIIs) in the field of energy. The EII on electrical grids is called the European Electricity Grid Initiative and has a budget estimated to 2 billion over a period of ten years with guidelines and activities for research and development (R&D) and a program with 20 large-scale demonstration projects [12].

The EU established the Third Energy Package in 2007 with objectives and regulations for the implementation of smart grids stating that all European citizens have a range of energy-related rights, such as consumer choice and fair prices. Dispositions are also taken to favor international energy (electricity and gas) trade, collaboration and investment, separation of generation and supply from transmission networks, decentralized generation and energy efficiency, and smart meters and effective national regulators. The European Technology Platforms began to operate in 2005 [13] in formulating and promoting a vision for the development of smart grids for year 2020 in compliance with the EU policy. "Smart Grids Task Force" was created in 2009 and is composed of European Commission officials, experts from the industry, policy makers, and academia [14]. The first projects related to smart grids were grouped within the Integration of Renewable Energy Sources and Distributed Generation into the European Electricity Grid cluster. Over 60 projects in the fields of smart grids have been supported by the Sixth Framework Program and correspond to an investment of about 190 million. The Seventh Framework Program, the current program, will run until 2013 and has a total budget of 51 billion, with 7% of it dedicated to energy-related projects [15]. Currently, the related EU associations for promoting smart grid projects are as follows:

1) the European Regulators Group for Electricity and Gas and the Council of European Energy Regulators, which allow national regulators to cooperate;
2) the new Agency for the Cooperation of Energy Regulators, a complement to the two previous organizations and ENTSO-E;
3) the European Distribution System Operators Association for Smart Grids;
4) the Union of the Electricity Industry (EURELECTRIC), which represents the common interests of the electricity industry at the European level.

IV. Enabling Technologies

Several technologies have to mature in order to make the smart grid a reality [16], [17].

A. DG

DG (also referred to as embedded generation or dispersed generation) refers to small rating electricity sources that are typically decentralized and located close to end-user locations on the distribution side of the electric grid. These may include conventional as well as renewable energy sources. The interconnection of DG to the grid provides a variety of advantages, including on-demand power quality of supply, enhanced reliability, deferrals in transmission investment, and avenues for meeting renewable mandates in the face of growing disinvestments in transmission assets—all of which cater to the smart grid philosophy. However, the interconnection of DG is a challenge due to the safety, control, and protection issues associated with bidirectional flows of electricity. In the U.S., the Energy Policy Act of 2005, enacted by the 109th Congress recognized the IEEE 1547 Standard as the national technical standard for interconnection of DG to the electric grid [18]. Further information about DG is available in [19].

B. Energy Storage

Electricity is a highly perishable commodity that must be consumed within a very short span of production and cannot be easily stored, particularly in high quantities. Alternatively, it may be converted into other forms such as mechanical or electrochemical energy. Storage technologies enable these processes and are among the desired features for the smart grid. Multiple existing technologies are compared in Fig. 3. Storage, which can be distributed in the grid, provides the following advantages: 1) makes the grid more efficient [20]; 2) enables load leveling and peak shaving, while it reduces dependence on spinning reserve; 3) improves grid reliability and

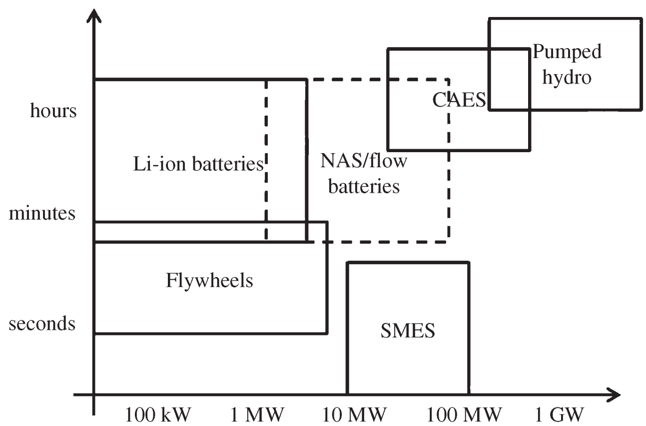

Fig. 3. Comparison of discharge duration versus rated power for some grid energy storage technologies.

power quality; 4) provides ancillary services, supplying reactive power for voltage regulation; and 5) supports transmission-and-distribution (T&D) investment deferral. Energy storage with power-electronics-interfaced units can create virtual rotational inertia, the so-called virtual synchronous generators, which can reduce the rate of change of frequency and frequency deviations [21].

