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FLEXIBILITY OPTIMISATION PLATFORMS FOR ENERGY MANAGEMENT OF SMART POWER SYSTEMS

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Acronyms

Acronym	Definition
AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
BRP	Balancing Responsible Parties
CA	Commercial Aggregators
CAPEX	CApital EXpenditure
CCGT	Combined-Cycle Gas Turbines
CEER	Council of European Energy Regulators
CHP	Combined Heat and Power
CL	Closed Loop
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
DMS	Distribution Management System
DR	Demand Response
DRP	Demand Response Provider
DSM	Demand Side Management
DSO	Distribution System Operator
DSS	Decision Support System
EBMS	ELSA Building Management System
EC	European Commission
EDEMS	ELSA District Energy Management System
EEMS	ELSA Energy Management System
EMS	Energy Management System
ESCO	Energy Service Company

ESDM	Energy Supply & Demand Matcher
ESMS	ELSA Storage Management System
EU	European Union
EV	Electric Vehicle
EVRS	Electric Vehicle Recharging System
FACTS	Flexible AC Transmission System
FC	Fuel Cell
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse Gas
GUI	Graphic User Interface
HMI	Human Machine Interface
HSS	Hydrogen Solid-state Storage
HTTP	Hyper Text Transfer Protocol
HVAC	Heating, Ventilation and Air Conditioning
HVDC	High Voltage Direct Current
ICT	Information and Communication Technologies
IDB	Integrated Data Base
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
IP	Internet Protocol
KPI	Key Performance Indicator
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NIST	National Institute of Standards and Technology
OL	Open Loop
OPC	Open Platform Communication
OpenADR	Open Automated Demand Response
OPEX	Operational EXpenditure
PEM	Proton Exchange Membrane

PLC	Programmable Logic Controllers
PMU	Phasor Measurement Unit
PV	Photovoltaic|
RES	Renewable Energy Resource
REST	REpresentational State Transfer
SCADA	Supervisory Control and Data Acquisition
TA	Technical Aggregators
TLS	Transport Layer Security
TSO	Transmission System Operator
VEN	Virtual End Node
VTN	Virtual Top Node
WE	Water Electrolyser
XML	eXtensible Markup Language
XMPP	eXtensible Messaging and Presence Protocol

Chapter 1

Introduction

1. Introduction

One of the main challenges of today research community in the field of energy, and not only, is to improve as much as possible the smart usage of the energy resources provided by the Earth. Since many decades, the human beings know how unconscious, and sometimes irresponsible, behaviours on the matter of energy supply, management and usage has led to serious and tangible effects on our Planet, affecting our everyday life but, above all, the quality of life of the future generations. In this direction, many national and international organisations focus their policy-making efforts in establishing clear and strict laws, directives as well as regulatory frameworks in order to change the habits of all the stakeholders involved in the process of energy supply, transformation, transmission as well as distribution, management and usage. Moreover, most of the local and national normative bodies responsible of the regulatory process have been pushed for ensuring and aligning their rules in the field of energy with the higher and wider decisions that have been taken on many occasions at international level. Among these latter, the most famous, known and effective were the Kyoto Protocol [1], the 2020 Climate & Energy Package imposed by the European Commission (EC) [2] and, more recently, the decisions taken at the Conference of Parties in Paris [3].

The unrestrained employment of fossil fuels in many areas of human activity, from heavy industry, going through transport fuelling, to electricity generation, is unquestionably one of the main reasons of the environmental pollution and of all the side effects derived from it, such as global warming, air and water pollution, endemic diseases, etc. The emission of Greenhouse Gas (GHG) is linked to an extraordinary number of human activities; in this view, the greatest effort has to be spent to perform a transition towards a cleaner way to address the same activities or drastically change their nature.

The great spread of the Renewable Energy Resources (RESs), and of all the systems and devices able to harvest, convert, partially control and exploit them, is one of the most important issues in the field of respect for the environment, involving not only the industrial and energy related companies, but also citizens and administrations, that took into account the enormous potential of these resources considered as inexhaustible. The employment and installation of these systems, that have become more and more spread within the last 20 years, gave actually the start to a revolution of the power grid assets, with a deep decentralisation of generation and the rise of new consumption control functions.

Another main aspect of this changing trend in the energy world is represented by the numerous innovative solutions, services and new actors that have appeared in very few years and that innovated deeply the configuration of the power system infrastructure as well as its management and all the related business model issues.

Various programs or actions have been set up in order to allow a better management of the energy resources, such as Demand Response (DR) and Demand Side Management (DSM) programs, led by economic or technical signals. These latter allow a safe operation of the power grid, by means of load shedding and peak shaving actions, among many others. Besides, these programs have been fostered by new trade opportunities and the liberalisation of the energy market, at many levels of the energy chain, ranging from a local market-place where the exchange of flexibility services takes place, to the wide continental market where great amounts of energy are exchanged among countries.

