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Smart grid futures: Perspectives on the integration of energy and ICT services

Monjur Mourshed[a,]*, Sylvain Robert[b], Andrea Ranalli[c], Thomas Messervey[d], Diego Reforgiato[d], Régis Contreau[e], Adrien Becue[f], Kevin Quinn[g], Yacine Rezgui[a], Zia Lennard[d]

[a]*School of Engineering, Cardiff University, Cardiff, CF24 3AA, United Kingdom*
[b]*CEA LIST, Boîte courrier 65, Gif-sur-Yvette cedex, F-91191, France*
[c]*Telecom Italia S.p.A., Via G. Reiss Romoli, 274, 10148, Torino, Italy*
[d]*R2M Solution, Piazza della Vittoria, 2, 27100 Pavia, Italy*
[e]*GDF SUEZ, Saint Denis, Plaine Cedex, 93211, France*
[f]*Airbus Defence & Space, Cybersecurity, Bd. Jean Moulin 78990, Elancourt, France*
[g]*Telecommunications Software & Systems Group, Waterford Institute of Technology, Waterford, Ireland*

Abstract

The entire electricity infrastructure and associated socio-technical system including transmission and distribution networks, the system operator, suppliers, generators, consumers and market mechanisms will need to evolve to realize the full potential of smart-grids. At the heart of this evolution is the integration of information and communication technology (ICT) and energy infrastructures for increasingly decentralized development, monitoring and management of a resilient grid. This paper identifies the challenges of integration and four key areas of future research and development at the intersection of energy and ICT: standards-based interoperability, reliability and security, decentralized and self-organizing grid architecture, and innovative business models to unlock the potential of the energy value chain. The ideas postulated here are envisaged to act as a starting-point for future R&D direction.

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1. Introduction

Smart-grids have an essential role to play in achieving the objectives of energy and environmental policies by transforming the existing electricity transmission and distribution grids so that they are able

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* Corresponding author. Tel.: +44 29 2087 4847; fax: +44 29 2087 4716.
E-mail address: MourshedM@Cardiff.ac.uk.

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to: provide a user-oriented service; increase the share of renewable energy in the supply mix; maximize the utilization of ageing infrastructure; reduce greenhouse gas emissions; and guarantee high security, quality and economic efficiency of supply in an increasingly liberalized market environment [1]. The high-level requirement of a smart-grid is the ability to cost-effectively integrate the behavior and actions of all connected users – energy producers, consumers and prosumers – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety [2]. In addition, the integration of renewable energy sources and energy storage technologies in the grid will result in dynamic electricity demand being an active factor within the electrical system.

At the heart of a demand-responsive smart-grid is the dynamic nature of generation and consumption patterns, as well as their organization and asset boundaries, which is where the traditional closed-loop, centralized energy management infrastructure becomes inadequate. The uni-directional flow of electricity; i.e., generation → transportation → distribution → usage, is increasingly being replaced by bi-directional flows where consumers consume and produce electricity [3] – often simultaneously. Widespread integration of distributed energy resources (DER) such as wind farms and photovoltaic (PV) systems will add further challenges, requiring smart management and high-resolution monitoring at all levels to enable the coordination of bi-directional flows so as to ensure the quality of supply (QoS) and balance out supply, demand and storage [4]. The vision of the wider integration DERs is also a prerequisite for efficient use of energy at the consumer level through intelligent demand response [5]. Distributed and intelligent grid is becoming a reality for most European nations; e.g. Germany intends to cease nuclear generation of electricity by 2022 and will increasingly rely on renewable energy resources – it has long planned to cease fossil fuel based electricity generation by 2050 [4].