C. Power Electronics

Power electronics is fundamental in the development of smart grids because a deeper penetration of renewable and alternative energy sources requires sophisticated power converter systems. Typically, a power converter is an interface between the smart grid and local power sources [22]. Solar photovoltaic and wind energy systems play a significant role as alternative sources for integration in smart grids and are increasingly being installed in residential and commercial locations (typically with a power range of a few kilowatts) as well at high rating in the high-voltage transmission grid. The intermittent nature of these sources affects the output characteristics of generator and converter sets. A power electronics converter is deemed necessary to smooth the output to the desired characteristics and to allow energy storage during surplus of input power and compensation in case of lack of input power. The following characteristics are important for power electronics systems for smart grids.

1) High efficiency: Only a negligible part of the power should be dissipated during conversion stages.
2) Optimal energy transfer: All renewable energy sources are energy constrained and, as such, need algorithms to achieve the maximum power point which must be considered in the design of the power electronics interface.
3) Bidirectional power flow: Power converters have to be able to supply the local load and/or the grid.
4) High reliability: Continuity of service is a major issue when delivering energy.
5) Synchronization capabilities: All power sources connected to the grid have to be fully synchronized, thus ensuring high efficiency and eliminating failures; therefore, standards such as IEEE 1547 should be incorporated in power electronics interfaces [23].
6) Electromagnetic-interference filtering: The quality of the energy injected into the grid must adhere to apt electromagnetic-compatibility standards.
7) Smart metering: The interface between the local source/load and the grid must be capable of tracking the power consumed by the load or injected into the grid.
8) Real-time information must be passed to an automatic billing system capable of taking into account parameters such as energy bought/sold in real time, informing end users of all required pricing parameters.
9) Communications: The intelligent functioning of the smart grid depends on the capability to support a communication layer in tandem with an energy delivery layer in the grid.
10) Fault tolerance/self-healing: A key issue is a built-in ability to minimize the propagation of failures and resilience against such local failures. This capability should be incorporated with monitoring, communication, and reconfiguration features of power electronics systems. Additionally, power electronics interfaces must be configured to avoid nuisance trips.

D. Control, Automation, and Monitoring

A smart grid is a highly complex nonlinear dynamic network of distributed-energy assets with bidirectional flow of power and information that presents many theoretical and practical challenges. Monitoring and control are key issues that need to be addressed to make it more intelligent and equip it with self-healing, self-organizing, and self-configuring capabilities. This requires much more sophisticated control, sensing, and computer-oriented monitoring than in the contemporary grid, where grid operations are rather reactive, with a number of critical tasks performed by human operators. Therefore, some modern control techniques have been claimed to be the best fit for smart grids, for example, agent-oriented programming and implementing computational intelligence into distributed-system operation [24]; however, most of these are yet to transcend the research domain into large-scale deployment. A combination of agent-based control techniques and power electronics possess the potential to create an intelligent and flexible interface between consumers, storage, DGs, and the network, as well as among network areas. Fig. 4 shows different power electronics layers to integrate a cluster of prosumers (an entity in the future grid capable of both producing and consuming electric power) into the grid.

The two-way communication ability of smart meters allows the transmission of delivered and generated energy data along with actionable commands to customers. With technologies such as WIFI, ZigBee, and home area network (HAN) communication systems, smart meters can now act as interfaces for energy management entities, customers, and utilities to control a number of appliances within a residential home based on price signals [25].

Power quality analyzing capabilities of smart meters may improve the ability to identify system and customer voltage

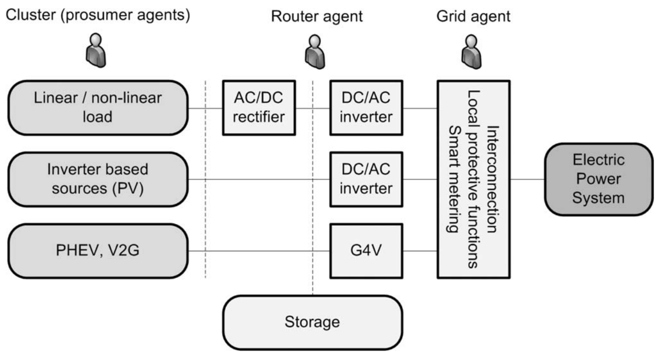

Fig. 4. Intelligence-based control structure for power electronics in smart grids.

deficiencies, harmonic distortions, and onset of equipment failure. Daily energy usage and generation profiles may be recorded for forecasting-relevant system parameters. Threshold voltage events can trigger communication with utilities for providing alerts to disturbances, prior to customer equipment failure or discomfort. These functionalities may also improve the ability of utilities to locate the source of system events, which is a difficult and complex task on the existing electric distribution system, but may introduce the risk of increased susceptibility to cyber intrusions by malicious agents [26]. Several utilities in the U.S. and Europe have already seen improved power quality due to the installation of smart meters [27].