All these deep changes, accompanied by a great evolution of hardware technologies, such as smart meters, smart controllers, and Information and Communication Technologies (ICT) infrastructures, as well as advanced software tools, algorithm and communication protocols, have radically changed the way in which the energy usage and its management is conceived, providing also the possibility of adding different levels of smartness in the power systems. These great developments have been achieved thanks to the great effort spent on funding a great amount of research projects in the energy area, allowing to test, prove and demonstrate some cutting-edge applications and solutions. In this view, the studies presented in this thesis have been carried out within two projects funded by the EC, in particular by the 7th Framework Programme [4] and the Horizon 2020 [5] funding programmes.

In this thesis, many of the above discussed topics have been addressed; in particular, the details of the implementation of ICT platforms through which different actors are allowed to exchange their flexibility for providing services to the grid operator are given. The thesis is organized as follows. Firstly, an overview on the smart grid paradigm and the context in which the proposed solution will be implemented is provided. Subsequently, the topic of flexibility and the architecture of the ICT infrastructures providing flexibility services to the power systems are shown and discussed, along with all their features and tools. The core of the this study presents the main topics of this thesis implemented into two real-life demonstrators: one within an industrial context, in which a proper Energy Management System (EMS) is deployed for the control of the equipment installed inside the plant, and another within an urban context, where an EMS is developed for the management of the energy units inside a district. Finally, the conclusions of the proposed study are given and an overview about the different outcomes obtained in these two contexts is provided and discussed

The present work is the results of the doctoral studies performed within the collaboration between the University of Palermo, namely Università degli Studi di Palermo, and the company Engineering Ingegneria Informatica S.p.A. The joined and participated research of both the Department of Energy, Information Engineering and Mathematical Models and the Research and Development Department, respectively, has led to the major achievements shown and discussed in this thesis.

Chapter 2

From power grid to smart grid

2. From power grid to smart grid

As mentioned in the opening section of this thesis, numerous phenomena are affecting the revolutionary change in the power grid paradigm which the current generations are witnessing and contributing to. The key change of power system management is to improve the smartness of the grid itself. Since the large majority of GHG emissions is directly connected to the combustion of fossil fuel, as shown in Figure 1 (already reported in [6]), the simplest approaches that have been adopted are the integration of RESs, the increase of energy efficiency and the improvement of energy consumption awareness.

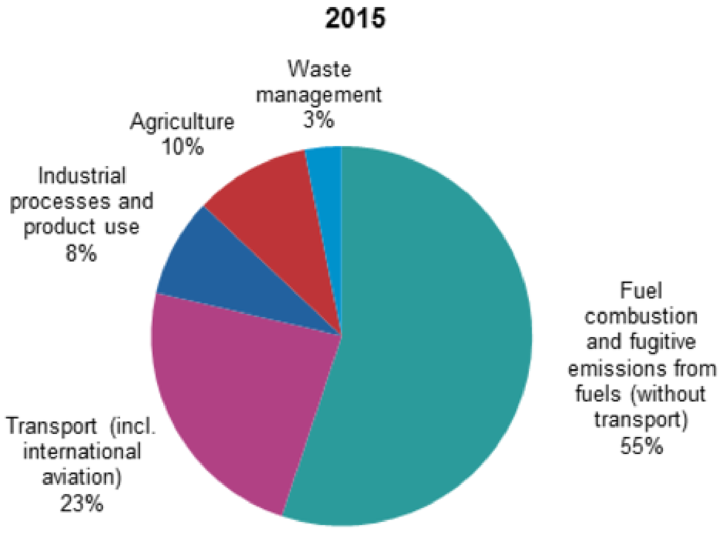


Figure 1 – Greenhouse Gas emissions, analysis by source sector, EU-28, for the 2015 (percentage of total).

All these approaches imply undertaking many complex actions that need an intelligent management system. As a matter of fact, the power systems, especially distribution grids, were designed and operated without any local injection of power, thus as passive grids: the last branch of a grid portion have always been considered as a passive branch where the power flows only in one direction, thus toward the loads. The presence of Distributed Generation (DG), in particular of local RES systems, characterised by high unpredictability, changes radically this paradigm forcing the grid operator to adopt new management and control strategies as well as new equipment. At the same time, in order to implement energy efficiency and awareness actions, a brand-new way of taking into account the management of the energy resources has to be designed and made effective, in the view of optimising system operation addressing the goals of the energy efficiency, for instance reducing peak loads or smoothing reverse power flows, avoiding overload phenomena, etc.