To achieve the above-mentioned social and technical objectives of demand-responsive active control in the smart grids, near real time access to control information related to the status of transmission and distribution network is essential [6]. An increased level of collaboration, integration and interoperability among the array of technologies and disciplines is thus required, opening up new frontiers of integration of information and communication technology (ICT) [7] with the energy infrastructure. Conventional applications of ICT in energy focus mostly on the exchange of data and control signals between the control center and substations, which is mostly based on inflexible, centralized and hierarchical topologies that are inadequate for the 21st century grid [6] where control topologies need to be flexible to accommodate various generation technologies, diverse communication needs and increased participation from stakeholders for the optimal management of the grid. New control architecture is needed, as well as standards-based interoperable solutions for communication, management and optimal control.

Achieving a demand-responsive smart-grid depends highly on the capacity of the business stakeholders to collaborate effectively, in order to give rise to a new generation of innovative, reliable, and secure smart-grid services. In an environment of increased collaboration, success depends on four strategic challenges at the intersection between ICT and energy infrastructures:

- **Interoperability** – for ensuring convergence of network (ICT) and transmission (grid) protocols for enhanced cooperation and communication;
- **Reliability and security** – for trusted provision of services and enhanced resilience;
- **Decentralized and self-organizing architecture** – for enhanced flexibility in grid control and management, and for increased resilience through self-healing; and
- **Innovative business models** – for increased participation by stakeholders (e.g., users, telecom operators, utilities, DSO, etc.) – to release investments required for a thorough infrastructure upgrade.

This paper aims to identify the challenges of integrating ICT and energy infrastructures and directions of future research and development. The collective experience and organizational knowledge of the authors representing ICT, energy and innovation sectors provide a unique and well-rounded perspective at an embryonic stage of smart grid evolution, as well as a platform for further deliberation and extension.

2. Integration challenges

2.1. Enhanced interoperability through standards and enabling technologies

Interoperability, the ability of devices or products and processes to exchange information and do useful work together [9], is vital to the realization of a decentralized smart grid [10]. The entire smart grid proposition is based on *open* communication between *smart* devices using common protocols, and therefore, *standards* are the key to interoperability [11]. True interoperability promises great reductions in cost for designing, replicating, modifying, and implementing systems [9]. Among the 300 smart grid standards that IEC has listed, the most relevant are those focusing on common information models and transport/communication protocols: IEC 60870-6, 61970/61968, 61850, 62357, 60870, 62325, 61850, 61400, and 62351. The focus of standards development for smart grids has traditionally been on network interoperability dealing with communication between devices and connected applications. However, with the proliferation of distributed applications for optimal control and management, there is an increasing need for developing protocols and standards for inter-applications messaging as typically found in the area of distributed computing. Standards institutions such as the NIST have acknowledged the need for inter-applications interoperability in their recent roadmap [12]. Although standards are central to interoperability support in the mid- and long-term, a critical issue for short-term market impact is the availability of enabling technologies. Initial success, therefore, will depend on the “openness” of the new standards in integrating existing devices, which may well be based on outdated standards or none at all.

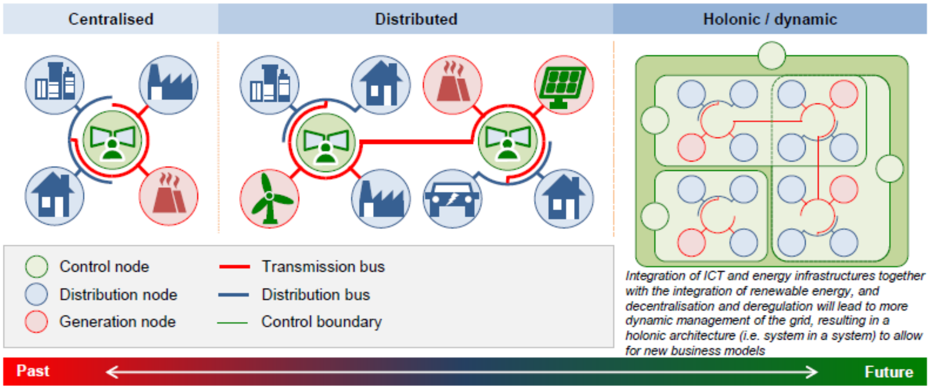
2.2. Security & reliability as key enablers of future smart grid business services