E. DSM

Demand-side management (DSM) refers to the ability to change energy consumption patterns and characteristics via structured programs. Historically, most DSM programs aimed at achieving targets in energy efficiency, while some conservation programs aimed at deferring investments in new assets (including generating facilities, power purchases, and T&D capacity additions). However, with the advent of the smart grid, DSM may provide paradigm shifts in the normal operation of the electricity market or from government-mandated energy-efficiency standards. In the last few years, there has been an increased interest in dynamic pricing, i.e., a time-varying pricing at the end-user level, different from the state of the art of tariffs. Dynamic pricing, which is available in the U.S. bulk power (transmission) markets since mid-1990s following deregulation of the industry, has enabled economic efficiency, fostered investments in technological innovations, and, for the most part, removed the ills of market power and monopoly [28]. Such a differentiated or tiered rate of electricity in the distribution system is viewed as an enabler for the smart grid. When enabled with such information on dynamic pricing of electricity, customers and utilities will need to interact via DSM structures aimed at increased energy efficiency, lowered cost of engaging inefficient and costly generators at peak periods, coordinated charging of PHEVs, or other similar objectives. Several dynamic pricing models have been proposed in order to better reflect the actual cost of producing energy on the specific day and time and provide incentives to customers to become more active in controlling their electricity consumption [29], [30]. The following time-varying pricing methodologies are viewed as possible enablers of DSM.

1) Time-of-use (TOU) electricity rates have been shown to be effective in promoting customer participation in demand management [30]. TOU rates use predetermined time intervals during which electricity use is recorded. Each time interval has a fixed price that is proportional to the electricity availability during that same time interval.
2) Real-time pricing is a methodology whereby the customer is informed a time period ahead of the electricity price so as to make rational decisions regarding the consumption of electric energy. The retail price of electricity in this pricing methodology floats based on the actual cost of electricity. If the time period is 1 h, then real-time pricing is known as hour-ahead pricing.
3) Critical peak pricing is used to "force" customers to avoid consuming electric energy during specific peak periods. These periods are well defined by the utility, and the cost of electricity during these periods is increased significantly.
4) The peak time rebate has a similar concept as the critical peak pricing. Instead of a penalty, the conscious customer receives a reward for reducing their electricity consumption below a certain baseline. If the customer consumes more than the baseline, there is no penalty imposed.

Data management is critical for the widespread operation of the smart grid in the near future, because vast raw data will have to be processed, aggregated, validated, and transmitted for further processing and analysis.

F. Distribution Automation and Protection

Smart grid technology supports a wide range of applications in power systems, such as protection and automation of the distribution system and security. It is possible to design self-healing protection systems using the capabilities of the advanced distribution automation [32]. The protection of the power system is a critical necessity in order to achieve continuity, reliability, and security of supply. Protection deals with the detection and clearance of abnormal system conditions such as faults and overloads. High penetrations of DG can compromise existing protection schemes, which are based on single sources supplying unidirectional power through radial distributed lines. In the smart grid, where bidirectional flow of electricity through partially networked systems in the distribution milieu will be prevalent, protection mechanisms are adaptive and incorporate intelligent automated functions. Recent activities in protection engineering focus on developing microprocessor-based devices called intelligent electronic devices. Such devices may be smart distribution switches or integrated solutions for substations. The International Electrotechnical Commission (IEC) 61850 Standard (Communication Networks and Systems in Substations) provides authoritative information relevant to the design of substation automation [33].

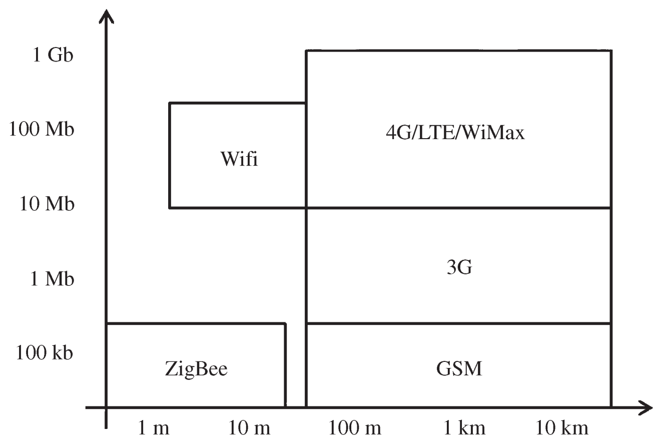

Fig. 5. Characteristics of some wireless communication technologies: Bandwidth versus transmission range.