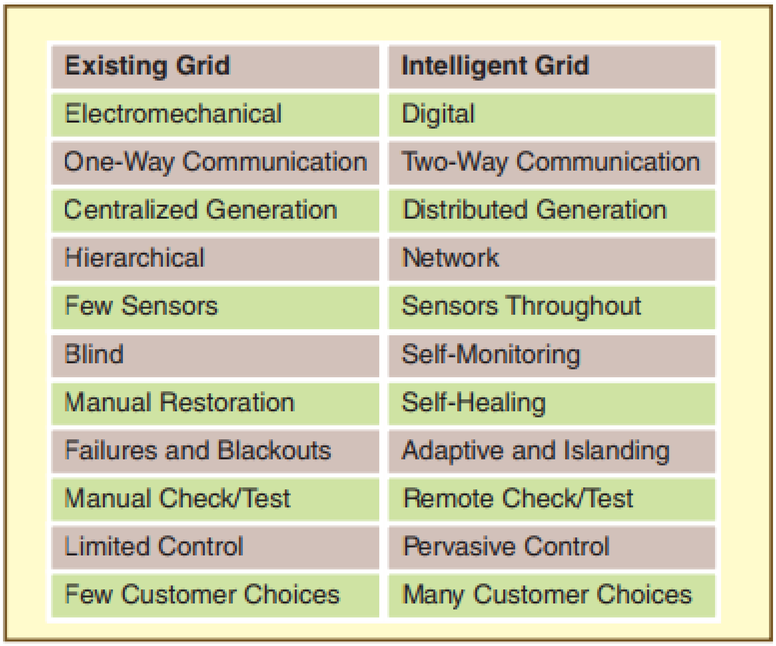
The concept of smart grid gathers all these aspects in a unique solution able to give the proper and effective smartness to the grid both in terms of operational criteria (management, control and optimisation of energy resources) and in terms of equipment (smart meter, energy efficient devices, storage systems, etc.). Many of the most important organisations and associations in the field of energy have provided their definitions of smart grid [7] [8] [9] [10] [11] [12]. A smart grid can be defined as a complex infrastructure able to integrate several devices and energy units (spanning from generations, both RES and DG, to storage devices, and considering also loads able to change their energy behaviour) that can handle the smart and automated control of all energy resources by implementing intelligence, provided by ICT computation and communication means. Such kind of smart grid is able to provide system services to the grid operator and allows high power quality levels and a safe operation of the system.

Here, a list of features that define properly all the topics addressed and managed by the functionalities of a smart grid are listed:

- resources integration;
- integration of the energy users (also prosumers);
- RES integration;
- storage integration;
- advanced equipment;
- communication protocols and devices;
- advanced DR protocols;
- ICT infrastructure (TCP/IP, web services, etc.);
- adaptation of industrial protocols;
- IT computing;
- control criteria and automation systems;
- complex management implementation;
- interoperability;
- multi-carrier exploitation;
- grid services;
- management of users’ energy behaviour;
- implementation of local and global energy services (DR, DSM);

- grid operation;
- efficiency improvement;
- sustainability
- power quality and security of supply;
- safety;
- emission reduction;
- market opportunities;
- interactive users’ transactions;
- local market-places;
- commercial and technical aggregation.

In Figure 2, the main differences between the two paradigms provided by the old conception of the power system and the smart one are shown [13].



Existing Grid	Intelligent Grid
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

Figure 2 – Main differences between the traditional power system and smart grid paradigm.

As discussed in the previous sections, many technological, market and regulatory figures are involved in the implementation of the infrastructure envisioned for a smart grid.

The innovation, carried out by many technological solutions in power systems, has fostered the vision for a system where many complex and automated tasks can be performed and successfully implemented. These innovative means are related to the hardware equipment, consisting often in complete systems able to deal with entire energy-related processes, like in the case of RES and Electric Vehicles (EVs), or auxiliary systems, such as smart meters or actuators. Great advancements have been also made in the field of power electronics, through which the desired electrical parameters can be attained. This hardware development has been accompanied by great effort on designing and creating software solutions, for allowing easy communication and, above all, the effective computation of data and the control of actions over the energy resources. This has led to the development of complex and multi-tasking EMSs able to address the operational tasks of very large portions of the grid, as entire smart grid or urban district.

In this context, new roles and responsibilities have to be defined for correctly setting up the operational scenarios linked to the smart grid, but sometime most of the power grid regulatory frameworks lack of tailored laws and rules for letting them exist and/or put into practice their tasks, whether technical or, above all, financial.

In this view, many movements and association are trying to create a unique regulatory framework to be taken as a reference, both in national and in international contexts, for allowing seamlessly the implementation of new technologies and new grid management techniques, as new trading platforms or the connection of power generation systems.

In this chapter, the main technologies and the key stakeholders of smart grids are presented and briefly discussed, as well as the socio-economic impacts of their appearance.

2.1 Technologies

One of the greatest enabling factors of the expansion of the smart grid paradigm is the great advancement achieved in many sectors of energy related technologies and hardware as well as software technologies [14] [15] [16].

2.1.1 RES systems

The last 30 years have been characterized by the explosion of investments and technological developments related to the RESs. Many governmental parties all over the world have set up significant regulatory frameworks in order to pave the way to widespread commercial availability and affordable installation and operation of such kind of systems. In Figure 3, a summary of the support schemes that have been put in place all over the Europe is shown; this lists is taken from the review document referenced in [17].

