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Review

Smart Grid Technologies in Europe: An Overview

Luca Ardito *, Giuseppe Procaccianti, Giuseppe Menga and Maurizio Morisio

Dipartimento di Automatica ed Informatica (DAUIN), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy; E-Mails: giuseppe.procaccianti@polito.it (G.P.); menga@polito.it (G.M.); maurizio.morisio@polito.it (M.M.)

* Author to whom correspondence should be addressed; E-Mail: luca.ardito@polito.it; Tex./Fax: 011-0907169.

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Abstract: The old electricity network infrastructure has proven to be inadequate, with respect to modern challenges such as alternative energy sources, electricity demand and energy saving policies. Moreover, Information and Communication Technologies (ICT) seem to have reached an adequate level of reliability and flexibility in order to support a new concept of electricity network—the smart grid. In this work, we will analyse the state-of-the-art of smart grids, in their technical, management, security, and optimization aspects. We will also provide a brief overview of the regulatory aspects involved in the development of a smart grid, mainly from the viewpoint of the European Union.

Keywords: smart grids; energy; renewables; grid intelligence; energy efficiency; energy storage

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1. Introduction

Over the past 50 years, electricity networks evolved from the "local grid" networks in the beginning of the century to interconnected electric grids, based on generating stations of notable scale (1000–3000 MW) distributing power to major load centres that divided energy to a large number of individual consumers. The generating stations, or power plants, were built in order to provide massive amounts of energy, due to the nature of power generation technologies in use (hydroelectric, coal, oil, and gas). By the end of the 20th century, however, this model proved to be unreliable and inadequate. First of all, the demand forecast techniques and the data processing technologies could not efficiently provide the desired energy at the desired time, thus power distribution was based upon rough average classifications. Moreover, the emerging environmental issues and the geopolitical interdependence of power sources limited the development of economies of scale. The main challenges that a modern electricity network has to face are [1]:

- Privacy issues between energy suppliers and customers;
- Security threats from cyber attack;
- National goals to employ alternative power generation sources;
- Significantly more complexity in maintaining stable power with intermittent supply;
- Conservation goals that seek to lessen peak demand surges during the day so that less energy is wasted in order to ensure adequate reserves;
- High demand for an electricity supply that is uninterrupted;
- Digitally controlled devices that can alter the nature of the electrical load and result in electricity demand that is incompatible with a power system that was built to serve an "analog economy".

These challenges require the development of an intelligent, self-balancing, integrated electric network that makes use of the modern ICT techniques to manipulate and share data. The smart grid technology tries to answer these needs. In this survey, we propose an overview of the main aspects of smart grids development and implementation. In Section 2 we give two different definitions of the smart grid concept. In Section 3 we will analyse how the smart grid paradigm modifies the energy market. In Section 4, we will review its technical aspects. In Section 5 we will see how a smart grid can be optimized. In Section 6 we will review the existing open source smart grids solutions. In Section 7 we will review the regulatory aspects related to the smart grids. In Section 8 some conclusions are given.

2. What Is a Smart Grid?

The smart grid is a complex system. As such, it can be described from various points of view. Here we report two different definitions. The first one sums up the "European" view of the smart grid:

"A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies. A smart grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies. Smart grids development must include not only technology, market and commercial considerations, environmental impact, regulatory framework, standardization usage, ICT and migration strategy, but also societal requirements and governmental edicts" [2].

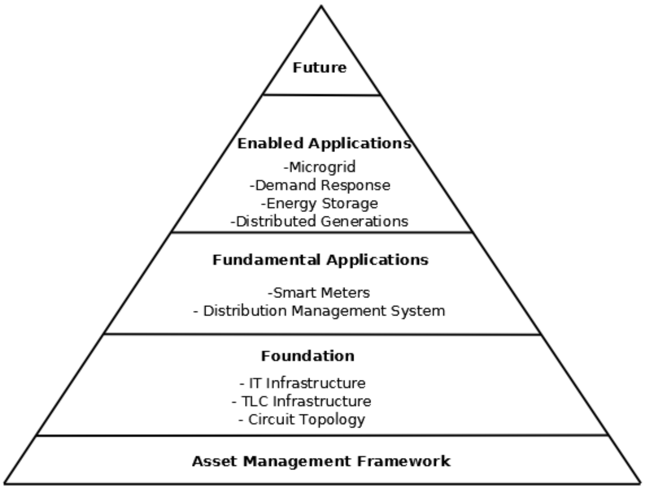
The second one, written in the Statement of Policy on the Modernization of Electricity Grid of the United States Government [3], characterizes the smart grids by means of a list of achievements. The most relevant are:

- the use of digital information to improve reliability, security and efficiency;
- integration of distributed resources and generation;
- "smart" technologies for metering, communication and automation;
- deployment of energy storage technologies (*i.e.*, electric vehicles).

According to professionals in the energy industry [4], it is clear that both definitions combine two dimensions: kWh and bytes. It is not argued the key role of ICT in developing a smart grid, and both viewpoints recognize the growing role of renewable technologies, distributed generation and energy storage.

The smart grid is not simply a technological innovation. It also involves an accurate economic and financial planning, in order to be realized successfully and in an efficient way. A visualization of this concept is given by Farhangi [5]. He depicts the smart grid as a pyramid, in which the asset management is the base for the realization of a smart grid infrastructure, as can be seen in Figure 1.

Figure 1. The smart grid pyramid (as described by Farhangi [5]).



The development of a smart grid does not involve replacing the existing electricity network. Such a process would be impossible for technical and economical reasons. Instead, the smart grid development is an enhancement of the existing network, by means of implementing new services and features, while maintaining, as much as possible, the old physical infrastructure. We have to define what functions a smart grid must provide. According to the United States Department of Energy's Modern Grid Initiative report [3], these functions are:

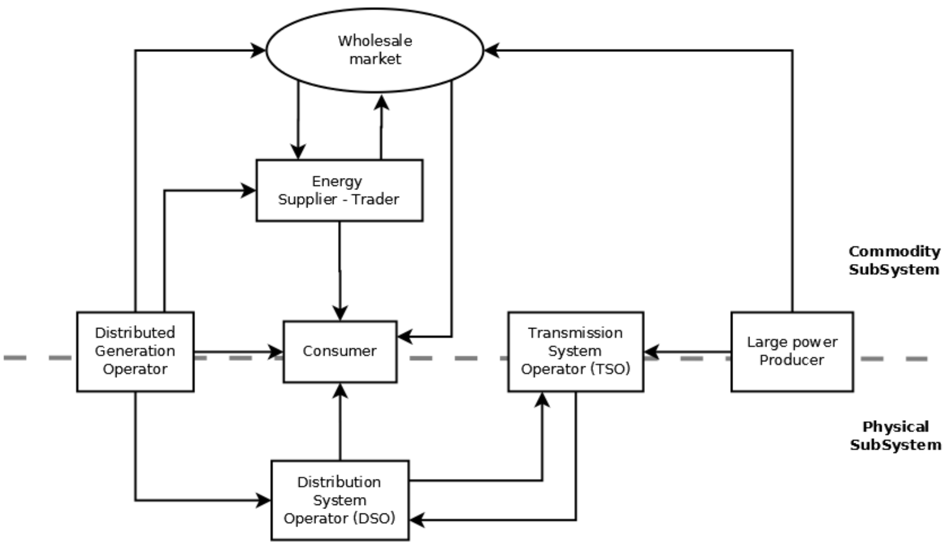
- Self-healing;
- Consumer participation;
- High quality power;
- Support for different types of storage and generation;
- Higher efficiency.

We will analyse how these functions can be provided from both the economical and technological point of view, focusing on the latter.

3. A New Energy Market

The smart grid technology radically changes the energy market scenario: new actors may arise, such as energy traders, distributed generation operators, *etc*. [6] (see Figure 2).

Figure 2. Overview of transactions within the electricity market [6].

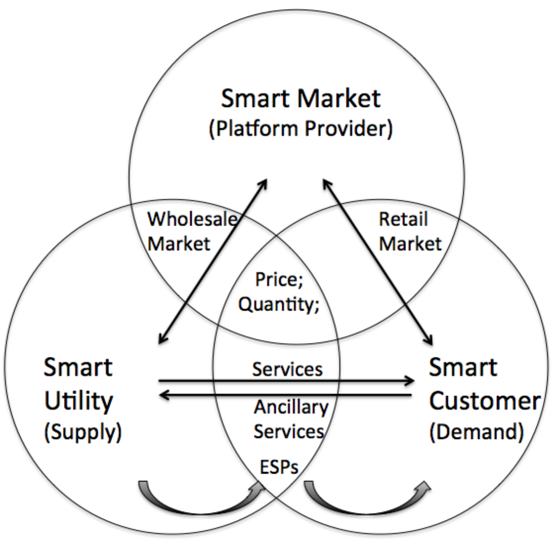


Tabors *et al.* [7] define three elements as the "pillars" of the smart grid. Those elements are:

- *Smart Customer*: the set of technologies that enable consumers to observe and control their consumption;
- *Smart Utility*: the utility that implements monitoring, control and pricing, and demand response;
- *Smart Market*: an economically efficient market structure to integrate technology, decision making and information.