G. Communication Systems

Self-healing systems have been sought to be incorporated into power systems, particularly as the complexity and interactions of several market players significantly increase the risk for large-scale failures. Reconfiguring the system in islanded mode may require hitherto unknown rate and amount of data exchange, two-way communication links, and advanced central computing facilities. Decentralized intelligent control could enable islands to accommodate their native load and generation in a more reliable and efficient manner. Local controllers may ensure that each island is operating within the security limits, safeguarding the electricity supply to its customers [34]. A self-healing system should be based on a wide-area monitoring network that incorporates a variety of sensors, such as PMUs that obtain phasor measurements by synchronizing with each other through the global positioning service [34], [35].

The measurements and signals obtained from sensors may be used either by local (distributed) or centralized controllers to enable the self-healing of the system under disturbance or fault conditions. These measurements and signals may be submitted for processing to a single controller, despite the fact that they may be originating from different proprietary networks [36]. IEEE Standard 1451.4 requires analog sensors to have a transducer electronic data sheet to provide calibration information to the data acquisition system [37], [38]. Fig. 5 shows how several communication technologies can be applied for such data, according to their characteristics. The ranges of operation and bandwidth of these technologies vary significantly; some of them may be chosen for HAN, while others may be used for longer distances such as from houses to concentrators or between substations [27].

Two-way-communication-enabled smart appliances, smart meters for control of sources, loads, and storage must be implemented in a platform that allows both digital information and electric energy to flow through a two-way smart infrastructure. The requirements for these communication infrastructures are reliability and resilience, bandwidth, interoperability, and costs. Several communication protocols and media are currently under various stages of R&D for implementation in smart grids. Examples include broadband over power line and power line communications, which use existing power lines to transmit information; Ethernet, digital subscriber line, and optic fiber, which are already in use for the Internet; ZigBee and WIFI, which are already used for HAN applications; WiMaX, a "super WIFI," with a much higher range; and 3G, LTE/4G, and other mobile telephone communication protocols.

V. Comparative Metrics for the U.S. Versus Europe

Making the grid smarter requires considering all aspects of smart grids as part of the decision-making process. This section compares the practices in the U.S. and the EU on several topics for the development of smart grid technologies.

A. Legislation in the U.S.

The legislation that led to the present-day U.S. Smart Grid Initiative might be traced back to the 1970s, when deregulation was initially introduced as a direct result of the Arabic oil embargo that escalated a nationwide energy crisis. In 1977, the Federal Power Commission was restructured to form the Federal Energy Regulatory Commission (FERC), with the objective of regulating energy transactions and transmission across different states in the Union. The National Energy Act of 1978 was passed to conserve energy and increase efficiency by judicious use of resources and amenities by utilities and introduced the Public Utilities Regulatory Policies Act, which advocated the need for small power productions, for cogeneration and for renewable energy sources that could compete as independent power producers in the electricity market with other utilities. The 102nd Congress of the United States passed the Energy Policy Act of 1992, which included provisions for alternative fuels, electric motor vehicles, energy-efficiency improvement, and energy-conservation techniques [39]. FERC mandated open transmission access, with the mandated open-access transmission tariff requiring that all investor-owned utilities make separate functionalities of generation, distribution, transmission, and marketing services. It also mandated the creation of independent system operators, eventually making possible the creation of an open-access same-time information system—a Web-based secure database of transmission-system-related information. These orders were the template for the evolution of the deregulated electricity market structure that is currently in place in the U.S.

Following the Northeast blackout of August 2003 in the U.S., the 109th U.S. Congress passed the 2005 Energy Policy Act, with provisions for tax incentives and subsidies for renewable-energy integration and energy-efficiency technologies. Fig. 6 shows a timeline of some key legislative events in the U.S. history vis-à-vis the smart grid. The 110th U.S. Congress is credited with passing the EISA07, which explicitly characterized the smart grid through the U.S. Smart Grid Initiative in Title XIII. The other highlights of this act included electrifying the transportation fleet, reductions in fossil fuel usage in certain sectors, and carbon sequestration. This was followed by the American Recovery and Reinvestment Act of 2009 (ARRA09), passed by the 111th U.S. Congress, which included provisions

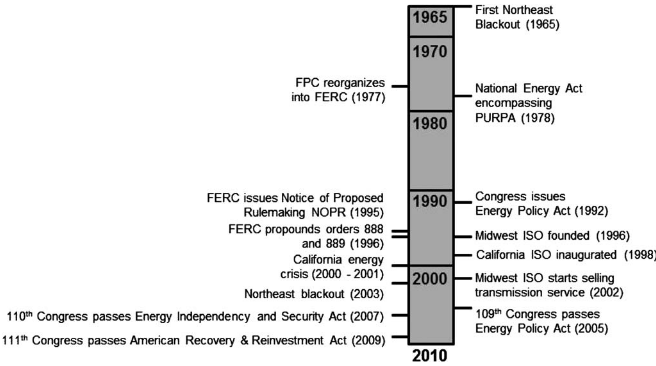

Fig. 6. Key U.S. legislative events vis-à-vis the smart grid.