	Bioenergy	Geo-thermal	Hydro	Ocean	Other	Solar	Wind
Austria	Feed-in tariff		Feed-in tariff, investment grant			Feed-in tariff, investment grant	Feed-in tariff
Belgium	Green Certificates		Green Certificates			Green Certificates	Green Certificates, investment grant
Croatia	Feed-in tariff		Feed-in tariff			Feed-in tariff	Feed-in tariff
Czech Republic	Feed-in tariff, Feed-in premium		Feed-in tariff, Feed-in premium			Feed-in tariff, Feed-in premium	Feed-in tariff, Feed-in premium
Denmark	Feed-in tariff, Feed-in premium				Feed-in tariff		Feed-in tariff, Feed-in premium
Estonia	Feed-in tariff		Feed-in tariff			Feed-in tariff	Feed-in tariff
Finland	Feed-in tariff, Feed-in premium, Investment grant	Investment grant	Investment grant		Investment grant	Investment grant	Feed-in tariff
France	Feed-in tariff, Call for tender	Feed-in tariff	Feed-in tariff		Feed-in tariff	Feed-in tariff, Call for tender	Feed-in tariff, Call for tender
Germany	Feed-in tariff, Feed-in premium	Feed-in tariff, Feed-in premium	Feed-in tariff, Feed-in premium			Feed-in tariff, Feed-in premium	Feed-in tariff, Feed-in premium
Greece	Feed-in tariff		Feed-in tariff			Feed-in tariff	Feed-in tariff
Hungary	Feed-in tariff		Feed-in tariff			Feed-in tariff	Feed-in tariff
Ireland	Feed-in tariff		Feed-in tariff		Feed-in tariff		Feed-in tariff
Italy	Feed-in tariff, Feed-in premium, Green Certificates	Feed-in premium, Green Certificates	Feed-in tariff, Feed-in premium, Green Certificates			Feed-in tariff, Feed-in premium (up to July 2013)	Feed-in tariff, Feed-in premium, Green Certificates
Lithuania	Feed-in tariff		Feed-in tariff			Feed-in tariff	Feed-in tariff
Netherlands	Feed-in premium	Feed-in premium	Feed-in premium			Feed-in premium	Feed-in premium
Norway			Green Certificates				Green Certificates
Poland	Green Certificates		Green Certificates			Green Certificates	Green Certificates
Portugal	Feed-in tariff		Feed-in tariff		Feed-in tariff	Feed-in tariff	Feed-in tariff
Romania	Green Certificates		Green Certificates			Green Certificates	Green Certificates
Spain	Feed-in tariff		Feed-in tariff			Feed-in tariff	Feed-in tariff
Sweden	Green Certificates		Green Certificates			Green Certificates	Green Certificates
UK	Feed-in tariff, Green Certificates		Feed-in tariff, Green Certificates	Green Certificates		Feed-in tariff, Green Certificates	Feed-in tariff, Green Certificates

Figure 3 – Support schemes in the European countries and corresponding incentivized technology.

It is clear how in a very large number of European countries, the actions aimed at installing and operating RES systems are supported and incentivised significantly, providing the proper instruments for gaining interest of the community, of private investors, of technological manufacturers, and research institutions. The most commonly employed support method are the feed-in-tariffs, structured in long term contracts with the RES plant owners allowing them to be rewarded in accordance to their technologies modifying energy tariffs, and releasing green certificates, that certificate the actual production of green energy and that can be traded.

Today, the employment of RES generation systems is a reality of the modern power grids. Many technologies have been consolidated in their employment and many others rose thanks to research on their manufacture and operation. The most common systems installed so far are:

- hydroelectric systems;
- wind systems;
- photovoltaic (PV) systems;
- solid biofuels and renewable waste;
- geothermal systems.

Today, the overall production from RES systems amounts to more than a fourth of the total European production [18]. The highest contribution to this production is linked to the solid biofuels and renewable waste, consisting in more than 60%, the second technology is the hydroelectricity, then wind systems and PV ones. Going deeper on the features of every technology is out of the scope of this thesis.

As discussed in many research works, the presence of such systems, connected mainly to the distribution grid, significantly affects its operation, causing bidirectional flows, the fault detection and isolation issue~~s~~, the power reverse flow phenomena, and many other issues related to the grid operation and power quality.

2.1.2 Storage systems

The possibility of storing electricity at any stage of the energy process allows several advantages from the grid operation perspective and fosters the implementation of many services provided by a smart grid [19]. As a matter of fact, the employment of a storage device allows to decouple the phase of power generation and the phase of power injection into the grid, creating a buffer layer that can cope with unbalances between supply and demand. This is unmistakeable and more and more relevant in the case of RES integration [20] [21]: the possibility of decoupling generation and injection permits to solve the problem of unpredictability of some kind of RES systems and to smooth some of the relevant drawbacks due to them. Moreover, a storage system can provide enough capacity for enabling the stand-alone operation of a large portion of the power system.

In this field, the presence of storage systems can be exploited for providing many services to the grid. The above mentioned power smoothing service is one of most relevant, as the load shaving obtained by shifting or controlling the load. In this context, many DR programs can be supported by the buffer provided by the storage system, even exploiting the possibility of performing energy trading and arbitrage in tailored market places. Moreover, system led DR actions can rely upon the employment of storage technologies, for instance exploiting the flexibility provided by storage systems for achieving many complex grid technical and economic goals [22].