Authors also identify Real-Time Pricing (RTP) as a fundamental tool to realize the Smart Market, because it provides consumers with a transparent way to control their energy bill, and utilities with a rate flexibility that allows them to increase their competitiveness and implement demand-side management. In Figure 3 these three figures are represented.

Figure 3. The three pillars of the smart grid [7].



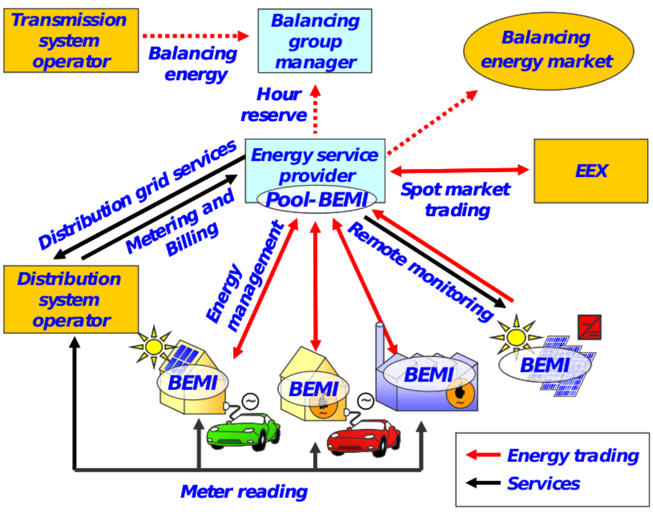
In this new scenario, the roles of producer and consumer get closer. The consumer is now able to produce energy, through distributed renewable energy sources. This new emerging entity is called the *prosumer*, which is discussed by Grijalva *et al.* [8]. Authors define it as an economically motivated entity that:

1. Consumes and produces power;
2. Operates a small or large power grid, thus transports electricity;
3. Optimizes the economic decisions regarding its energy utilization.

The prosumer may not be strictly a physical entity, but rather a combination of components: energy sources, loads, an electric grid, controls to operate his system, and a market, or other economic decision making system.

This new market must be supported through a management system that takes into account these new figures. An example of a strategic approach for a complete energy management system is BEMI (Bidirectional Energy Management System) [9]. BEMI is an energy management system designed for installation at Low Voltage grid connection points. Its main task is to optimize the so-called Controllable Distributed Electrical (CDE) units, which means locally connected loads or generators. This optimization is done accordingly to consumption and generation tariffs, set by an energy service provider through a Pool-BEMI system. BEMI supervises the CDE unit switching and operation, and also provides grid costumers complete information about the variable tariffs, energy cost and device schedules. The BEMI system is shown in Figure 4. As emerges from the picture, the BEMI system supports the new prosumer entity, modeling distributed generation with CDE units. Moreover, it also enables dynamic pricing, which we cited before as a key element of the new market. Thus, BEMI represents a useful example of an ICT system designed for a liberalized energy market.

Figure 4. BEMI System in the liberalized energy market [9].



When speaking about energy network management, the biggest problem is energy dispatch. A utility provider must be able to deliver a service in the smallest time possible, at the minimum cost and simultaneously keep alive the other critical services they are providing. This implies a careful planning of strategies and road maps considering also the return on the required investments for such major undertakings. As an example, Pica *et al*. [10] provide an analysis of the Brazilian smart grid development. In Latin America, many investors decided to undertake smart grid projects. The area is known to be a challenging but returning market for these kinds of investments. Moreover, the barriers for the smart grid development in Brazil are basically the same as every other country: market uncertainty, low public knowledge and awareness, lack of interoperability between energy providers, lack of regulatory definitions.

4. Technology

In this section, we will review some technical aspects of the implementation of a smart grid and its features.

4.1. Distributed Generation

Distributed generation (DG) is a driving factor for the smart grid implementation. Its integration in the energy network proved to bring many benefits [11] for customers, energy efficiency, and network operation itself. This integration is enabled through a number of different technologies [12], some of which are discussed in this survey:

- Advanced Metering Infrastructure (see Section 4.2);
- Energy Storage Systems (see Section 5);
- Advanced Distributed Management Systems (see Section 3).

Hidalgo *et al*. [12] provide a methodology for the integration of DG in a smart grid Network. It is based upon the connection of a distributed generator with a feeder, combined with an Automatic Voltage Control (AVC) system and a Dynamic Line Rating (DLR) function. In their study, they also provide an economic feasibility study, as a series of steps, which may be extended to a general project involving DG technologies. The defined steps are:

- Define the installation, operation and maintenance costs of the project;
- Define additional financial parameters like electricity rates, discount rates, inflation rate, *etc*.;
- Quantify additional benefits brought to the network, in terms of a premium to the electricity rate per output unit;
- Evaluate externalities, such as Greenhouses gases (GHG) reduction, to add them as a benefit;
- Calculate the economic parameters internal rate of return (IRR) and net present value (NPV) to evaluate the feasibility of the project.

Another project worth to be mentioned is SmartGen [13], an Italian project driven by several industries and two different research institutes (University of Bologna and Genova). This project aims at finding and implementing industrial solutions for smart grid management. The authors propose the definition of a DMS (Distribution Management System) for each portion of the grid, able to control and optimize power flows, distributed generation and load balancing. The base function of a DMS can be divided into:

- Supervisory Control and Data Acquisition (SCADA);
- Control Stations.

The SCADA system provides specific monitoring and real-time control operations, in an automated way, while the Control Stations allow human operators to interact with the system.

4.2. Metering

In order to efficiently implement a smart grid, a smart metering infrastructure is essential. Traditional metering devices, provided by energy distribution companies for their customers, typically measure energy consumption only in terms of total energy consumed. If they could also provide information about when and how energy is consumed, energy provision would be more intelligent, finely tuned to suit specific customer needs—and optimizing energy distribution over the entire network would be easier. In this context, the AMI (Advanced Metering Infrastructure) represents the reference for defining next generation metering technologies. AMI features include: [14,15]

- Two way communication to the electric meter to enable information interchange;
- Self-registration of metering points;
- Auto-configuration after a failure in communications;
- AMI system interconnection to utility billing, outage management systems, and other applications.

Hart [14] names the integration between smart grid and AMI as AGI, which stands for "Advanced Grid Infrastructure". The AGI has the following enhancements [14]:

- **Outage**: *Improved Customer Service*
  "Utilizing the AMI infrastructure, a utility can know when an outage occurs. The AMI system can notify the trouble call system automatically, facilitating rapid crew deployment and reduced outage times".

- **Loss Detection**: *Improved Network Operation*
  "By connecting information nodes at key points of the medium voltage distribution lines and distribution transformers, it is possible to directly calculate the system technical and non-technical losses. This enables better tracking and efficiency on the distribution network".

- **State Estimation**: *Integration of Renewable Sources*
  "By utilizing information from the customer site, medium voltage lines, and transformers, accurate load models can be computed allowing accurate load estimation on the distribution grid. This information is critical to understanding the impact and benefit of connecting renewable energy sources to the distribution grid".

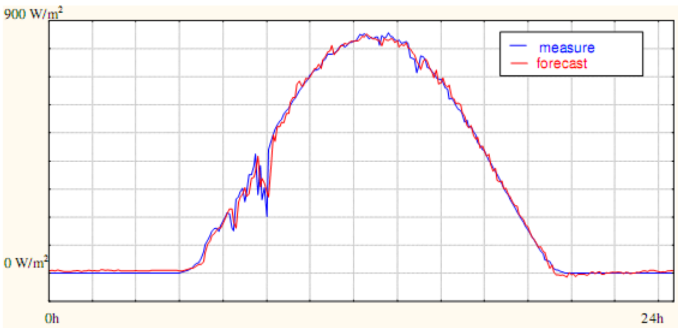
For further information, Karnouskos *et al*. [16] give a more detailed view of the AMI infrastructure.

4.3. Forecasting

Forecasting is a key functionality of a smart grid system. Through forecasting, the Grid is able to balance loads, optimize power distribution and handle failures. The main problem of forecasting, in a modern electricity network, is given by the Renewable Energy Sources (RES). The energy produced by RES can vary, and its variation depends on several parameters (climate conditions, source plant location, *etc*.) In this sense, their contribution in terms of energy can be difficult to predict, because there are too many variables to observe. In some cases, this unpredictability may become a limitation: since energy providers are unable to cope with massive amounts of unpredictable renewable energy sources, many countries and states impose by law specific limits for customer participation in energy generation. In Massachusetts, for example, this limit is set to 1% of all customers [17]. In this section we will provide some examples of forecasting techniques and algorithms for smart grids.