Physical and cyber security has become a critical factor for reliability and quality of supply (QoS) in smart grids, as more and more distributed energy resources are integrated with the grid. Smart control systems, intelligent market processes, demand responsive management and advanced metering infrastructure (AMI) with bidirectional flow of energy and information, along with their ability to receive and act upon price control signals contribute to the enhanced efficiency and reliability, but they may also create many new vulnerabilities if not deployed with appropriate security controls [13]. The vulnerabilities will arise particularly from the higher degree of connectivity between the smart components, as well as between market processes. The need for secure authentication and transaction at every interface between devices/subsystems and processes will therefore become more important as the grid itself becomes more distributed and intelligent, and communication capacities (e.g. broadband, 4G, WiMax) increase. Security is thus considered to be a ubiquitous requirement and needs to be integrated with most, if not all activities within a smart grid ecosystem, which is highlighted in recent industry and government communications in Europe [8] and USA [10].

Various standardization efforts on smart grid cyber security are underway and are closely interlinked with the efforts on interoperability. There are three main layers to smart grid security: (a) secure authentication, (b) secure communication and (c) information security management. Secure authentication deals with various interfaces (e.g., Home to Grid – H2G, Building to Grid – B2G, Industrial to Grid – I2G, Transmission and Distribution – T&D and Business and Policy – B&P) and is based on many existing standards and ongoing efforts on cyber security and privacy technologies in cognate domains. Efforts such as ISO 17799, Federal Information Processing Standard (FIPS) 201, Advanced Encryption Standard (AES) and Triple Data Encryption Algorithm (3DES) offer the least cost option for strong security and high performance, and can be applied in various scenarios depending on the communication resource being protected. Diverse communication requirements in smart grids will require the implementation different standards; e.g. IEEE 802.11i and 802.16e for wireless links, whereas wired links can be secured with firewalls and virtual private network (VPN) technologies such as IPSec, as well as higher layer security mechanism such as Secure Shell (SSH) and SSL/TLS [13]. Information security management, on the other hand, are dealt within ISO/IEC 27002 that provides best practice recommendations for initiating, implementing or maintaining information security management systems (ISMS) and is aimed at the preservation of confidentiality, integrity and availability.

2.3. Decentralized and self-healing grid architecture

To reap the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand, the centralized grid need to be transformed [10] into multi-layer information and control system architecture, where *power transmission and distribution layer* acts in synergy with the *ICT layer*. The required transformation implies a move from traditional hierarchical topology with distributed data acquisitions but central decision-making, to dynamic and decentralized decision-making [14]. Fig. 1 illustrates various grid architectures, from the centralized where data and power flows are unidirectional to the dynamic where data and power flow can be bi-directional; e.g., from an IED to the centralized data store or from a substation to substation. Inspired by examples of recursive organization in nature, the holonic architecture is based upon the concept of a *holon* [15], which is a logic control entity that is both a whole and a part, and can take decisions autonomously in a cooperative way. Multiple holons can aggregate to form a higher-level meta-holon, leading to scalable and recursive architecture, highly suited for the 21st century grid. For example, a DSO can be a *holon*; i.e., an aggregated entity in the grid which can make autonomous decisions as well as cooperate with other holons to make mutually optimal decisions. The recursive participation of a *holon* in a meta-holon is a dynamic one based upon utility optimization; i.e., holons dynamically organize in a coherent and complementary manner. Examples of clustering objectives are global/local energy balancing, islanding and blackout prevention.



