The potential of Industry 4.0 toward smart grids: opportunities and challenges

Bortolini M.*, Cafarella C.*, Galizia F.G.*, Gamberi M.*, Mora C.*, Ventura V.*

** Department of Industrial Engineering, Alma Mater Studiorum – University of Bologna, Viale del Risorgimento 2, 40136 – Bologna – Italy (marco.bortolini3@unibo.it, cristian.cafarella2@unibo.it, francesco.galizia3@unibo.it, mauro.gamberi@unibo.it, cristina.mora@unibo.it, valentina.ventura7@unibo.it)*

Abstract: The technology progresses based on the ‘Industry 4.0’ paradigm, the cornerstone role of the electrical energy grid to feed industries and the need of increasing the share of the renewable energy sources in the global energy mix to address the climate change, are some of the key factors asking for efficient, reliable and smart energy systems. Smart grid projects are emerging across the European continent as a promising approach for relieving the energy crisis, increasing the adoption of the renewables, and building high-resilient grids. Decentralized systems, compared to the traditional energy grids fuelled by large scale fossil-fuel power plants, join greater flexibility to high efficiency. In addition, they increase the overall system reliability, limiting supply interruptions and facility inefficiencies. In this context, the ‘Industry 4.0’ technologies, such as the Internet of Things (IoT), blockchain, Big Data analytics, can help and enable the real-time system running. However, integrating and coordinating a complex and bidirectional network of nodes is more challenging than a conventional centralized grid system. At the same time, ‘Industry 4.0’ provides several solutions in this field. The aim of this paper is to analyse the potential of smart grids, ‘Industry 4.0’ enabling technologies, and current applications focusing on the architecture of smart grid energy systems. Opportunities and challenges of the smart grids are presented and exemplified through an energy and information flows management framework ‘Industry 4.0’-based.

Keywords: smart grids, Industry 4.0, renewables, methodological framework

ACRONYMS

AI	Artificial Intelligence	LV	Low Voltage
AMI	Advanced Metering Infrastructure	M2M	Machine-To-Machine
BAN	Building Area Network	MV	Medium Voltage
CPS	Cyber Physical Systems	NAN	Neighbourhood Area Network
DER	Distributed Energy Sources	P2P	Peer-To-Peer
EV	Electrical Vehicles	PEV	Plug-in Electric Vehicles
DOS	Distribution System Operator	PV	Photovoltaic
HAN	Home Area Network	PL	Physical Layer
I4.0	Industry 4.0	SG	Smart Grid
IAN	Industry Area Network	SGAM	Smart Grid Architecture Model
IL	Information Layer	UC	Utility Center
IoT	Internet of Things	WAN	Wide Area Network

I. INTRODUCTION

The modernization of the 20^{th} century power grid is central for international efforts to reduce energy consumption, enabling the transition towards the use of renewables and building a sustainable society that guarantees prosperity for future generations [1].

Traditional energy systems are commonly used to deliver power from few generation points to many consumers. Distances between power generation facilities and consumption points are significant, causing high losses related to energy transport. The smart grid (SG) overcomes the traditional electricity systems maximizing the use of distributed generation and renewable sources, and increasing, at the same time, the energy system reliability. The SG is based on two-way flows (electricity and information) aiming at creating an advanced and distributed energy delivery network with the support of digital technologies. The system is therefore characterized by security, safety, reliability, resilience, efficiency and sustainability [2, 3]. In this context, Industry 4.0 (I4.0) plays a major role through the integration of digital technologies within, but not limited to, industrial processes. Internet of Things (IoT) [4], Cyber Physical Systems (CPS), Big Data analytics, Artificial Intelligence (AI), Cloud Computing and cybersecurity are some of the main technologies of the I4.0 paradigm [5]. The need for reliability, efficiency, and security in a SG leads to embed these advanced technologies in its architectures.