Bertani *et al*. [18] present a solution based upon a central dispatcher with the following functions: short-term forecast of the power produced by renewable energy sources (RES), short-term load forecast and day-ahead load profile prediction, distribution system state estimation, day-ahead economic dispatching and on-line scheduling of the optimal distributed resources' operating conditions. The forecast algorithm was based on a neural network. The results can be seen in Figure 5.

Figure 5. Example of forecasted vs. measured global radiation [18].



Another approach is presented by Sharma *et al*. [17], where the goal is automatic prediction of energy generation from renewable sources using weather forecasts. In their work, authors focus on solar generation. They collected 10 months of weather forecast and solar intensity data, searching for possible correlations. Then they used a machine-learning technique to develop a prediction model for short-term forecasting, specifically three hours ahead. Upon cross-validation, the prediction accuracy of their model as regards solar intensity (from which solar energy production can be calculated) is in the order of 130 W/m^2. They claim this accuracy to be 51% higher with respect to the traditional PPF (Past-Predicts-Future) models where the previous day solar intensity is used to predict the next day values.

Another dimension of smart grid forecasting techniques regards demand forecasting. This is crucial to energy providers and traders, because as dynamic pricing is enabled, the reaction of the customers to price changes may cause significant shifts in the demand curve. A possible solution to this problem is presented by Motamedi *et al*. [19]. Authors designed a hybrid forecasting framework, based upon two different models: a Multi-Input, Multi-Output (MIMO) engine that generates initial demand and price forecasting, and a Data Association Mining (DAM) algorithm to refine the predictions in order to improve the accuracy. The framework is divided into three logical phases: during the first phase, the MIMO engine extracts demand and price forecasting from historical data. Subsequently, in the second phase the DAM algorithm extracts possible rules and patterns in deviation curves of the observed values. In the third phase, these patterns are applied to the initial forecasting, using Fuzzy Inference Systems (FIS) to improve its accuracy. Authors applied their techniques to two different datasets (the actual Australian Market data and simulated New England Market data) to generate 24-hours ahead forecasts. Authors claim an accuracy in the order of 2% for demand forecasting and 10% for price forecasting.

4.4. Communication

The integration of information and communication is crucial, in order to realize the future-oriented energy system. This integration has to be done on an Internet-based infrastructure, able to provide access to energy information in a simple, quick and economic way. This is because energy providers, either centralized or decentralized, need a constant flow of updates, regarding the energy demands, in order to provide the precise amount of energy needed. The timing of these updates may vary from seconds to hours, depending on the management level of the grid. Optimization of energy consumption is based on integrated and near-real-time electronic communication between producers and loads on all levels of the grid.

This infrastructure will also be profitable for consumers. In fact, intelligent and inter-connected end devices will be able to optimize their power consumption and they will provide customers the possibility to monitor their consumption values, even remotely. This will allow customers who want to optimize their electricity usage to analyze their behaviour, to spot possible anomalies and to take appropriate countermeasures [20].

In this section, we will analyze some examples of integration between ICT technologies and the energy network. These examples are based on very common communication protocols and software architectures:

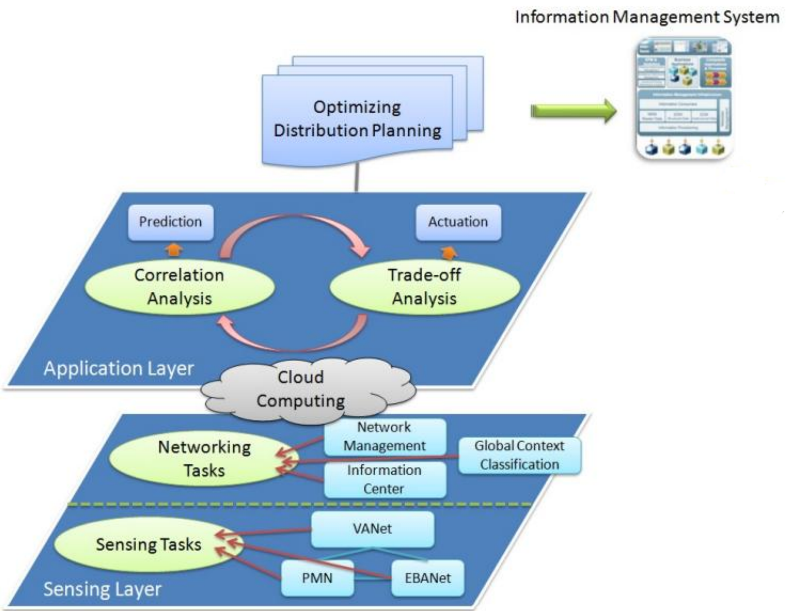
- The Network Time Protocol (NTP) is an application-layer networking protocol for clock synchronization between computer systems. It has been developed by Mills *et al.* [21] in 1989 and the current reference implementation is version 4, which has been proposed as a standard by IETF [22].
- The Service Oriented Architecture is a software architecture that defines the interactions between computer systems in form of interoperable and distributed services, defined through a description language.
- Web Services are the most common implementation of the SOA. According to the W3C, "a Web service is a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically WSDL)" [23].

An example of integration between the energy network and ICT networking technologies is a solution proposed by Shannon *et al.* [24]. In modern energy distribution systems, generation and demand need to be always matched in real-time. This means that the modern grid is a real-time distributed system, thus it needs a precise synchronization between its devices. Modern grid infrastructures realize several functions, such as protection testing, fault detection, load balancing and scheduling through synchronization. The authors propose a solution based on the implementation of the Network Time Protocol (NTP) over 802.11 networks along with an optimisation technique to reduce the energy usage of a common Wireless Sensor Network (WSN) synchronisation protocol [24].

Another example focusing on integration is provided by Ding *et al.* [25], where authors investigate the consumer energy consumption of Beijing, in order to perform statistical analysis aimed at recognizing city events and dynamics.

Thus, they realized a two-layer architecture (see Figure 6) to realize an application framework based on the urban sensing for supporting the optimization of energy consumption. Through the proposed middleware ODP, utilities could get more intelligence and value from the data that will be collected from existing USI (Urban Sensing Infrastructure) and other smart grid devices, like AMI (Advanced Metering Infrastructure, see Section 4.2).

Figure 6. System architecture of two-layer approach used by Ding *et al.* [25].

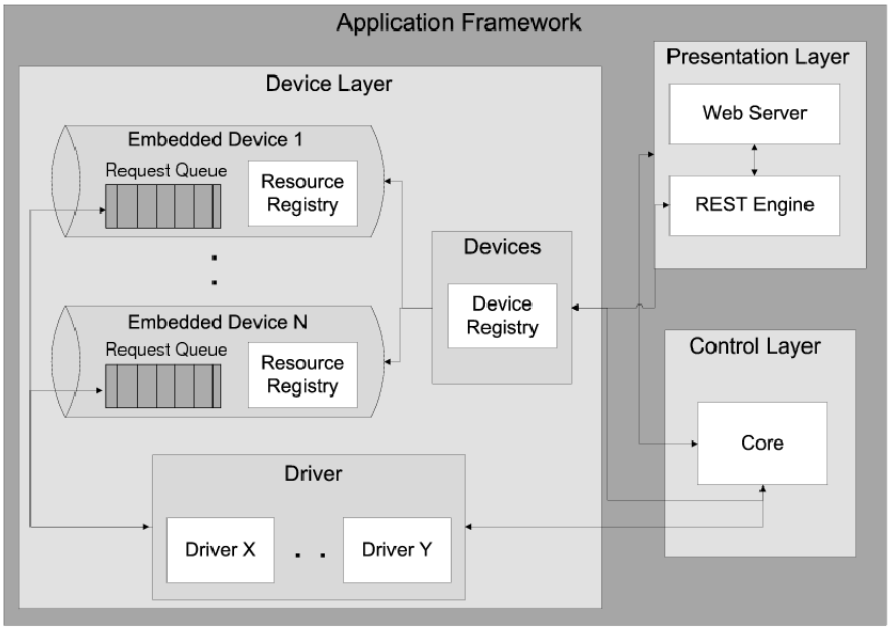


The Service-Oriented Architecture (SOA) provides concepts particularly suitable for an energy distribution network. In fact, it decouples functionalities from implementation, integrating them through message exchange protocols in a dedicated Service Bus. Moreover, it is not needed to develop interfaces between every application: each application only needs to be interfaced to the integration platform [15].

The only issue of the SOA is finding the correct semantics for data. Without open interface definitions and a standard semantic structure for message exchange, it is not possible to realize an efficient energy network.

Web Services are especially useful in the context of Smart Houses. An Energy-Aware Smart House is a residential building equipped with a Smart Metering system (see Section 4.2) able to measure and control in real-time the power consumption of every electrical device installed. Kamilaris *et al.* [26] presented a Web-Oriented Application Framework for embedded devices. The framework is based on a RESTful architecture, which is shown in Figure 7. The embedded devices represent sensor nodes, which may provide all sort of information (power consumption, for instance). This solution has shown a response time for querying each device lower than 60 ms, even with high workload.