The energy storage can be performed in many ways, employing different technologies according to the desired performances to be obtained [23]. The simplest way of storing electricity is by means of electric storages, but in some contexts their performance are not compliant with the provision of grid services. Many other kind of storages have been studied, developed and successfully tested: mechanical storages (flywheel, etc.), thermal storages (water based, salt based, etc.), chemical storages (hydrogen, etc.), flow batteries, supercapacitors, hydrogen storage; etc. As said for RESs, the features of each of these technological storage solutions are not in the scope of this work.

2.1.3 EV technologies and programs

The number of EVs in use all over the world is more than decupled in less than 5 years, from 2012 to 2016, Figure 4 taken from [24]. The great technological advancements and the efforts of the main car manufacturers from almost every country have fostered and supported the great diffusion of the EV or electrics means of transport, being today a realistic choice even in the common sense.

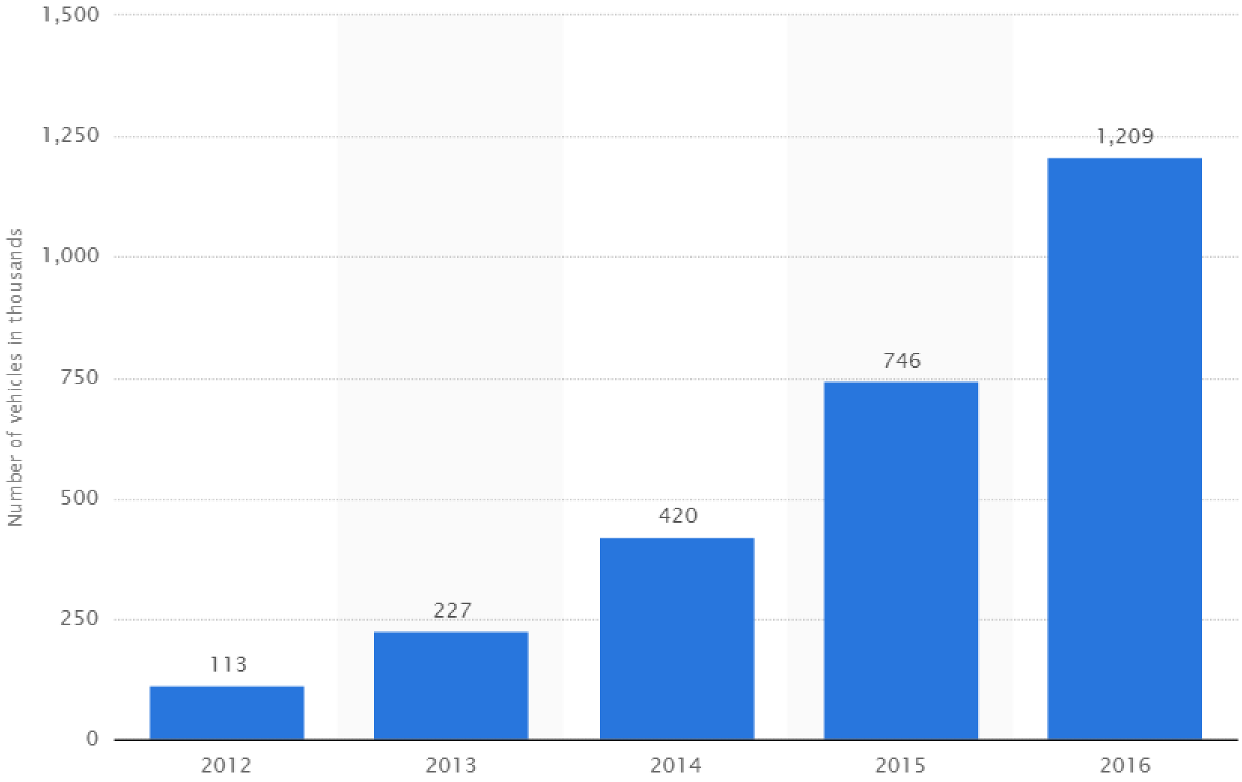


Figure 4 – Worldwide number of battery electric vehicles 2016.

Besides the business orientation of almost all automakers, enormous interest has been paid by national and local administration and private entrepreneurs to the provision of electromobility services to the citizenry and the entire community. The actions involved are mainly the implementation of public transport services relying upon electric buses or car-sharing services, as well as a network of EVs recharging points available in many areas.

In the same way, many researches have been conducted for allowing the EVs to be as much autonomous as possible, so great efforts have been spent of developing both new high-performing batteries and high-speed recharging station.

Moreover, this phenomenon brings new challenges and opportunities related to power system. Firstly, the possibility of possessing an EV is becoming more and more concrete, so residential buildings, offices, and other facilities have to be equipped properly for allowing the power recharge of the EVs. Secondly, once this technology will be deeply spread, its power management can be exploited for providing services to the grid: grid-to-vehicle services, in the case of tailored programs aimed at using the recharge of the EVs as a flexibility source for power management, and vehicle-to-grid services, when the EVs are available to be used for reinjecting power into the grid in order to support its operation [25].