There is a wide range of surveys and studies that cover specific topics about SG, such as communication network, cybersecurity, impacts, or applications. The lack of an agreed standard for SG architecture which integrates I4.0 technologies revealed the need to fill this gap. The purpose of this paper is to present a conceptual framework of a new generation of SG and its main components. Then, some of the main opportunities and challenges of a SG I4.0-based are briefly discussed.

The remainder of the paper is structured as follows: Section II gives an overview of SG key features and the most widely accepted architectures. Section III proposes a SG framework within I4.0 context, while Section IV provides future research directions and conclusions.

II. SMART GRID FEATURES AND ARCHITECTURES

According to the U.S. Department of Energy, the main features of a SG are: self-healing, consumer friendly, high reliability and power quality, resistant to cyber-attacks, flexible distributed generation and storage options, optimization of the asset utilization, minimization of maintenance expenses [6]. Thus, the smart grid aims to solve the problems of the traditional power grid such as low reliability, high outages, high greenhouse gas emissions, safety, and energy security. As discussed by the National Institute for Standards and Technology (NIST), hundreds of standards will need to be developed in the near future to implement increasingly high-level of SG functionalities. Among the possible features required by a SG, NIST chose to focus on seven key functionalities plus cybersecurity and network communications, presented below, which are particularly critical for ongoing and near-term implementations of SG technologies and services [1, 7]:

• *Demand response and consumer energy efficiency* – optimising the balance between energy supply and demand and ensuring greater access to detailed information on energy consumption. In this way, consumers can save energy through efficiency behaviour and investments which generate measurable results. It also provides mechanisms and incentives for different kind of customers (utilities, businesses, industrial and residential) to modify energy use during peak demand periods or when energy reliability is at risk [8].

• *Wide-area monitoring* – real-time monitoring of power system components and performance across interconnections and over large geographical areas, to optimise their performance and anticipate, prevent, or respond to problems before interruptions occur [9].

• *Distributed energy resources (DER)* - using a wide range of generation (e.g., renewable energies) and storage technologies (e.g., batteries, plug-in electric cars with bi-directional chargers) interconnected with distribution energy systems, including devices located on a customer premise. The advanced capabilities of DERs also enable new network architectures that incorporate "microgrids". Microgrids can separate from the grid when the power is interrupted, thereby increasing the resilience and adaptability of the power system [10, 11].

• *Energy Storage* – using direct or indirect energy storage systems. Increased storage capacity, especially distributed storage, would bring benefits across the whole grid from generation to end use [12, 13].

• *Electric transportation* – integrating plug-in electric vehicles (PEVs) in a large-scale. Electric transportation could reduce dependence on fossil fuels, increase the use of renewable energy sources, provide electricity storage to improve peak loads, and reduce the carbon footprint [14, 15].

• *Advanced metering infrastructure (AMI)* – represents one of the key elements of SGs, allowing near real-time monitoring of energy use through a two-way communication network between smart sensors and the utility centre. The utility centre collects, stores, and analyses data acquired from smart devices [16, 17, 18].

• *Distribution network management* – maximising the performance of distribution system components and their integration with transmission systems and customer operations. With the development of SG capabilities, distribution system automation is increasingly important for the efficient and reliable operation of the entire energy system. Optimal management of the distribution network in SG context could lead to significant benefits such as reducing peak loads, increasing the efficiency of the distribution system, and improving the management capabilities of distributed renewable energy sources [19].

• *Network communications* – public and private communication networks, both wired and wireless, that can be used as the communication infrastructure for SG. In this field, the identification of performance metrics and the development and maintenance of appropriate security and access controls are critical to the implementation of the SG [20, 21].

• *Cybersecurity* – Determining measures to guarantee the confidentiality, integrity, and availability of the communication and the control systems, which are necessary to manage, operate and protect the whole SG's energy infrastructure [22].

Several projects have been developed concerning the design of SG and its possible architectures. Among the various philosophies for designing a SG, the most widely accepted standardised models are the following [23]:

- Smart Grid Architecture Model (SGAM) [24];
- NIST smart grid conceptual model [1].