TABLE I
SELECTED U.S. SMART GRID PROJECTS (FROM [40])

Project Type	**Number of Projects**
Automated meter infrastructure (AMI)	81
Customer systems	8
Distribution systems	15
Equipment manufacturing	2
Integrated systems	54
Regional demonstration	16
Storage demonstration	16
Transmission system	10
Total number as of June 2011	**~ 202**

for energy infrastructure improvements via the implementation of the smart grid. Table I lists some details of selected smart grid projects in the U.S. supported under ARRA09 [40]. The Smart Grid Clearing House is a Web resource that lists all ARRA09-funded smart grid projects geographically as well as according to their technical focus.

B. Legislation in Europe

Energy needs are responsible for 80% of all European GHG emissions [13]. Therefore, climate change legislation and energy policy have been intimately linked with a strong impact on investment decisions from private companies. As a consequence of the Kyoto protocol, European leaders made a unilateral commitment to reach three legally binding objectives by 2020, known as the "20–20–20" targets [41]:

1) reach a 20% share of energy consumption coming from renewable sources;
2) achieve a reduction of 20% of primary energy use through energy-efficiency measures;
3) reduce GHG emissions by at least 20% below 1990 levels.

With the Third Energy Package, additional requirements were introduced, such as the encouragement to roll out 80% smart meters in Europe by 2020 [42]. GHG target reductions may be increased to 30% if other major emitting countries set themselves ambitious objectives. A proposal to cut emissions by 80% to 95% by 2050 has also been suggested. Table II shows a list of selected smart grid projects in Europe supported by EU funding in the last few years [43].

TABLE II
SELECTED EU SMART GRID PROJECTS (FROM [43])

Project	**Focus**
More-Microgrids (FP6)	DER, microgrids
FENIX (FP6)	RES integration
EU-DEEP (FP6)	Business models
ADDRESS (FP7)	DER integration, demand management
SmartHouse/SmartGrid (FP7)	Smart buildings
MERGE, G4V (FP7)	Impact of electric vehicles
Green eMotion (FP7)	Business models for electric vehicles

C. Barriers

Several barriers may slow down the development of smart grids on both continents, as depicted next. A first issue is related to financing. During 2009, stimulus plans were used for funding dozens of projects. However, as more and more governments are taking austerity measures, this funding is expected to decrease, or not be renewed, and will need to be either replaced or supplemented by private funding sources. This raises the question of the real interests of the many stakeholders in the smart grid. The cost to modernize distribution networks is high, and utilities may consider if the benefits will overweigh the costs. Moreover, the smart grid requires utilities to make significant changes to their present business models (e.g., reducing demand is contradictory with present-day models). Regulators are expected to balance costs in order to ensure that each player finds an acceptable ratio between the costs and returns on investments. They should also enable dynamic electricity pricing, a requirement for demand response actions and DSM programs to achieve success. The acceptance of consumers regarding smart metering and changes in general is a challenge. In some U.S. states, consumers raised concerns to the installation of smart meters, regarding an increase of the electricity bill, or the privacy of information transmitted to the utility. Technology maturity and availability present another challenge, particularly regarding distributed-energy-resource integration and control. The operating security is also critical, as shown by the Stuxnet case [44]. The establishment of standards for smart grids is also a crucial step. By allowing components to interact with each other, and ultimately to reduce costs, standards will enable true interoperability between assets produced by various companies. The U.S. NIST, IEEE, IEC, and other organizations have been working on several standardization activities.

VI. PATH FORWARD

The EU and the U.S. have different approaches in fostering smart grid technology. Europe has been influenced by concerns derived from the diversity and evolution of power grids across European countries, while the U.S. needs to increase security and to respond to the predicted growth in demand for a long-term vision. It is expected that such technologies will have widespread growth subject to economies of scale. Distribution networks will dramatically change in the near future, and energy storage is expected to become increasingly available, even at the distribution level, in order to compensate the intermittent nature of renewable energy sources that will penetrate the distribution sector. Communication and user interfaces will be pervasive, and the integration with the new web of things will allow individual home and business electric devices to be controlled and operated from remote locations. Power distribution will be more controllable and dispatchable, and new distribution systems will have massive automation and sensing systems that will allow any user to interact with any other one on the electrical network. A smart grid is expected to emerge in the U.S. and in Europe in the next decade and to evolve thereafter; notwithstanding the avatar of this smart grid, which will be a function of the policies shaping this evolution, the desired characteristics of resilience, sustainability, increased energy efficiency, engaging highly dispersed assets with temporal and spatial stochastics, and breeding a new class of informed customers who engage in the grid operations are expected to be achieved.