Figure 7. Application Framework Architecture for embedded devices [26].



The suitability of Web Service architectures for the smart grid/smart houses is also stressed by Warmer *et al*. [6].

4.5. Security

As said above, smart grids exploit ICT technologies to provide "awareness" about the state of the grid. Thus, it is possible to implement load shedding features to manage peak demands, production analysis for energy generation, dynamic pricing, *etc*. On the other hand, ICT introduces issues related to security. Smart grids lead to a set of new challenges that require new approaches in the field of cyber security, because many of the already existing mechanisms are not applicable. This difficulty is mainly due to the nature of the equipment installed in the power grid. They were purpose-built and they do not have the computational resource needed to manage security features.

The National Institute of Standard and Technology (NIST) describes the problem of smart grid cyber security strategy [27]. The first goal is prevention, but on the other hand, a response and recovery strategy in event of a cyber attack is required. This strategy can be described in five steps:

1. Use cases description of the applications will be developed. The information needs will be mapped to existing transmission and distribution power system models, which will be extended as required.
2. Definition and implementation of an overall cyber security risk assessment process for the smart grid. Risk is the potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated impacts.

3. Creation of a common framework provided by the set of use cases, which perform the risk assessment, develop the security architecture, and select/tailor the security requirements.
4. Development of a security architecture, which will overlay the security requirements on this architecture. The objective is to ensure that cyber security is addressed as a critical cross-cutting requirement of the smart grid. It is also needed the assessment of smart grid standards that are not conflicting with security requirements.
5. Develop a conformity assessment program for security requirements.

We can distinguish between two different classes of attack on a smart grid: cyber and physical.

The first class of attacks may lead to eavesdropping of private information or may cause a misbehaviour of physical components managed by software routines. On the other hand, physical attacks may lead to AMI bypassing in order to falsify accounting values or may cause instability due to physical destruction.

Considering cyber attacks, we can divide them into four categories as proposed by Li *et al.* in [28]

- **Device attack:** compromise the control of a grid device. Typically it is the first step of a complex attack.
- **Data attack:** aims at inserting, altering or deleting the data flow in the network, in order to get misbehaviours.
- **Privacy attack:** attempts to use electricity usage data to learn or infer users' personal information.
- **Network availability attack:** it aims to use up or overwhelm the communication and computational resources of smart grid and to result in delay or failure of communication.

The main issue in gaining good levels of security in the smart grid is achieving a reliable protection against mixed physical and cyber attacks. Typically, cyber security does not provide an analysis of the possible consequences of physical attacks and, similarly, system theory does not provide a complete modelling of the IT infrastructure.

From the viewpoint of IT, we can identify three main requirements related to cyber security in smart grids as described in Mo *et al.*[29]:

- Confidentiality of power usage: energy usage patterns can reveal personal activities.
- Integrity of data, commands and software: integrity of price data is critical, because an attack can cause a misbehaviour of the grid and, on the other hand, integrity of meter data and commands is important but not so critical because it is mostly limited to revenues losses.
- Availability against DoS/DDoS attacks: data availability is a key aspect in smart grids because it can lead to financial and legal implications [30]. Price data availability is critical because outdated data can affect the energy demand. Commands availability is important for economic aspects related to billing, and the availability of meter data does not represent a critical issue because the data can be read at a later point.

Table 1 summarizes the levels of importance for the security properties in smart grid environments.

Table 1. Importance of security properties in smart grid environments.

	Price Information	**Control Command**	**Meter Data**	**Software**
Confidentiality	Low	Low	Medium	Low
Integrity	High	High	High	High
Availability	High	High	Low	N/A

The main entry points in a smart grid are:

- infiltration through infected devices, *i.e.*, USB sticks.
- network-based intrusion, *i.e.*, misconfigured or poorly configured firewalls.

Backdoors and holes in network perimeter may be caused by components of the IT infrastructure that can be exploited for bypassing the access control mechanisms. When an attacker enters the trusted network, he/she can compromise some devices. Another issue can be provoked by a malicious insider (someone who is authorized to access the system) whose actions, listed in Table 2, can be difficult to detect or prevent.

Table 2. Threat Type classification based on Security Properties.

	Price Information	**Control Command**	**Meter Data**	**Software**
Confidentiality	Leakage of price info	Exposure of control structure	Unauthorized access to meter data	Theft of proprietary software
Integrity	Incorrect price info	Changes of control commands	Incorrect meter data	Malicious software
Availability	Unavailability of price info	Inability to control grid	Unavailability of billing info	N/A

Countermeasures needed to avoid attacks on smart grids range from key management to network communications and system security. We report some examples below according to Mo *et al.* [29]:

- Key management is fundamental for information security: shared secret keys and authentic public keys ensure secrecy and authenticity if used properly. The key setup in this kind of solutions is the root of trust.
- Secure Communication Architecture has some critical aspect such as the network topology design in order to make nodes highly resilient under attack; Secure Routing Protocol, which must be on top of the network topology; Secure Broadcasting that is typically used in smart grid environments; DoS defense to avoid an interruption of the data flow; Jamming detection mechanism can be used to detect attacks and trigger security procedures.
- System and devices security has mainly to deal with software-based attacks and these techniques must prevent the injection of malicious code into the system.

In literature, some projects related to cyber security can be found, focused on different aspects of a smart grid. Wei *et al.* [31] presented a security framework for smart grids, which exploits the layered architecture. This solution, scalable and distributed, integrates security at agents level, switches level, and management level, to prevent both internal and external network attacks. Boroomand *et al.* [32] used Adapted Autonomy and Human-Automation interaction theories to create cyber security strategies for the smart grid. McLaughlin *et al.* introduced some variations in smart meter firmware [33] to avoid common vulnerabilities. LeMay *et al.* proposed Attestation techniques based on hardware approaches [34,35]. Seshadri *et al.* [36] showed an Attestation solution based on software, which *"verifies the memory contents of embedded devices and establishes the absence of malicious changes to the memory contents"*. Shah *et al.* proved the applicability of Attestation on SCADA systems [37].

5. Optimization

In this section, we will present how a smart grid network can be optimized through new technologies and approaches.

5.1. Cloud Computing

Coordinating smart grids through cloud computing services is an innovative idea. Brynjolfsson *et al.* [38] performed a deep analysis on the weak and strong aspects of the cooperation between the cloud computing technology and the electricity market. In their contribution, they suggest going beyond the "utility model" of cloud computing, (*i.e.*, using Cloud resources instead of local ones) and taking advantage of the subsequent innovations that this new technology will bring in the next few years. To summarize their point of view, cloud computing brings issues that must be addressed specifically, such as security, latency and scalability, when applied to an electricity distribution context. Nevertheless, authors advise that cloud computing and the new IT technologies it enables will, inevitably, transform the electricity industry.

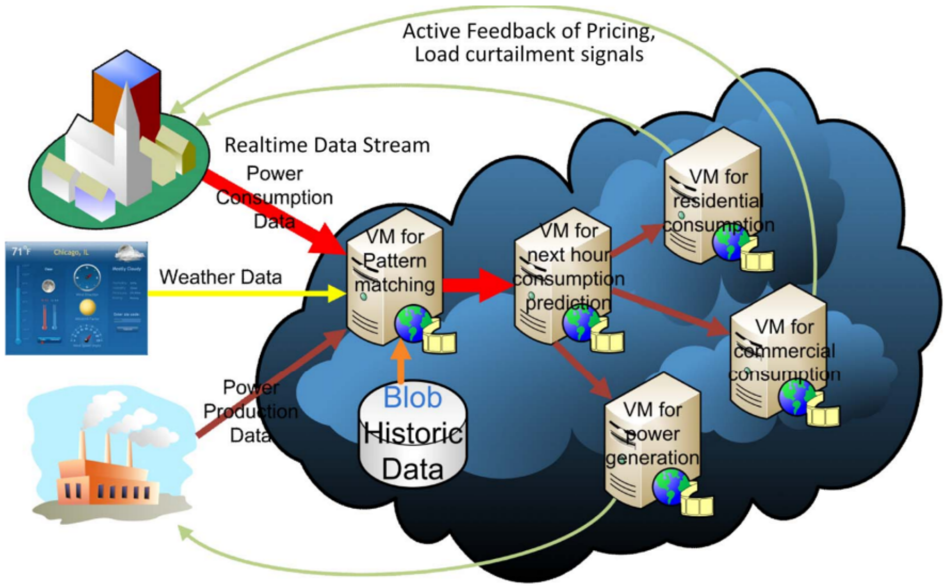
Another vision of the opportunities and challenges of applying cloud computing services in smart grid networks is given by Simmhan *et al.* [39]. In their contribution, it is stressed how the scalable and elastic resources of a Cloud infrastructure is suited to support the dynamic applications of a smart grid, such as energy forecasting, load balancing and demand-response optimization. The data streams from consumers' Smart Meters acts as data sources for the distributed system. Clouds provide a ready platform for data sharing and also allow third-party applications to be collocated with the data source (see Figure 8).