As shown in Fig. 1, the SGAM model is composed by three dimensions:

1. domains;
2. interoperability layers;
3. zones.

The interoperability dimension is developed through five different levels: component, communication, information, function and business. Each layer covers a SG plane, which is crossed by electricity domains and information management zones. The domains cover the entire energy conversion chains (generation, transmission, distribution, DER, consumption premises). The zones are divided according to hierarchical levels of power systems management (process, field, station, operation, enterprise, and market). The aim of the SGAM model is to highlight on which information management domains interactions take place. In addition, it allows to present the current state of implementations in the energy grid, but also to represent the evolution towards future SG scenarios [24]. Fig. 2 shows a conceptual view of NIST reference model for SG, highlighting the two-way flow of electricity and information and the integration of renewable energy plants both concentrated and distributed [25].

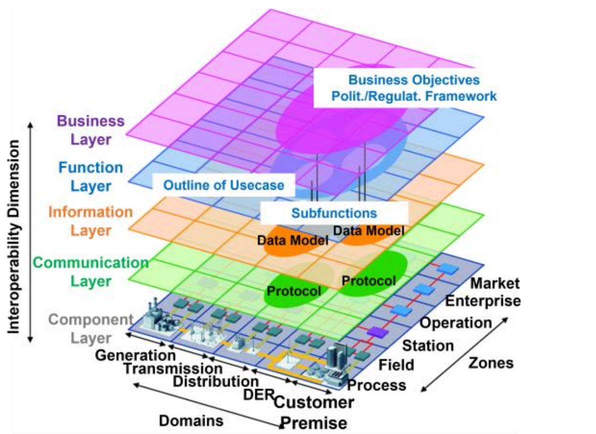

Fig. 1. SGAM framework [24]

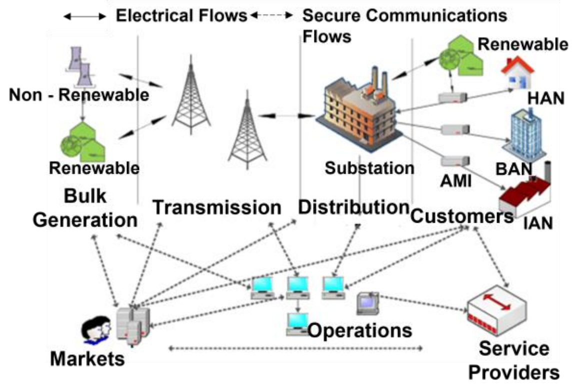

Fig. 2. NIST conceptual framework [25]

III. FRAMEWORK FOR SMART GRID I4.0-BASED

As shown in the previous section, there are several literature studies dealing with different aspects related to SG. However, most of them focus on specific SG aspects, such as communication network, cybersecurity, impacts, or applications. Nowadays, there is no agreed standard for the SG architecture, although, in this research field, a variety of frameworks with some common features are present. In the context of I4.0, it is possible to leverage digital technologies to build a new generation of SG architectures.

Yapa et al. [26] presented a comparison between first-generation SG (SG 1.0) and envisioned future electrical networks (SG 2.0). Table A1 shows some features of these energy networks by domains.

In this section, a conceptual architecture of a new generation smart grid is proposed, integrating physical systems with information systems, empowered by I4.0 technologies. Fig. A1 shows this SG I4.0-based architecture where the main elements are highlighted. The architecture can be detailed as follows:

- Physical Layer (PL);
- Information Layer (IL).

The PL is responsible for generating and delivering electrical energy to the consumers. Power is generated both by large energy production plants based on renewable and non-renewable energy sources, then through transmission and interconnection network, it is often distributed over long distances to different users that vary in size and location: Industry Area Network (IAN), Building Area Network (BAN), Home Area Network (HAN). Differently from traditional networks, the PL in the SG I4.0-based comprises widespread IoT devices, such as smart meters and smart sensors; small/medium power generators located near the users, usually powered by renewable sources, e.g., solar panels; energy storage devices and Electrical Vehicles (EV) charging station. The SG manages two-way flows of electricity and information through smart devices collecting and exchanging real-time data. In particular, the AMI is one of the key components of the SG and it allows a two-way communication infrastructure between the smart meters and the utility centre (UC).