ACKNOWLEDGMENT

The authors dedicate this paper to the memory of their friend and coauthor, Dr. B. Blunier, formerly an Associate Professor with the Université de Technologie de Belfort–Montbéliard, who passed away on February 23, 2012.

REFERENCES

[1] W. A. Wolf, “Great achievements and grand challenges,” *Nat. Acad. Eng. Bridge*, vol. 30, no. 3/4, p. 6, 2000.
[2] S. M. Amin and B. F. Wollenberg, “Toward a smart grid: Power delivery for the 21st century,” *IEEE Power Energy Mag.*, vol. 3, no. 5, pp. 34–41, Sep.–Oct. 2005.
[3] S. M. Amin, “Balancing market priorities with security issues,” *IEEE Power Energy Mag.*, vol. 2, no. 4, pp. 30–38, Jul./Aug. 2004.
[4] Energy Information Administration, “Electric power annual report revision,” U.S. Dept. Energy, Washington, DC, Apr. 2011. [Online]. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_noticerev2.html
[5] American Society of Civil Engineers, “Report card for American’s infrastructure: U.S. electric power grid,” ASCE, Reston, VA, 2005. [Online]. Available: http://www.asce.org/reportcard/2005/page.cfm?id=25
[6] IEEE Global History Network, Pearl Street Station, (accessed: Jun. 2011) 2008. [Online]. Available: http://www.ieeeghn.org/wiki/index.php/Pearl_Street_Station
[7] T. J. Overbye and J. D. Weber, “Visualizing the electric grid,” *IEEE Spectr.*, vol. 38, no. 2, pp. 52–58, Feb. 2000.
[8] ENTSO-E, Annual report 2009, 2010. [Online]. Available: https://ww.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/Annual_Report/100610_ENTSO-E_Annual_Report_2009.pdf
[9] 110th US Congress, 2007 Energy Independence and Security Act (EISA07), Dec. 2007.
[10] Framework and Roadmap for Smart Grid Interoperability Standards, 2010, Release 1.0.
[11] European Commission, COM(2010) 639 final, Energy 2020: A Strategy for Competitive, Sustainable and Secure Energy, 2010.
[12] European Electricity Grids Initiative, Roadmap 2010-18 and Detailed Implementation Plan 2010–2012, 2010.
[13] European Commission, “Vision and strategy for Europe’s electricity networks of the future,” Smart Grids European Technology Platform, 2006.
[14] Task Force Smart Grids—Vision and Work Programme, 2010. [Online]. Available: http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/work_programme.pdf
[15] European Commission, FP7 Tomorrow’s Answers Start Today, 2006. [Online]. Available: http://ec.europa.eu/research/fp7/pdf/fp7-factsheets_en.pdf
[16] S. Suryanarayanan and J. Mitra, “Enabling technologies for the customer-driven microgrid,” in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Calgary, AB, Canada, 2009, pp. 1–3.
[17] Y. Xinghuo, C. Cecati, T. Dillon, and M. G. Simões, “The new frontier of smart grids,” *IEEE Ind. Electron. Mag.*, vol. 5, no. 3, pp. 49–63, Sep. 2011.
[18] 109th U.S. Congress, 2005 Energy Policy Act (EPAct05), Jul. 2005.
[19] F. A. Farret and M. G. Simões, *Integration of Alternative Sources of Energy*. Hoboken, NJ: Wiley, 2006.
[20] G. D. Rodriguez, “A utility perspective of the role of energy storage in the smart grid,” in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Minneapolis, MN, Jul. 2010, pp. 1–2.
[21] ECN, VSYNC Project. [Online]. Available: http://www.vsync.eu/
[22] R. Carnieletto, D. I. Brandão, S. Suryanarayanan, F. Farret, and M. G. Simões, “Smart grid initiative,” *IEEE Ind. Appl. Mag.*, vol. 17, no. 5, pp. 27–35, Sep./Oct. 2011.
[23] *IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems*, IEEE 1547 Standard, 2003.
[24] T. Ericsen, Y. Khersonsky, P. Schugart, and P. Steimer, “PEBB—Power electronics building blocks, from concept to reality,” in *Proc. 3rd IET Int. Conf. Power Electron., Mach. Drivers*, 2006, pp. 12–16.
[25] A. R. Metke and R. L. Ekl, “Security technology for smart grid networks,” *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 99–107, Jun. 2010.
[26] S. Clements and H. Kirkham, “Cyber-security considerations for the smart grid,” in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Minneapolis, MN, Jul. 2010, pp. 1–5.
[27] K. D. McBee and M. G. Simões, “Utilizing a smart grid monitoring system to improve voltage quality of customers,” *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 738–743, Jun. 2012, doi: 10.1109/TSG.2012.2185857, [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=6191343&isnumber=6204228
[28] D. Kirschen and G. Strbac, *Fundamentals of Power Systems Economics*. Chichester, U.K.: Wiley, 2004.
[29] A.-H. Mohsenian-Rad and A. Leon-Garcia, “Optimal residential load control with price prediction in real-time electricity pricing environments,” *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 120–133, Sep. 2010.
[30] S. Shao, T. Zhang, M. Pipattanasomporn, and S. Rahman, “Impact of TOU rates on distribution load shapes in a smart grid with PHEV penetration,” in *Proc. IEEE PES Transmiss. Distrib. Conf. Expo.*, New Orleans, LA, Apr. 2010, pp. 1–6.
[31] R. W. Uluski, “The role of advanced distribution automation in the smart grid,” in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Minneapolis, MN, Jul. 2010, pp. 1–5.
[32] N. Higgins, V. Vyatkin, N. C. Nair, and K. Schwarz, “Distributed power system automation with IEC 61850, IEC 61499, and intelligent control,” *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 41, no. 1, pp. 81–92, Jan. 2011.
[33] *Communication Networks and Systems in Substations*, International Electrotechnical Committee Standard IEC 61850, 2003.
[34] S. M. Amin, “For the good of the grid,” *IEEE Power Energy Mag.*, vol. 6, no. 6, pp. 48–59, Oct. 2008.
[35] S. Chakrabarti, E. Kyriakides, and D. G. Eliades, “Placement of synchronized measurements for power system observability,” *IEEE Trans. Power Del.*, vol. 24, no. 1, pp. 12–19, Jan. 2009.
[36] B. Betts, “Smart sensors,” *IEEE Spectr.*, vol. 43, no. 4, pp. 50–53, Apr. 2006.
[37] *IEEE Standard for a Smart Transducer Interface for Sensors and Actuators—Mixed-Mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats*, IEEE Standard 1451.4-2004, Dec. 2004.
[38] Q. Zou and L. Qin, “Integrated communications in smart distribution grid,” in *Proc. Int. Conf. POWERCON*, Oct. 2010, pp. 1–6.
[39] 102nd US Congress, 1992 Energy Policy Act (EPAct92), Oct. 1992.
[40] Smart Grid Clearing House, 2011. [Online]. Available: http://www.sgiclearinghouse.com
[41] European Commission, Combating Climate Change: The EU Leads the Way, 2008.
[42] European Parliament, PE 425.401 Texts Adopted—Part II, At the Sitting of Wednesday, 22 April, 2009, PE 425.401.
[43] European Commission CORDIS, 2011. [Online]. Available: http://cordis.europa.eu
[44] J. Stromback and C. Dromacque, “Evaluation of residential smart meter policies,” WEC-ADEME Case Studies on Energy Efficiency Measures and Policies, Jul. 2010. [Online]. Available: http://www.ffydd.org/documents/ee_case_study__smart_meters.pdf
[45] B. Kroposki, C. Pink, R. DeBlasio, H. Thomas, M. G. Simões, and P. K. Sen, “Benefits of power electronic interfaces for distributed energy systems,” *IEEE Trans. Energy Convers.*, vol. 25, no. 3, pp. 901–908, Sep. 2010.