The research challenges that the Cloud infrastructure has to address are:

- *Streaming applications in the Cloud*: at present, Cloud providers do not provide specialized data abstractions for these kinds of data streams.
- *Scheduling Latency Sensitive Applications*: the demand-response applications need to be highly responsive.
- *Scalable Data Sharing and Privacy Preservation*: information on energy assets has a very relevant size, thus sharing of the information needs to be highly scalable. Also, typical public Cloud storage

platforms do not provide fine grained authorization control for data. Models for using the shared Cloud repository by multiple users and their software agents, with different levels of access, need to be examined.

Figure 8. Smart grid and cloud computing: a sample infrastructure [39].



The interaction between smart grids and cloud computing creates a new scenario for the different actors of the system. Rusitschka *et al.* [40] presented a data cloud model for a smart grid. This model is realized through the interaction of several software systems, connected through the Internet, operating through REST APIs. The low-level sensors and metering devices continuously provide their data through the *PUT* primitive of the data cloud, while high-level information systems, representing the energy market actors, are able to query the data cloud via *GET*. This process is shown in Figure 9. Depending on data availability requirements and the data types involved, load balancing mechanisms may be needed.

Figure 10 shows how this model is able to separate the control flow from the data and information flow. This allows an event-based handling of the various actuators of the system (e.g., the physical devices) by the actors (e.g., information systems). It is important to notice that this model assumes that all the actors of the energy market use the same infrastructures for information retrieval. Otherwise, data management would require too much resources, both technological and economical, in order to be efficiently implemented.

Finally, Mohsenian *et al.* [41] relate the Service Request Routing problem, typical of cloud computing infrastructures, with the Power Flow Analysis in a smart grid network. Through simulation, they showed that an efficient service routing algorithm applied to a smart grid can significantly improve the robustness of the grid design.

5.2. Agents

Figure 9. Smart grid web application scheme [40].

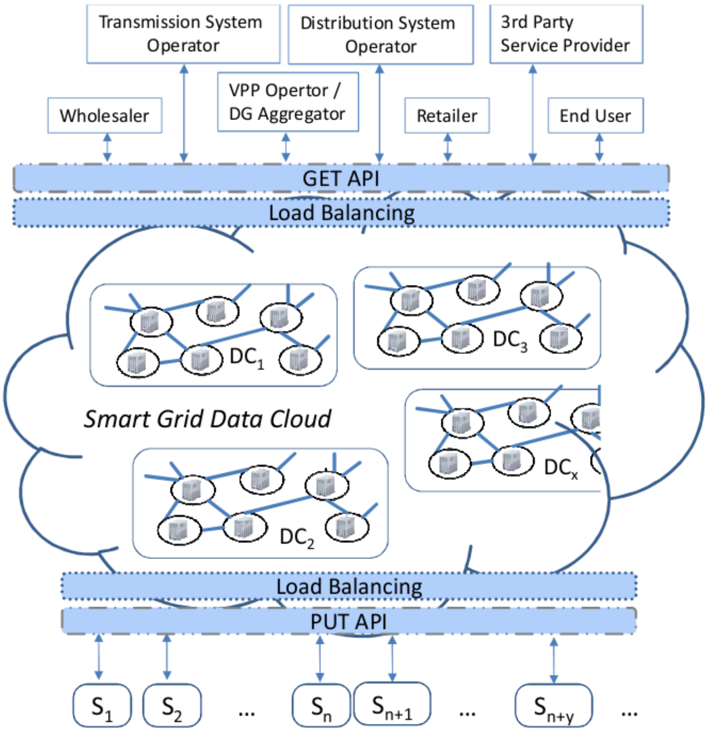
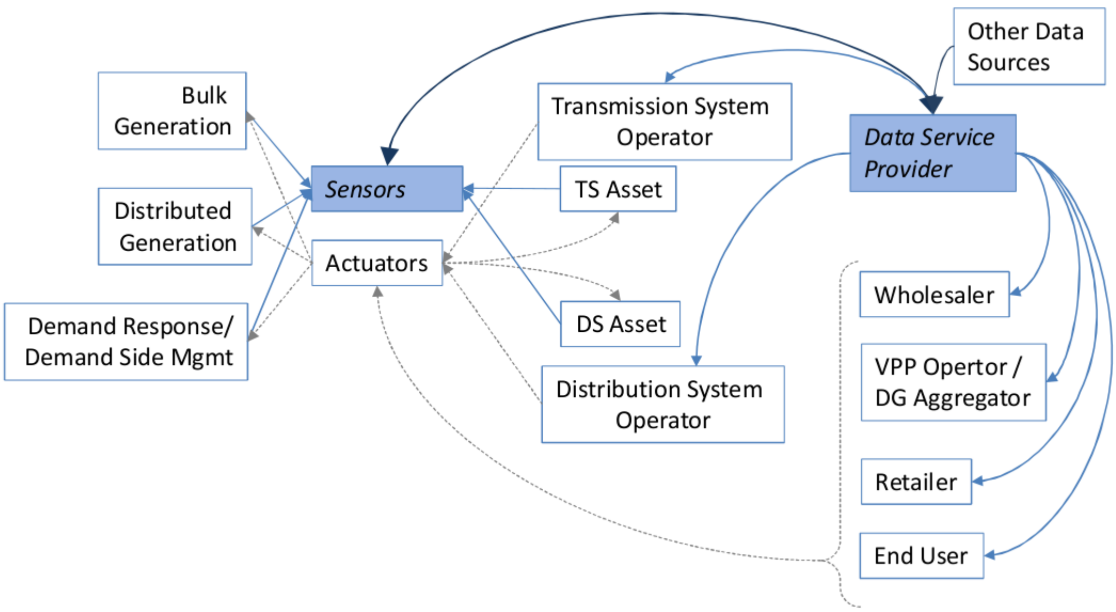


Figure 10. The smart grid information flows [40].



A smart grid is, by itself, a decentralized network, where intelligence is distributed across several devices. These devices may have to take autonomous decisions, in order to react quickly and efficiently to changes in energy demands, faults, and such events.

Thus, the Software Agents paradigm may provide a way to implement a system like that. In fact, in this paradigm, it is possible to design a distributed system with specific functionalities through the cooperation of autonomous, intelligent components.

"A multi-agent system (MAS) is a system of multiple interacting software agents. A software agent is a self-contained software program that acts as a representative of something or someone (e.g., a device or a user). A software agent is goal-oriented: it carries out a task, and embodies knowledge for this purpose. For this task, it uses information from and performs actions in its local environment or context. Further, it is able to communicate with other entities (agents, systems, humans) for its tasks" [42].

Karnouskos *et al.* [43] presented a Multi-Agent System (MAS) simulating a Smart City. The simulated entities were:

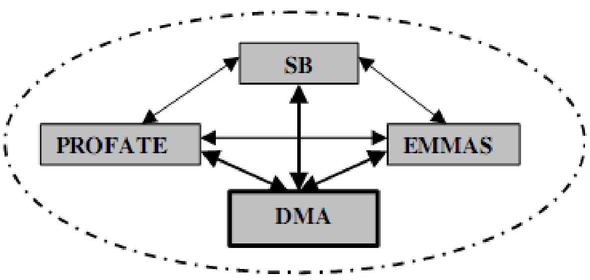
- Houses;
- Appliances (Single devices, of different classes, installed into a house);
- Vehicles (Electric Vehicles able to store energy into batteries);
- Cities;
- Power Stations.

The system was implemented using JADE (Java Agents Development Environment). Each entity was represented by a software agent. Then, an energy controller agent is able to act in order to balance power demand and power generation (for example, turning off some devices when power consumption is too high). Authors performed a simulation of their system to demonstrate how it is able to dynamically adjust generation, keeping the difference between generation and consumption within ideally close limits. The proposed scenario involved 300 houses evenly divided into three cities, and a total of 3840 appliances.

MAS are often associated to *electronic markets*, computing frameworks for distributed decision making based on microeconomics and Game Theories. By applying this paradigm to the energy distribution networks, we can make use of the already developed techniques and methodologies to realize the so-called *Market-Based Control*.

Several works following this idea have been proposed. Gnansounou *et al.* [44], for example, presented a complex multi-agent architecture composed of different components: the Problem Formulator and Attributes Evaluator (PROFATE), the Scenarios Builder, the Electricity Market Multi-Agent System (EMMAS), the Decision Making Assistant (DMA) (see Figure 11).

Figure 11. Outline of the IDSS structure [44].