The AMI is usually composed of smart meters, concentrators, the UC and a two-way communication infrastructure among them. The elements of the AMI are placed in different networks and layers. A number of IoT devices communicate with a concentrator via a Neighbourhood Area Network (NAN), while the concentrator is connected to the UC using Wide Area Network (WAN). The UC collects, stores, and analyses data acquired from smart devices for offering services and applications to users and suppliers along the entire SG [27].

As shown in Fig. A1, the IL includes three sub-layers:

1. Communication & Control;
2. Application;
3. Data Analysis.

The IL can provide different functionalities through I4.0 technologies, such as Cloud Computing, Cyber-security, Big Data Analysis, Cyber Physical System (CPS), Artificial Intelligence. The main objective of the Communication & Control layer is to enable fast, reliable, real-time Machine-To-Machine (M2M) communication among intelligent devices while minimizing the involvement of a third-part provider, e.g., through a Peer-To-Peer (P2P) energy trading application without the intervention of an intermediary. In this sub-layer, data security can be guaranteed through technologies as Blockchain and advanced firewall systems. The Application layer includes several potential applications resulting from the implementation of a SG, such as Demand Management, Energy Data Management, Renewable Energy Source Integration and more others. These applications can be relevant to all actors involved and the different domains of SG. The Data Analysis layer, in a cloud-centric perspective, provides support in data management, predictive analysis of trends and control at the base of the grid.

To sum up, an SG I4.0-based incorporates large data sets related to real-time power grid measurements, energy consumption and exchange, and demand-supply balancing control. These large volumes of heterogeneous data are processed to provide applications in each smart grid domain and toward SG's actors. For this reason, secure data management, privacy protection, and reliable storage are critical elements of the I4.0-enhanced SG infrastructure.

The integration of emerging I4.0 technologies within a SG offers several opportunities from an energy and an information management perspective. A SG I4.0-based can collect data, analyse them and address necessary operations. In this system, all the stakeholders are interconnected and cooperate strictly, improving power efficiency and enhancing an autonomous exchange of data. However, in a large-scale SG, a huge amount of heterogeneous data is generated, which increase the complexity of the system and lead to unpredictable events. Some of the main benefits of introducing I4.0 technologies into an SG are: autonomous and decentralized decisions regarding the remote monitoring of power lines, automated distribution, load control and management, fault detection and error diagnosis, and real-time meter reading. The two-way flow of information and energy allows to frequently reconfigure the parameters of the system and, especially during peak loads, to provide electricity without any blackout [28]. The complexity of a SG I4.0-based reveals at the same time several challenges that need to be addressed to ensure a robust, reliable and scalable grid. The main challenges discussed in the literature regard communication system (interference, need of common standards and data transmission rates), Big Data (real-time applications, heterogeneous data, data compression and visualization), Cloud Computing (lack of consistent policies and disaster recovery plans, international laws) and security (cyber-attacks and privacy issues) [5, 29].

Concerning the practical implementations of SG, the European Union (EU) launched in 2011 the Grid4EU project. The aim was to dynamically manage electricity supply and demand for maximizing the integration of DER and empowering consumers to become active participants in their energy consumptions. Innovative technologies were tested in real-size environments to assess their potential in the European context. This project involved six electricity Distribution System Operators (DSOs) from different European countries, i.e., Germany, Sweden, Spain, Italy, Czech Republic, France, in close partnership with a set of major electricity retailers, manufacturers and research organizations [30]. Fig. A2 synthetizes the main purposes of the six "Demonstrators" with specific boundary conditions.