Marcelo Godoy Simões (S'89–SM'98) received the B.S. and M.S. degrees from the University of São Paulo, São Paulo, Brazil, in 1985 and 1990, respectively, the Ph.D. degree from The University of Tennessee, Knoxville, in 1995, and the D.Sc. degree (Livre-Docência) from the University of São Paulo in 1998.

He is currently an Associate Professor at the Colorado School of Mines, Golden, where he has been establishing research and education activities in the development of intelligent control for high-power-electronics applications in renewable- and distributed-energy systems.

Dr. Simões is currently the Past Chair of the IEEE Industry Applications Society/International Advance Computing Conference and a Cochair of the IEEE Industrial Electronics Society Smartgrid Committee. He has been involved in activities related to the control and management of smart grid applications since 2002 with his National Science Foundation CAREER award "*Intelligent Based Performance Enhancement Control of Micropower Energy Systems*."

Robin Roche (S'09) received the M.S. degree in electrical engineering from the Université de Technologie de Belfort–Montbéliard, Belfort, France, in 2009, where he is currently working toward the Ph.D. degree in electrical engineering in the Research Institute on Transportation, Energy and Society (IRTES).

His research interests include intelligent energy management in power systems, smart grids, applications of computational intelligence, energy storage, and hybrid vehicles, as well as the societal and economic impacts of these technologies.

Elias Kyriakides (S'00–M'04–SM'09) received the B.Sc. degree in electrical engineering from Illinois Institute of Technology, Chicago, in 2000, and the M.Sc. and Ph.D. degrees in electrical engineering from Arizona State University, Tempe, in 2001 and 2003, respectively.