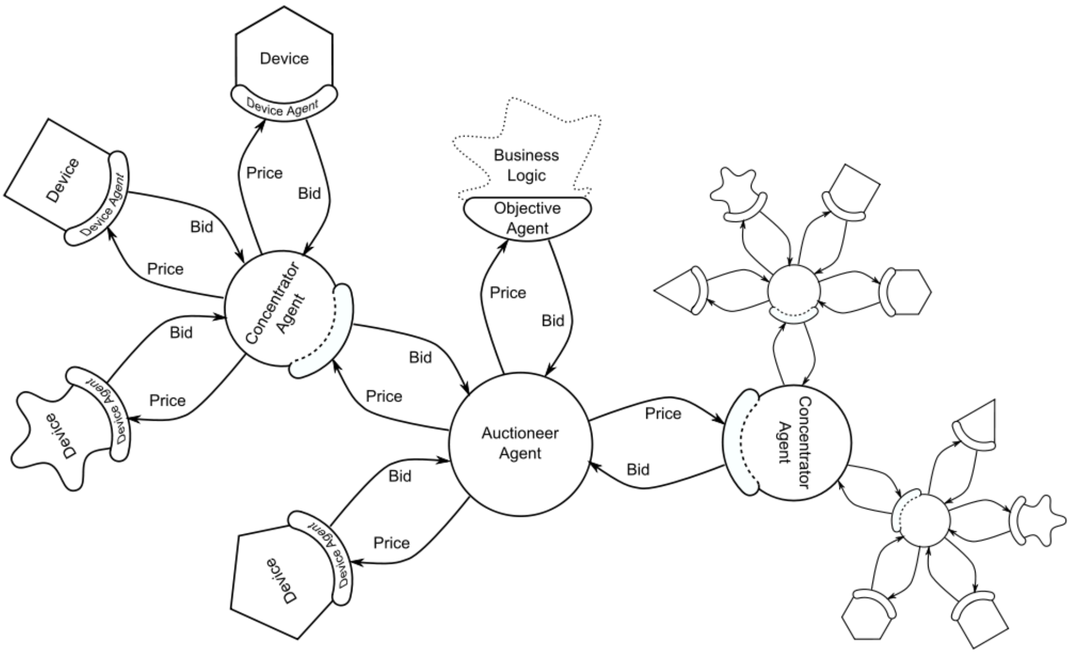
Of these components, the most interesting is without any doubt the EMMAS. In order to forecast market prices, both at medium and long-term, accurate simulation models are needed, able to react to structural changes. The EMMAS realizes these models, by means of a complex taxonomy of software agents that represent every actor in the transaction process.

Another example of a MAS designed for controlling energy networks is PowerMatcher [42].

"The Power Matcher is a general-purpose coordination mechanism for balancing demand and supply in clusters of Distributed Energy Resources. These 'clusters' might be electricity networks with a high share of distributed generation or commercial trading portfolios with high levels of renewable electricity sources, to name a few. Within a PowerMatcher cluster, the agents are organized into a logical tree. The leaves of this tree are a number of local device agents and, optionally, a unique objective agent. The root of the tree is formed by the auctioneer agent, a unique agent that handles the price forming, i.e., the search for the equilibrium price. In order to obtain scalability, concentrator agents can be added to the structure as tree nodes" [42].

In Figure 12 an overview of a cluster structure is given. From this figure, it is possible to appreciate that the "core" of the cluster is the Auctioneer agent, which receives a series of bids from other agents (Objective or Device). Upon receiving their bids, the Auctioneer is able to determine the prices and subsequently communicate them to the other agents. Concentrator agents represent group of agents, in order to encapsulate complex subsystems. An integration of the BEMI system, PowerMatcher and another MAS known as Magic, realized through a SOA, is proposed by Karnouskos *et al.* [45]. Authors also performed a field testing of these three systems, publishing their results in another work [46].

Figure 12. Example PowerMatcher agent cluster [42].



5.3. Energy Storage

Another aspect that can substantially improve the efficiency of a smart grid is the energy storage. Basically, it is the problem of keeping energy available directly on the grid, in storage components efficient enough to minimize energy losses. In cases of energy production peaks, when there is an overproduction of energy, having a distributed storage system increases the overall efficiency and compensates the variability of Renewable Energy Sources (RES), also enabling local optimization strategies for energy consumption.

An agent-based technique is exposed by Vytelingum *et al.* [47]. Basically, they propose a game-theoretic framework that analyses the Nash equilibrium of an electricity network, and develops learning strategies for agents that dynamically adapt to the energy market. As regards storage devices, they embrace the so-called Vehicle-to-Grid (V2G) view, where the unused energy is stored in the batteries of electric vehicles (EVs) or Plug-in Hybrid Electric Vehicles (PHEVs). Since this practice can raise problems of peaks in energy demand, a Multi-Agent System is adopted in order to optimise usage and storage of electricity. In particular, the proposed system models a situation where each device is represented as an intelligent software agent, and every agent can try to "buy" the needed amount of energy at every time, meanwhile learning what is the most profitable amount of energy to buy, according to the specific usage. The authors claim that, implementing their technique, a single consumer may save up to 13% on his electricity bill [47].

Other approaches related to the V2G view have been proposed. For example, Ramezani *et al.* [48] used a multi-objective evolutionary algorithm to schedule a smart charging of the batteries in the EVs. In their work, they presented a simulation environment that takes into account different scenarios and parameters. Different charging stations are simulated, in different locations. For each of them, there are an expected number of car arrivals. The simulation defines arrival and departure time, as well as initial and requested charge levels. For each car, a specific battery type is simulated, with different charging curves. All of these parameters are modelled as parameterized Gaussian curves, in order to obtain a realistic simulation. Subsequently, authors established a set of hard constraints (*i.e.*, grid capacity, battery characteristics) and soft constraints (objectives, such as minimize battery degradation) to be respected. Afterwards, the algorithm tries to find the optimal scheduling for the battery charging, in order to minimize the total energy cost. Results of this optimization can be appreciated in Figure 13, which shows how the charging schedules are optimized so that more cars are charged when the price is cheaper. The used power (in blue) decreases when the energy price (in green) rises. This is another example of how smart charging of EVs may result in energy savings.

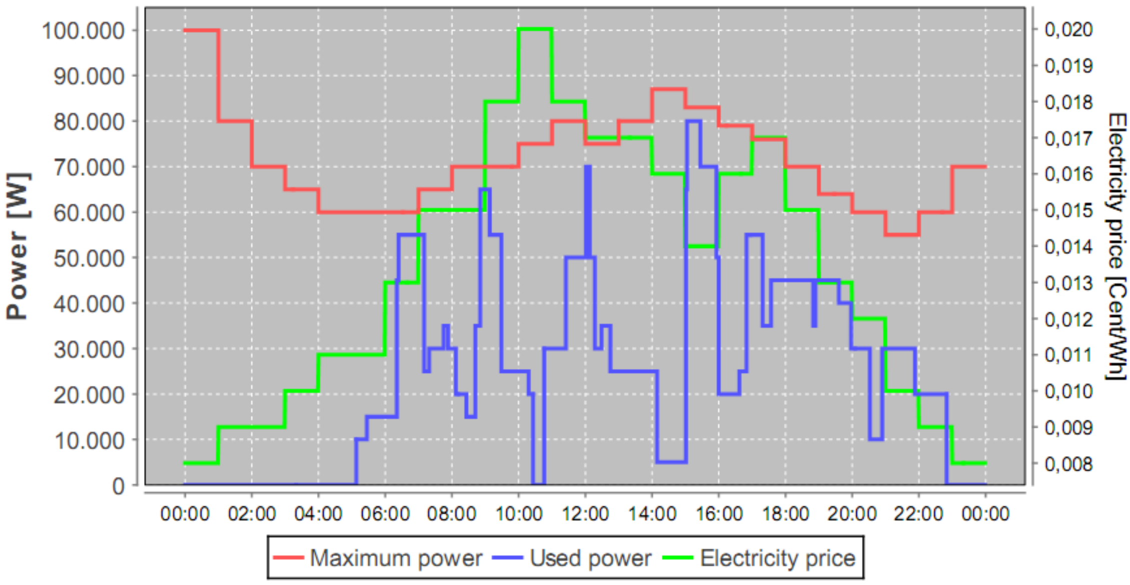
5.4. Unit Commitment Problem

One of the key objectives of a smart grid architecture is dispatching energy from all the available sources in order to meet the electric load. In other terms, there is a problem of coordination between energy demand and generation. This problem has been formalized under the name of Unit Commitment.

Unit commitment (UC), also known as pre-dispatch, is the problem of scheduling the production of energy by generation units of a power system. The objective is to minimize total production costs, while observing several operating constraints.

Thus, UC is a complex mathematical problem, based on both integer and continuous variables. In order to solve this problem, an optimized algorithm is needed, because complete enumeration of all the possible solutions would require excessive computation time. For this survey's purposes, we analysed two possible solutions, which involve different approaches for solving the Unit Commitment Problem. Momoh *et al.* [49] propose a solution based on Adaptive Dynamic Programming (ADP).

Figure 13. Electricity price, grid capacity and charging power chart [48].



"ADP is able to optimize the system over time under conditions of noise and uncertainty. If optimal operation samples are used to train the networks, ADP can learn how to commit the generators and follow the operators customs. When load is changed, it can change the operation according to the load changing"[49].