IV. CONCLUSIONS AND FUTURE RESEARCH

Smart grid is a promising approach for relieving the energy crisis, increasing the adoption of the renewables, and building high-resilient energy grids. Compared to the traditional energy systems, SG joins greater flexibility to efficiency, limiting supply interruptions and facility blackouts. In this context, the 'Industry 4.0' technologies, such as the Internet of Things (IoT), blockchain, Artificial Intelligence (AI), Big Data analytics, could help and enable the real-time system running. Although integrating and coordinating a complex and bidirectional network of nodes is more challenging than a conventional centralized grid system, 'Industry 4.0' (I4.0) provides several solutions in this field. The lack of an agreed standard for SG architecture which integrates I4.0 technologies revealed the need to fill this gap. The aim of this paper is to provide an outline of the main features of a SG and a new generation of architecture which integrates SG and I4.0 technologies. The proposed framework is organized in a Physical Layer (PL) and an Information Layer (IL). PL contributes to generate and deliver electrical energy to the consumers, that vary in size and location. IL includes three sub-layers (Communication & Control, Application, Data Analysis) and it provides different operative functionalities through I4.0 technologies.

The integration of I4.0 technologies within a SG offers several opportunities, such as autonomous and decentralized decisions, automated distribution, load control and management, fault detection and diagnosis, and real-time meter reading. However, the huge amount of heterogeneous data produced increases the overall system complexity, leading to different types of challenges about communication, data management and security.

The near future of SG would be empowered through advancement in simulating real energy grids, e.g., microgrids, to test performances, cost and energy savings and monitoring them in real-time. In addition, KPIs or specific energy metrics would assess the effectiveness of a microgrid.

REFERENCES

[1] National Institute for standards and Technology (NIST). NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0. [Accessed on 21 March 2022] https://www.nist.gov/smartgrid/upload/NIST-SP-1108r3.pdf (2014).

[2] Fang, X., Misra, S., Xue, G., and Yang, D. (2011). Smart grid — The new and improved power grid: A survey. *IEEE communications surveys & tutorials*, 14(4), 944-980.

[3] Bortolini, M., Gamberi, M., & Graziani, A. (2014). Technical and economic design of photovoltaic and battery energy storage system. *Energy Conversion and Management*, 86, 81-92.

[4] Bevilacqua, M., Ciarapica, F. E., Diamantini, C., & Potena, D. (2017). Big data analytics methodologies applied at energy management in industrial sector: A case study. *International Journal of RF Technologies*, 8(3), 105-122.

[5] Qarabsh, N.A., Sabry, S.S., and Qarabash, H.A. (2020). Smart grid in the context of industry 4.0: An overview of communications technologies and challenges. *Indonesian Journal of Electrical Engineering and Computer Science*, 18(2), 656-665.

[6] U.S. Department of Energy (DOE). Smart Grid System Report. [Accessed on 15 March 2022] https://www.energy.gov/sites/default/files/2009%20Smart%20Grid%20System%20Report.pdf (2009).

[7] Ghasempour, A. (2019). Internet of Things in Smart Grid: Architecture, Applications, Services, Key Technologies, and Challenges. *Inventions*, 4(1):22

[8] Rafiei, S., and Bakhshai, A. (2012, October). A review on energy efficiency optimization in smart grid. In IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society (pp. 5916-5919). IEEE.

[9] Qi, F., Yu, P., Chen, B., Li, W., Zhang, Q., Jin, D., and Wang, Y. (2018, May). Optimal planning of smart grid communication network for interregional wide-area monitoring protection and control system. In 2018 IEEE International Conference on Energy Internet (ICEI) (pp. 190-195). IEEE.

[10] Refaat, S.S., Abu-Rub, H., Trabelsi, M., and Mohamed, A. (2018, February). Reliability evaluation of smart grid system with large penetration of distributed energy resources. In 2018 IEEE International Conference on Industrial Technology (ICIT) (pp. 1279-1284). IEEE.

[11] Aiello, G., Enea, M., La Scalia, G., & Longo, F. (2014). A DECISION SUPPORT SYSTEM FOR SUSTAINABLE OPERATIONS MANAGEMENT IN SMALL POWER PLANTS. In CIE44 & IMSS'14.