Integration of ICT and energy infrastructures together with the integration of renewable energy, and decentralisation and deregulation will lead to more dynamic management of the grid, resulting in a holonic architecture (i.e. system in a system) to allow for new business models

Fig. 1. Evolution of smart grid control and management architecture, from centralized to dynamic and decentralized

The transition to holonic grid architecture will require rethinking of the way decision-making problems are formulated and results are visualized and/or decisions are made. Global balancing is concerned with matching demand and supply globally and is mainly ensured through electricity markets involving energy providers and their customers. One of the challenges is to provide the stakeholders with a reliable real-time picture of their portfolio of consumers and supply means, and to enable them to react effectively to variations in the markets, especially in their portfolios. This requires implementing advanced prediction and optimization strategies; fast, effective and reliable communication means and tighter integration between telecom operators and utilities/aggregators. Visualization of the optimization/solution landscape and decision-making will be challenging, as often encountered in other engineering domains [16, 17]. Local balancing is concerned with ensuring local production, storage, and consumption (i.e., LV) are optimized locally. This is needed to ensure that electricity is, as much as possible, consumed locally decreasing energy losses due to long distance electricity transportation and, above all, to enhance network resilience. This becomes more important with increasing integration of DERs and in particular small-scale household installations of intermittent PV (<4 kWp) and wind (0.1–20 kW) that result in high amplitude variations of energy provision on the network. Resilience can be ensured if the network can self-heal by dealing with local issues timely to avoid propagation of problems on the wider network.

2.4. Innovative cross-sectoral business model

Direct (first order) benefits of realizing the smart grid are in the order of a 10-15% reduction in the electricity sector energy and CO_2 emissions [18], associated strictly with improved grid and power system management made possible by information, control, and pricing strategies implemented by grid operators or producers/suppliers as well as actions taken by end users with access to smart meter information. The indirect benefit, probably the biggest opportunity from increased monitoring of the low voltage distribution networks, is likely to be the exponential growth of the market for hardware and service providers, typically operating in telecommunications and other vertically connected sectors. With an increased understanding of consumer behavior there will be new opportunities for the development and marketing of user-centric value-added products and services. In addition, consumers will benefit from the increased competition in a liberalized energy market [19] that is integrated with other infrastructure ensembles. Putting smart grid infrastructure in place is investment-intensive [20]. Buy-in from all stakeholders is essential to unlock the full potential of the evolving energy value chain, shown in Fig. 2. The pace of change will likely depend on R&D investment volume, as past research suggest a relationship between R&D investments and energy policy goals [21].

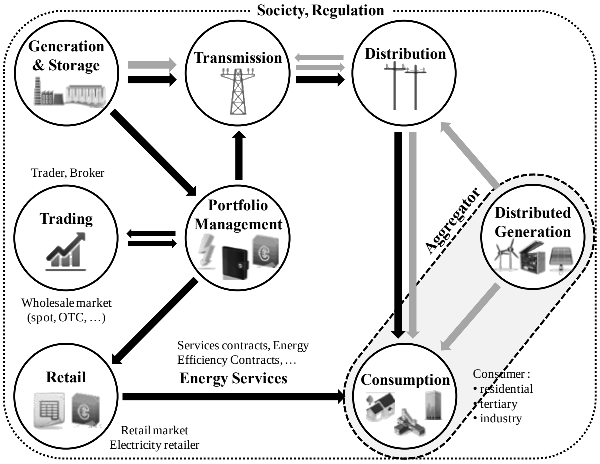


Fig. 2. Energy value chain in a smart grid.

3. Conclusion

The integration of ICT and energy infrastructures is one of the most critical factors for the successful evolution of smart-grids. Standards-based interoperability is identified as the basis for future-proofing the process of integration, on which a decentralized grid architecture can be implemented to account for increasingly dynamic and distributed nature of the assets (generation, consumption, monitoring, control and management). This article argues for secure-transactions in a standards-based decentralized grid to ensure grid reliability, security and resilience. However, the success of integration will depend on the development of innovative business model to unlock the full potential of the evolving energy value chain.

Acknowledgements

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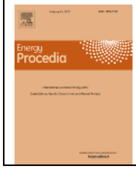

Biography

Monjur Mourshed is Senior Lecturer in Sustainable Engineering at the School of Engineering, Cardiff University. His research interests are at the intersection between energy and ICT with an emphasis on smart and sustainable buildings and cities.