The solution presented by the authors focuses on a specific family of ADP: the Heuristics Dynamic Programming (HDP).

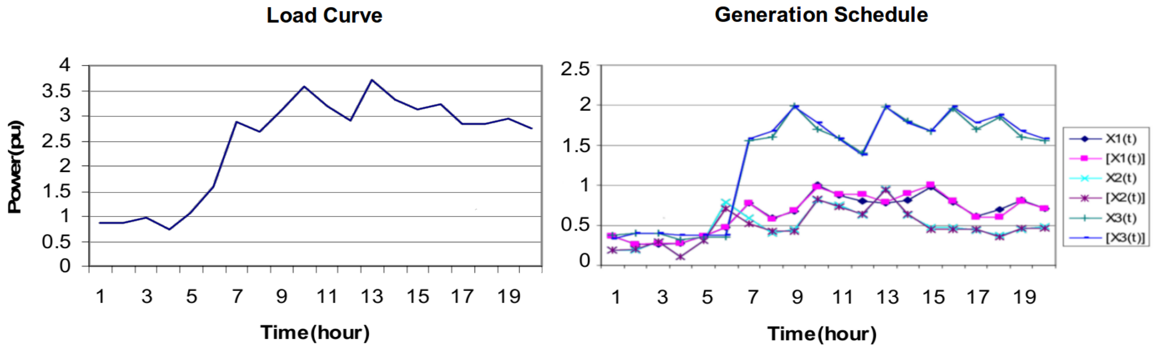
"The implementation is divided into ***action network****,* ***critic network*** *and* ***model network****. The function of* ***action network*** *is to determine the feasibility region of operation of the power systems and to detect the emergency state with corresponding violations under different contingencies. The function of* ***critic network*** *is for post-optimization process, evaluation and assessment of control options during contingencies. And the function of* ***model network*** *is to read power system parameters and obtain distribution function for state estimation of measurement errors inherent in data, ascertain and improve accuracy of data. The aim of all these kinds of methods is to approximate the cost-to-go function which is relative to the output of critic network"*[49].

After training, the HDP gives the generation plan. Figure 14 shows the load curve and the generation schedule of a three-generators system. X1, X2, X3 and [X1], [X2], [X3] represent the actual and expected output of the three generators respectively.

Another approach for the UC problem is presented by Kazarlis *et al.* [50], where the authors introduce a solution using Genetic Algorithms (GAs).

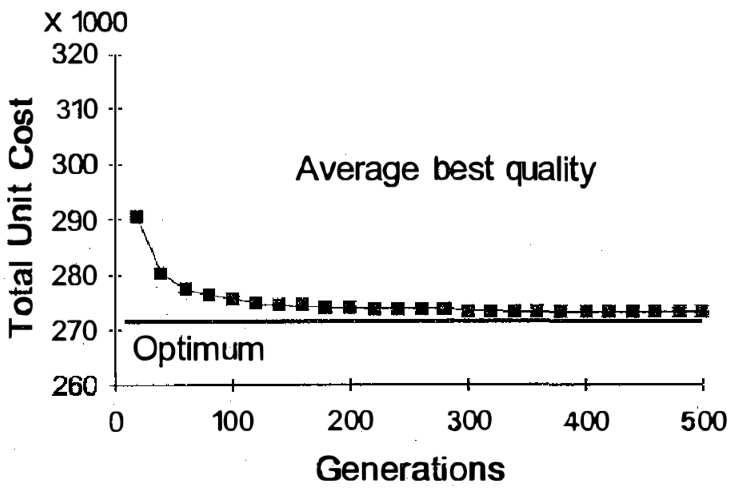
The application of the GAs to the UC problem included encoding each solution with a simple binary alphabet. At first, a number of initial binary-coded solutions (*genotypes*) are produced randomly to form the initial population. Then, a fitness value is given to each solution, calculated as a sum of penalties for violating certain problem constraints. Afterwards, a new offspring genotype (new solution) is produced by means of the two basic genetic operators: *crossover* (combining different solutions by mixing their binary codes) and *mutation* (modifying randomly chosen bits of the offspring genotypes. The above

Figure 14. Load curve of a 3-generators system and the corresponding HDP generation plan [49].



procedure is repeated until a new set of genotypes is produced, which is considered as the new generation of solutions. The new generation totally replaces the parents. By also implementing some adjustments to the fitness calculation, the GA technique has proven to converge in the order of hundreds of generations, as can be seen from Figure 15.

Figure 15. GA with varying penalties added: average progress of the best chromosome's quality over 20 runs [50].



Zhang *et al.* [51] provide another view of the Unit Commitment problem. In their work, the authors propose a mathematical model for power consumption in a Smart House, and present an algorithm, based on mixed-integer linear programming, to minimize the cost of the daily forecasted energy consumption. Their model schedules an operation time window for each device in the house (dishwasher, air conditioners, boiler, *etc.*) and then forecasts a duration for each usage. Based upon these data, and also on various parameters of tariffs and efficiency, the algorithm solves the objective function, which, according to the authors, can provide 18.7% saving on the energy bill.

6. Open Source Smart Grid Solutions

As we stated previously in this work, ICT and advanced software technologies are key enablers for the smart grid paradigm. Open Source smart grid software would present many advantages in terms of interoperability, initial investments and technological development. For this reason, we decided to dedicate this section of our work to review the open source software solutions for smart grid management, available at the time of writing this article.

A first example is provided by Strasser *et al.* [52]. In their work, they propose a distributed automation system for controlling electrical power systems with DG, using a framework of open source software and standards. More in detail, their system is based on:

- IEC 61499 [53]: Open Standard for Distributed Control, it provides a standard methodology to distribute control applications through different devices, thanks to a modular approach based on "Function Blocks";
- IEC 61850 [54]: Open Standard for Power System Automation, it defines an information model for power utility systems, and also the different communication services available between compliant devices;

The aim of the work is to prove the interoperability between these two standards and the following open source software applications:

- 4DIAC Framework for Distributed Industrial Automation and Control [55]: an open 61499-compliant framework, which can be considered a reference implementation of the standard. It provides a runtime environment for embedded devices and a modelling IDE for engineering purposes;
- GNU Octave [56]: an open source computational environment, compatible with MATLAB®.
- PSAT (Power Systems Analysis Toolbox): a MATLAB®-Octave toolbox, developed for the analysis of electric power systems. It provides several features like power flow analysis and computation, time domain simulations and support for DG.

In Figure 16 an architectural view of the complete solution is given.

As we stated several times throughout this work, one of the key aspects for smart grid implementation is data management, in terms of acquisition (metering), storage, and analysis. In this sense, a relevant solution has been presented by Brewer and Johnson [57] where they introduce WattDepot, an open source framework for energy data collection, storage, and visualization. WattDepot consists of three kinds of services: software *sensors*, which retrieve power consumption/generation data from different classes of devices, *servers*, which collect data from sensors, store them in a relational database and provide them publicly through RESTful APIs, and *clients*, which either present data to the final user using different visualization techniques or provide input data for analysis tools. In Figure 17 the architecture of WattDepot is presented.

The system provides device independence at server level, although software sensors must be specifically developed for a particular power meter. Actually only a few brands of meters are supported. One of the most interesting features of this system is the decoupling of data from particular representations, a benefit deriving from the RESTful approach. Servers may provide power data in different formats (currently JSON, XML, CSV) through simple Web Service technologies. Servers

Figure 16. Power Systems Simulator on PC-based and Controller Execution on Embedded Hardware [52].