[12] Akaber, P., Moussa, B., Debbabi, M., & Assi, C. (2019). Automated post-failure service restoration in smart grid through network reconfiguration in the presence of energy storage systems. *IEEE Systems Journal*, 13(3), 3358-3367.

[13] Saccani, C., Pellegrini, M., & Guzzini, A. (2020). Analysis of the existing barriers for the market development of power to hydrogen (P2H) in Italy. *Energies*, 13(18), 4835.

[14] Jarvis, R., and Moses, P. (2019, February). Smart grid congestion caused by plug-in electric vehicle charging. In 2019 IEEE Texas Power and Energy Conference (TPEC) (pp. 1-5). IEEE.

[15] Faccio, M., Gamberi, M., Bortolini, M., & Nedaei, M. (2018). State-of-art review of the optimization methods to design the configuration of hybrid renewable energy systems (HRESs). *Frontiers in Energy*, 12(4), 591-622.

[16] Ghasempour, A. (2016, April). Optimum packet service and arrival rates in advanced metering infrastructure architecture of smart grid. In 2016 IEEE Green Technologies Conference (GreenTech) (pp. 1-5). IEEE.

[17] Ghasempour, A., and Gunther, J.H. (2016, January). Finding the optimal number of aggregators in machine-to-machine advanced metering infrastructure architecture of smart grid based on cost, delay, and energy consumption. In 2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC) (pp. 960-963). IEEE.

[18] Ghasempour, A. (2015, November). Optimized scalable decentralized hybrid advanced metering infrastructure for smart grid. In 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm) (pp. 223-228). IEEE.

[19] Refaat, S.S., Mohamed, A., and Kakosimos, P. (2018, April). Self-Healing control strategy; Challenges and opportunities for distribution systems in smart grid. In 2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018) (pp. 1-6). IEEE.

[20] Lemercier, F., Habault, G., Papadopoulos, G.Z., Maille, P., Montavont, N., and Chatzimisios, P. (2018). Communication architectures and technologies for advanced smart grid services. In Transportation and Power Grid in Smart Cities: Communication Networks and Services (pp. 217-246). Wiley.

[21] Longo, F., Padovano, A., Aiello, G., Fusto, C., & Certa, A. (2021). How 5G-based industrial IoT is transforming human-centered smart factories: a Quality of Experience model for Operator 4.0 applications. *IFAC-PapersOnLine*, 54(1), 255-262.

[22] Zhao, Z., and Chen, G. (2018, June). An overview of cyber security for smart grid. In 2018 IEEE 27th International Symposium on Industrial Electronics (ISIE) (pp. 1127-1131). IEEE.

[23] Panda, D.K., and Das, S. (2021). Smart grid architecture model for control, optimization and data analytics of future power networks with more renewable energy. *Journal of Cleaner Production*, 301, 126877

[24] CEN-CENELEC-ETSI Smart Grid Coordination Group. Smart Grid Reference Architecture [Accessed on 29 March 2022] https://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf (2012).

[25] Uludag, S., Sauer, P., Nahrstedt, K., & Yardley, T. (2014, October). Towards designing and developing curriculum for the challenges of the smart grid education. In 2014 IEEE Frontiers in Education Conference (FIE) Proceedings (pp. 1-8). IEEE.

[26] Yapa, C., de Alwis, C., Liyanage, M., & Ekanayake, J. (2021). Survey on blockchain for future smart grids: Technical aspects, applications, integration challenges and future research. Energy Reports, 7, 6530-6564.

[27] Ghasempour, A., and Moon, T.K. (2016, April). Optimizing the number of collectors in machine-to-machine advanced metering infrastructure architecture for internet of things-based smart grid. In 2016 IEEE Green Technologies Conference (GreenTech) (pp. 51-55). IEEE.

[28] Faheem, M., Shah, S.B.H., Butt, R. A., Raza, B., Anwar, M., Ashraf, M. W., and Gungor, V.C. (2018). Smart grid communication and information technologies in the perspective of Industry 4.0: Opportunities and challenges. *Computer Science Review*, 30, 1-30.