2.1.4 Monitoring and SCADA systems

The Supervisory Control and Data Acquisition (SCADA) systems are key elements of the smartness of modern power systems. Actually they allow the data exchange between several components and physical devices of the energy context they serve and provide tools to the operators to handle their equipment, both remotely and on-site.

A typical SCADA system consists of a software layer dealing with the control system, that effectively evaluates and schedules the operating condition of the entire system, and the hardware and software components. Part of the hardware components are usually equipped with Programmable Logic Controllers (PLCs) that are in charge of input/output and communication tasks, as well as low level control of the single device. Moreover, the SCADA systems often provide a graphic representation of the data acquisition by means of a Human Machine Interface (HMI). Finally, they allow sending high level commands and setpoints to the plant equipment, or, in the context here presented, to the devices of each energy resource installed in the monitored system [26].

The employment of these control and monitoring solutions started in industrial and manufacturing companies for monitoring the operating conditions of all the machinery involved in the production process and for commanding simple setpoints regarding the status of the equipment or of the entire process. More recently, SCADA technology has also been employed for controlling also tertiary plants and domestic installations through EMS.

Today, many research projects in the field of energy flexibility and efficiency implement off-the-shelf solutions from high-experienced industrial manufacturers that provide a standard product, consisting of both software and hardware tools able to monitor, supervise, and control all the energy resources. Nevertheless, many initiatives have appeared recently to design and set-up an own proprietary solution, customizing and adapting protocols and SCADA systems for tailored solutions [27].

Since these monitoring systems are being employed for purposes that are different from the original ones, such as industrial and manufacturing systems, the solution provided by a SCADA system has to be tailored to the energy field, especially in terms of communication means [28]. Due to the great amount of heterogeneous devices employed in energy systems, several different communication protocols have to be taken into consideration, as well as the possibility of connecting over the Internet. In this view, great research efforts have been spent in order to provide customised communication solutions for allowing new smart grid ICT technology to exchange data with well-established SCADA systems. The most innovative technology implementation of monitoring framework for smart grid is indeed related to the easiness and accessibility of the data. The opportunity of adopting cloud systems [29] for monitoring smart grid environments enable the implementation of a green solution that, besides lowering hardware and software cost, increase the productivity of the proposed system by allowing to access and control electrical parameters remotely through internet connection. Another key technology is represented by the Internet of Things (IoT) paradigm [30] [31] that provides the smart grid concepts with high performances communication means, characterised by teal-time, high-speed, and bidirectional data exchange capability. These features fit with the requirements of a typical smart grid that needs for active participation of the actors, mutual operations of the devices, fast responses, and distributed actions.

It worth mentioning that this variety has risen many security issues for the management of the data flow: the installation of a SCADA system in machines used in an office, for instance, may be exposed to many cyber-attacks and information leakage, dangerous for both the operation of the system and the privacy of the users.

2.1.5 Power electronics

The evolution of modern power systems has been unquestionably accompanied and supported by the great developments achieved in the field of power electronics [32]. The employment of power converters is widely spread in almost every application in energy production, transmission and distribution, storage, consumption, etc. In Figure 5, a prospective scenario of interaction between all the devices composing a smart grid is depicted [33].

As it can be easily noticed from the figure above, the adoption of a conversion stage occurs between every system acting in the smart grid scenario and the power system. There are several reasons and various purposes for such a large employment of power electronics technologies, both in the power flow management and in the data exchange among all the systems.

The most relevant and innovative area in which the employment of power electronic devices is crucial is the integration and management of storage units and RES systems for allowing the proper power exploitation and injection into the grid [33]. Actually, all of the RES based generation systems harvest natural phenomena for generating electricity, phenomena that are not under human control. It is clear that on one hand there is the need to extract as much energy as possible from the source and, at the same time, to inject it in the grid with suitable electrical parameters. As such, there is a need to optimise the operations of these systems towards the features of the energy transformed and to adapt the electricity generated to the operational parameter of the power system which the generator is connected to.