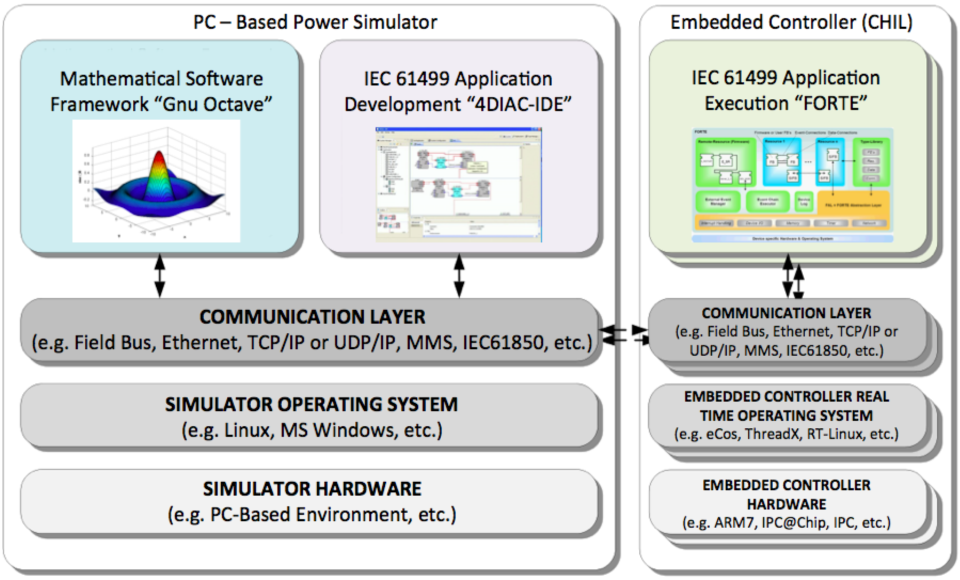
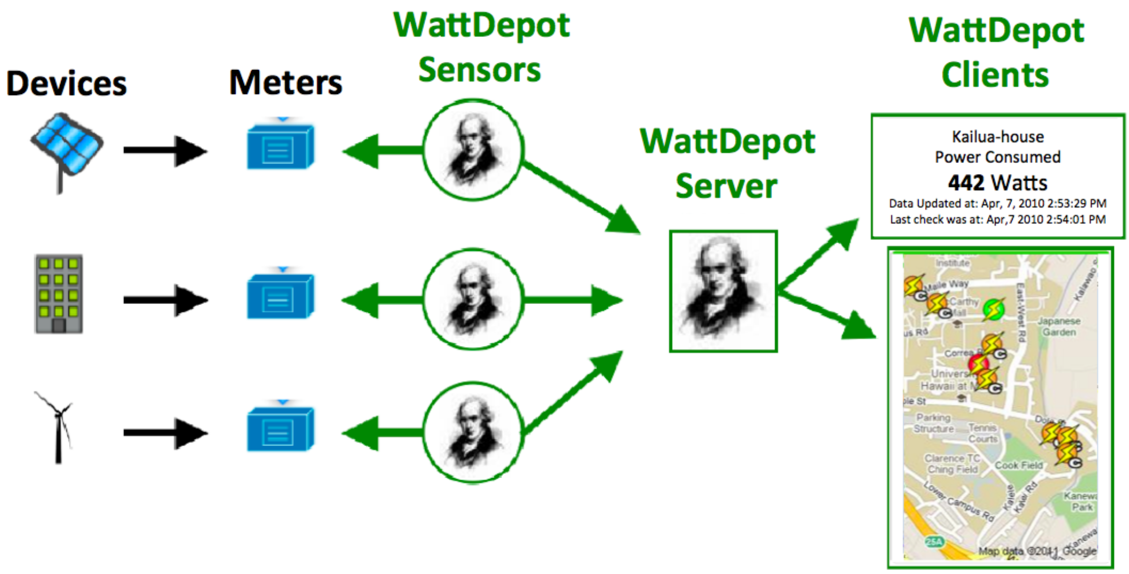


Figure 17. The WattDepot software architecture [57].



also perform an interpolation of time series data, because there is no guaranteed matching between the timestamps of data provided by the different sensors. An open issue regards data privacy. The system has indeed a very simple privacy model, based on a common username/password system with only two levels of access (public/private). This issue has been addressed by authors as one of the future development directions for the work.

In Section 5 we introduced software agents as a suitable technology for smart grid systems. Bankier [58] presents an interesting solution called GridIQ, an open source test bed for smart grid agents. Basically, GridIQ provides a bridge between a Multi-Agent System (MAS) implemented using JADE platform, and the PSAT power simulation tool, previously introduced in this section. The operation model of GridIQ basically assigns agents of the MAS to single "buses", or power lines, in the electric network model provided by PSAT. Agents' roles and behaviours have to be defined in the MAS previously. Then, after the initial configuration of the system, it is possible to run simulations of the overall system, in order to detect how agents will behave according to the defined policies and how they react to network disturbances (simulated events affecting the electric network, e.g., an unforeseen power consumption increase on a single line). It is then possible to log simulation results for subsequent analysis and tuning of the agent system. The GridIQ solution is available on the Sourceforge platform [66], as well as the other components of the presented test bed.

7. Regulatory Aspects

One of the main obstacles to the smart grid development and diffusion is the lack of a precise regulatory environment [10]. In this section, we will illustrate the organisms and the activities made to support the development of the infrastructure in the European Union.

In 2005, the European Technology Platform for Electricity Network of the Future (ETP) was instituted. Its mission was to develop a vision for a future electricity network over the entire European continent. In 2006, ETP released its first official document [59]. In the document, the vision of the new electricity network is given, defining it as

- Flexible;
- Accessible;
- Reliable;
- Economic.

It also stresses the importance of the liberalization of the electricity markets, in order to decrease prices and increase flexibility. It is a key point to ensure that consumers may choose their preferred energy provider at every time, according to their needs and economic situation. This also means that interoperability between different providers must be granted.

In 2007, ETP released its second document [60], a non-prescriptive document for European and National programmes. It proposes a Framework for a research programme with the following goals:

- develop smart grids in order to increase Europe's competitive position;
- increase collaboration between the Member States;
- set clear objectives for researchers.

This document was basically meant to inspire R&D projects regarding smart grids within EU and national institutions.

Their third and final document, the Strategic Deployment Document (SDD) [2] was firstly released as a draft in 2008, and later finalized in 2010. Its aim is to highlight the barriers against the smart grids, encouraging the Member States to eliminate them in order to fulfil the Sustainability Targets set for 2020 and 2050. It sets six Deployment Priorities:

- Deployment Priority 1: Optimizing Grid Operation and Use;
- Deployment Priority 2: Optimizing Grid Infrastructure;
- Deployment Priority 3: Integrating Large Scale Intermittent Generation;

- Deployment Priority 4: Information & Communication Technology;
- Deployment Priority 5: Active Distribution Networks;
- Deployment Priority 6: New Market Places, Users & Energy Efficiency.

This document also contained the key issues that compromise the development of a smart grid, mostly of a technical nature, and the Recommendations for the Member States, where it is clearly stated that

"The European legislation for an open market in the electricity sector has been implemented in most Member and Associated States for several years. The resulting national legislation, however, varies and is fragmented. In particular, the degree of unbundling of network services from generation, supply and trading of electricity is still very diverse. Also, as a consequence of this, TSO and DSOs do not have clear incentives to evolve into service provider businesses. Harmonized regulation in the Member and Associated States is needed to speed up the necessary changes" [2].

Furthermore, the document suggests some funding options available to enable smart grid projects.

Apart from the ETP, two other organisms have been instituted in the EU, to support the introduction of regulations for the implementation of the smart grids. In November 2009, the European Commission set up a Task Force on smart grids, composed of a Committee (SC) of high level representatives from European, institutional and market actors, including consumers, and one or more Expert Groups as decided by the SC. As stated in the Mission for the Task Force for the implementation of smart grids into the European Internal Market:

"The mission of the Task Force smart grids is to advice the Commission on policy and regulatory directions at European level and to coordinate the first steps towards the implementation of smart grids under the provision of the Third Energy Package" [61].

So far, the Task Force has organized four Expert Groups, each focused on a particular aspect of the smart grid development:

- EG 1: Functionalities of smart grids and Smart Meters [62];
- EG 2: Regulatory Recommendations for Data Safety, Data Handling and Data Protection [63];
- EG 3: Roles and Responsibilities of Actors involved in the smart grids Deployment [64];
- EG 4: smart grid aspects related to Gas [65].

Each of these EGs ended with a Report giving directions and recommendations for the European Commission.

Another institution that is worth mentioning is the Agency for the Cooperation of Energy Regulators (ACER), established in March 2011 in Ljubljana, Slovenia. Its mission is to harmonise the actions of the National Regulators in order to create a competitive, secure and sustainable European Energy Market.

8. Conclusions

In this work, we surveyed the smart grid project from different points of view, analysing the efforts that the scientific community is making to implement this infrastructure. We presented management solutions, technological aspects and different kinds of optimization techniques. We also analysed the current European regulatory environment and listed the relevant organisms and EU bodies responsible of supporting the smart grid.

One of the facts that this survey has shown is that, from a technological point of view, there are plenty of solutions already available. Several management systems have been tested and are ready for deployment. However, another fact is evident: although many different standards exist, especially for data communication and protocols, few of them have been widely accepted for application in energy distribution networks. This can be an issue, because one of the keys to an efficient energy network is interoperability between different energy providers. A partial solution can be using Web Services and system integration techniques, but there has to be a standard definition for data structures and models in order to enlarge the scope of the network. The biggest obstacle to standardization, and in general to smart grid implementation in Europe, from our point of view, is given by the complex situation of the European energy market, where regulated and liberalized regimes still coexist. In regulated markets, the main grid operator establishes a monopoly business that does not allow consumers to choose among different technologies. Typical examples are metering services, forecasting, and so on. Also, energy retailers, although present on the territory, are not able to assume their innovative role in the Future Energy Market depicted in Section 3, in terms of demand response, consumer services and network operation.

As far as concerns the research activity, what should be done is embracing a common view of the problem, focusing on interoperability and supporting the creation and affirmation of technology standards. In this way, the development of solutions and optimization techniques can be immediately followed by field testing and deployment, speeding up the overall infrastructure realization process.

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