[29] Caponio, G., Massaro, V., Mossa, G., & Mummolo, G. (2015). Strategic energy planning of residential buildings in a smart city: a system dynamics approach. *International Journal of Engineering Business Management*, 7, 20.

[30] Rodriguez-Calvo, A., Cossent, R., & Frías, P. (2018). Scalability and replicability analysis of large-scale smart grid implementations: Approaches and proposals in Europe. *Renewable and Sustainable Energy Reviews*, 93, 1-15.

[31] Wiedemann, T. GRID4EU - Large-Scale Demonstration of Advanced Smart Grid Solutions with wide Replication and Scalability Potential for Europe [Accessed on 3 July 2022] http://site.ieee.org/isgt2014/files/2014/03/Day2_Panel2A_Wiedemann.pdf (2014).

Appendix A. SUPPORTING CONTENTS

TABLE A1
COMPARISON BETWEEN FIRST-GENARATION AND FUTURE SMART GRID [26]

Domains	Smart Grid 1.0	Smart Grid 2.0
Power Generation	Centralized and distributed energy plants with use of energy storage systems.	Centralized and distributed energy plants with use of energy storage systems.
Power Transmission	Energy transmission from large-scale generation plants to the different users.	Energy transmission from large-scale generation plants to the different users. Integrating an effective management of assets and faults.
Power Distribution	Integrating limited types of energy sources at the distribution domain, including generation and energy storage prosumer-side.	Integrating heterogeneous types of energy sources, including renewable energy sources and storage, EV and charging station. Offering grid automation benefits to increase resilience and efficient asset management at distribution level.
Power Consumption	Through data from smart meters self-management of energy consumptions.	Autonomous demand response that incentive sustainable energy consumption.
Energy Market	Based on intermediary.	Promoting self-energy generation and P2P trading without intermediary.
Application	Energy trading and communication flow between the DOS and customers.	Energy trading and real-time communication among prosumers with plug-and-play interfaces.
Power and Communication Networks	Application and Energy market domains are connected only with two-way information channels. The other domains are connected with energy and communication network.	Every grid domain is connected with a P2P network for energy delivery and the information flows through to the Internet Protocol.