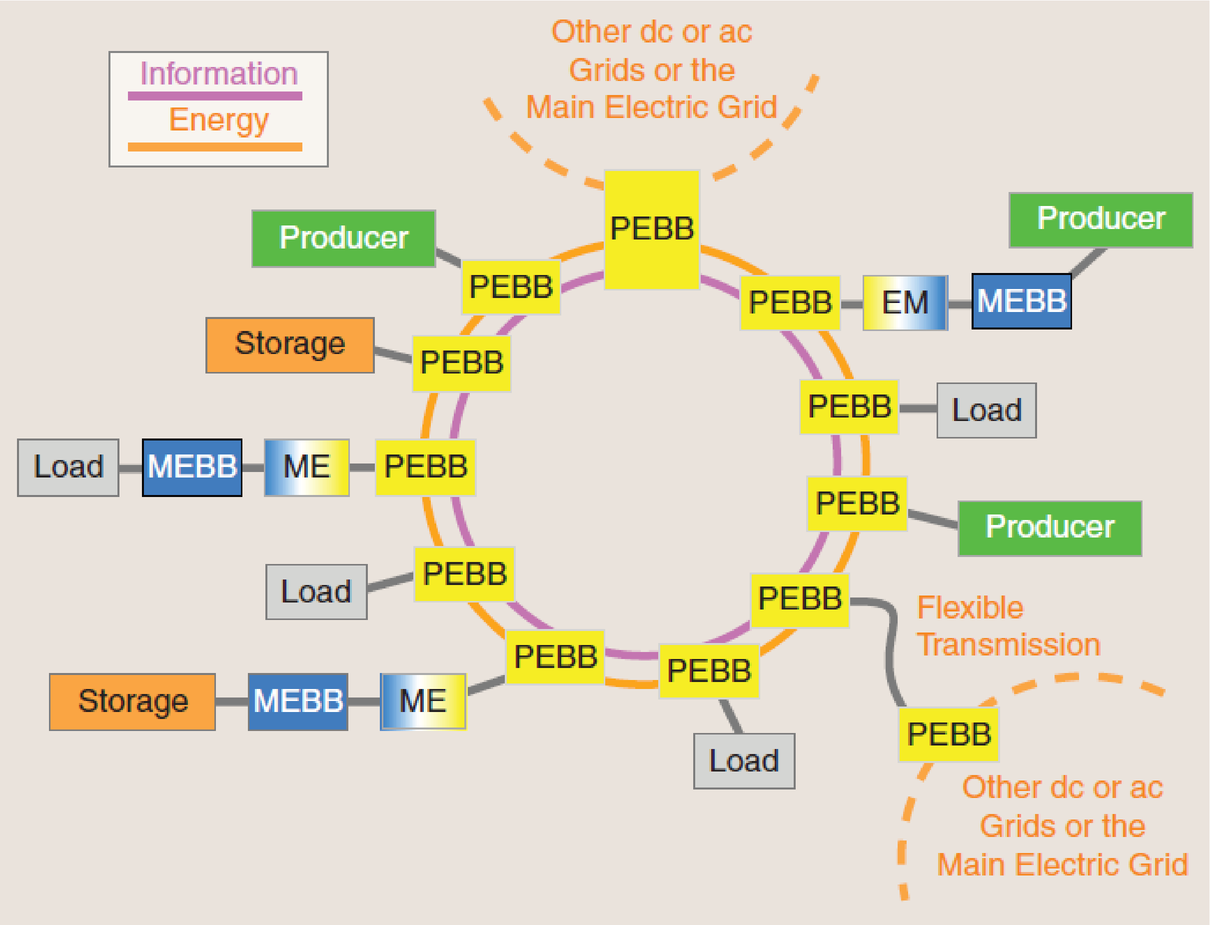


Figure 5 – A possible scenario of future power system based on smart grid technologies, composed by Power Electronics Building Blocks (PEBBs) and Mechanical Building Blocks (MEBBs) for smart conversion.

Considering PV and wind generators, it is possible to provide some clear examples. As far as PV generation is concerned, besides the obvious conversion from Direct Current (DC) to Alternating Current (AC), other aspects have to be managed by means of power electronics. The operating point where the system takes full advantage of the available energy from the sun varies depending from the solar radiation. For this reason, the converters installed in the PV plants usually implement Maximum Power Point Tracking (MPPT) techniques in order to adapt current-voltage behaviour and load characteristic to the weather condition and convert the maximum of the available solar energy. At the same time, in the case of wind systems, the peak of aerodynamic efficiency is achieved at a fixed ratio between the speed of blade tip and wind. For allowing variable speed operations of the turbine, a system able to adjust the frequency of the generated electricity to rated frequency of the power system is required. In many cases, different solutions of AC/AC stage or AC/DC stage plus a DC/AC one are adopted, ensuring the optimal operation of the turbine and exploiting all the wind energy that runs over it.

Another substantial role of power electronics in the management of modern power systems consists in the possibility of providing ancillary services for grids characterized by high penetration of distributed and local energy resources. The control of the injection of active and reactive power into the grid allows to perform the regulation of voltage and frequency of the grid itself. By means of various control techniques, the converters allow to provide these services using many energy devices also in different points of a distribution network. The ability to control the power injection enables other features such as the synchronization and regulation of the grid electric parameters [34].

Besides the power injection, also the harmonic content can be controlled and managed by the power electronics devices, addressing the topics of power quality. This challenge is also dealt by reducing the number of faults or their impacts on the power systems operation and reliability. Moreover, in the view of ensuring power quality and safety, many converters are able to detect and manage the islanding condition, in order to prevent it or allow to arrange the proper sequence of actions for operating part of the system in islanded mode.