He is currently an Assistant Professor in the Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, Cyprus, where he is a Founding Member of the KIOS Research Center for Intelligent Systems and Networks. He is the Action Chair of the European Science Foundation COST Action IC0806 "Intelligent Monitoring, Control, and Security of Critical Infrastructure Systems" (2009–2013). His research interests include synchronized measurements in power systems, security and reliability of the power system network, optimization of power system operation techniques, modeling of electric machines, and renewable energy sources.

Sid Suryanarayanan (S'00–M'04–SM'10) received the Ph.D. degree in electrical engineering from Arizona State University, Tempe, in 2004.

He is currently an Assistant Professor in the Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, where he serves as the Site Director of the Center for Research and Education in Wind and as a 2011–2012 Resident Faculty Fellow of the School of Global Environmental Sustainability. His research interests are in the design, operation, and economics of finite-inertia systems and integration of renewable-energy systems to electric grids.

Benjamin Blunier (S'07–M'07) received the M.Sc. and Ph.D degrees in electrical engineering from the Université de Technologie de Belfort–Montbéliard (UTBM), Belfort, France, in 2004 and 2007, respectively. He studied fuel-cell-system modeling, particularly the system's air management and control for hybrid and electric vehicles.

He was an Associate Professor at UTBM until his death on February 23, 2012. His research interests included fuel cell systems; electric, hybrid, and plug-in hybrid vehicles; and intelligent energy management in smart grids and microgrids.

Kerry D. McBee received the B.Sc. degree from the Department of Engineering, Colorado School of Mines, Golden, in 1999, and the M.Sc. degree in electric power engineering from Rensselaer Polytechnic Institute, Troy, NY, in 2000. He is currently working toward the Ph.D. degree in the Department of Engineering, Colorado School of Mines.

During his career, he has focused on power quality, reliability, forensic engineering, and distribution design for companies such as NEI Power Engineers, Peak Power Engineering, Knott Laboratory, and Xcel Energy. His field of interest is the effect of smart grid implementation upon distribution engineering and utility operations.

Phuong H. Nguyen (M'06) was born in Hanoi, Vietnam, in 1980. He received the B.E. degree in electrical engineering from Hanoi University of Technology, Hanoi, in 2002, the M.Eng. degree in electrical engineering from the Asian Institute of Technology, Pathum Thani, Thailand, in 2004, and the Ph.D. degree from the Technische Universiteit Eindhoven, Eindhoven, The Netherlands, in 2010, where he started the Ph.D. program with the "Electrical Infrastructure of the Future" project in 2006.

Since the end of 2010, he has been a Postdoctoral Researcher at the Technische Universiteit Eindhoven. His research interests include distributed state estimation, control and operation of the power systems, multiagent systems, and their applications in smart grids.

Paulo F. Ribeiro (M'79–SM'88–F'03) received the Ph.D. degree from the University of Manchester, Manchester, U.K.

He is currently an Associate Professor of electrical engineering at the Technische Universiteit Eindhoven, Eindhoven, The Netherlands. His research interests include power electronics, power quality, system modeling and simulation, energy storage, integration of renewable resources, smart grids, engineering education, and philosophy of technology.

Abdellatif Miraoui (SM'09) was born in Morocco in 1962. He received the M.Sc. degree from Haute Alsace University, Mulhouse, France, in 1988, and the Ph.D. and Habilitation degrees from the University of Franche-Comté, Besancon, France, in 1992 and 1999, respectively.

He is currently the President of Cadi Ayyad University, Marrakesh, Morocco. Since 2000, he has been a Full Professor of electrical engineering (electrical machines and energy) at the Université de Technologie de Belfort–Montbéliard1, Belfort, France, where he was the Vice-President of Research Affairs from 2008 to 2011, the Director of the Electrical Engineering Department from 2001 to 2009, and the Head of the "Energy Conversion and Command" Research Team (38 researchers in 2007). He is Doctor Honoris Causa of the Technical University of Cluj-Napoca, Cluj-Napoca, Romania. He was an Editor of the *International Journal on Electrical Engineering Transportation*. He is the author of over 80 journal and 150 international conference papers. He is also the author of four textbooks (three in French and one in English) about fuel cells. His special interests include fuel cell energy, energy management (ultracapacitor, batteries, etc.) in transportation, and design and optimization of electrical propulsions/tractions.

Dr. Miraoui is a member of several international journal and conference committees. He is a member of IEEE Power Electronics Society, IEEE Industrial Electronics Society, and IEEE Vehicular Technology Society. In 2007, he received a high distinction from the French Higher Education Ministry, "Chevalier dans l'Ordre des Palmes Académiques." He was also distinguished as an Honorary Professor by the Transylvania University of Brasov, Brasov, Romania.