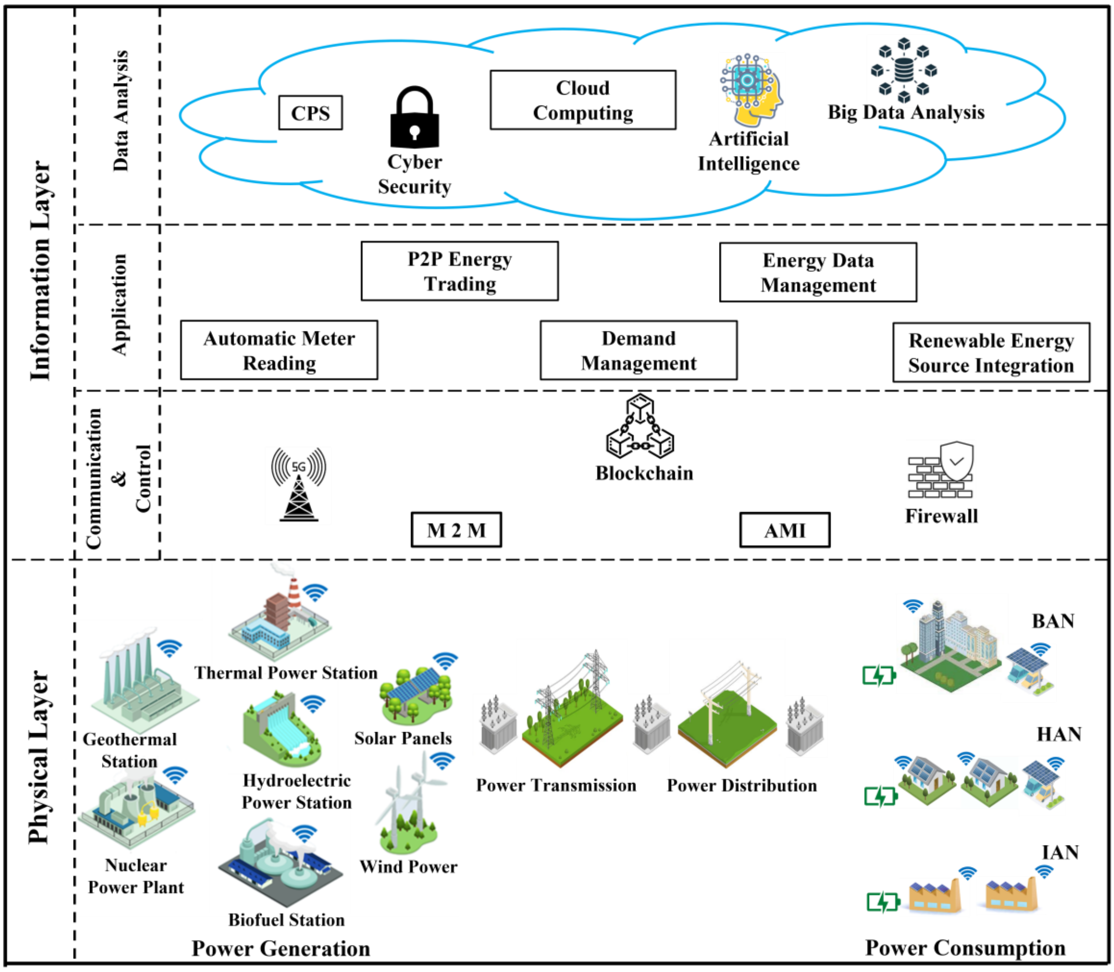

Fig. A1. Proposed conceptual architecture of a next-generation smart grid integrating physical and information systems enhanced by I4.0 technologies

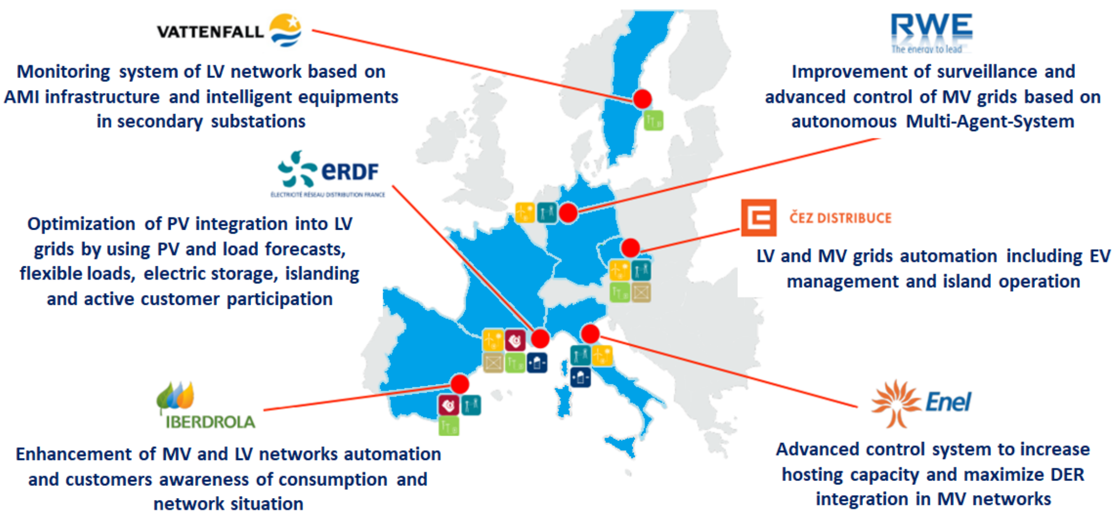

Fig. A2. The six Demonstrators of the Grid for EU Project [31]