Great research efforts have been conducted also in the field of High Voltage Direct Current (HVDC) interconnection systems or simply in allowing the connection of two portions of the grid at distribution level (e.g., microgrid with main grid). In the former case, the possibility of avoiding the huge reactive flow on transmission lines, especially cables, allows to have longer connections, for instance by submarine lines, transporting a greater amount of power. In AC, the use of Flexible AC Transmission System (FACTS) based on power electronics allows larger transport capacity and improved stability.

As already said, at distribution level, where the implementation of smart and micro grid solutions fits the envisioned services and scenarios, this kind of application could be performed for connecting two grids, that could be also asynchronous, for managing internally their energy resources, or for self-healing purpose, or even for implementing market or technical oriented aggregation operations.

The electrical energy storage systems are always equipped with a converter interface and power electronics instrumentation. Moreover, regardless the storage technology adopted, in most cases, the process through which the energy is stored requires a DC supply that should be provided from an AC network; the need of a rectifier is clear. Moreover, for allowing the correct charging and discharging phases, as well as the proper cycling of these operations, the power converter has a main role in controlling the power flows and voltage level between the two systems connected by the converter.

As far as load consumption is concerned, for allowing flexibility of energy appliances or particular equipment needing DC supply, today more and more loads employ a power converter. In particular, many studies are exploring the possibility of realising complex micro grid architectures where the users, that could be building, offices or similar users, are supplied directly in DC at different voltage levels through different DC buses.

Boosted by the great exploitation of the power electronics devices features, the related technologies are facing great developments [35] [36]. On architectural side, new topologies are investigated, such as the introduction of multi-level converters. Moreover, the usage of new semiconductors are under study, accompanied by the introduction innovative control techniques for optimising system performances, or for improving power quality, as well as reducing noise and leakage current.

2.1.6 Advanced metering systems

As outlined in many occasions through this thesis, the implementation of a smart grid framework is strictly related to the availability of a proper communication infrastructure and data management system [37]. In this view, the concept of monitoring the energy flow has radically changed from the traditional way of operating and using it. As a matter of fact, in the modern power systems, all the resources in the grid can cooperate and communicate. These apparatus are smart, embeddable, and able to exchange data in bidirectional way, to elaborate as well as store them properly.

The functionalities that such intelligent metering system can provide cover a wide range of system operations that are essential for the smart grid implementation. Firstly, they can manage the exchange of information in both ways, allowing to receive data from other actors regarding setpoints, system configuration, price signals, etc. In particular, the importance of installing a smart meter gains more and more momentum when considering communication about prices and the possibility of participating to complex tariff programs or energy market-places. Moreover, advanced meters could be able to perform advanced billing, making also prediction and providing the users with economical information about their energy behaviour. Another crucial topics relies indeed on the implementation of user oriented monitoring and control systems for allowing the user to manage and observe the power consumption of its appliances.

The features of a smart meter address also many complex technical and grid tasks, such as power quality, reliability and fault location. These functionalities become more and more important in the described context, because the presence of such a great number of smart and partially autonomous energy units could lead to unusual grid operation, stress or overload conditions, unexpected power flows, and faults.

In this view, today the literature refers to Advanced Metering Infrastructure (AMI) as a complex system in which smart meters, sensors, remote monitoring devices, tailored communication means, control and management systems, grid operators, and users work coherently for ensuring the data exchange among all these actor in order to perform properly all the tasks that a smart scenario implies [38].

A great effort is therefore spent to create effective standards and communication protocols able to ease the data exchange between the actors involved in the meter processes, for instance by the Institute of Electrical and Electronic Engineers (IEEE) [39]. Today, many technologies are under investigation; the main categories are composed by wireless and cables solutions. Regarding the former, Wi-Fi and related technologies, accompanied by their standards, are the most employed, whilst, regarding cabled solutions, fibre optic and power line communication are the appointed technological solutions for smart power systems.

Besides all the benefits carried by the AMIs, there also many issues related to their wide implementation. Firstly, they should be integrated with the existing grid infrastructure and the old ones have to be replaced, implying enormous costs and investments by the grid operators (for buying, installing, ensuring maintenance, etc.), whilst there is still no clear regulation and evaluation of the business scenarios connected to their employment. Moreover, the adoption of the smart meter has to be as coherent as possible, in order to have large portions of the grid equipped by means of compliant devices. The other crucial topic concerns the data management: proper storage for saving all the information are needed, requiring infrastructural and economic efforts, and cyber-security of the data has to be ensured. In any case, the smart metering concept is under large scale deployment and implementation all over the world in many different energy contexts, such as in Italy [40].

2.1.7 Load control switches and protection devices

Due to the great number of new players interacting with the power grid, the way in which all these actors are connected to the grid has changed. This section addresses the devices in charge of managing the interruption of the power circuits in accordance to the smart grid scenario of that particular energy context.

Many implementations of the energy efficiency and/or flexibility actions require a top-down approach to the load management [41]: the decision is taken at a higher level, often a central control entity that sends signals to the users in order to regulate their power absorption accordingly.

In this case, the users are provided with load control switches [42] that are remotely controlled relays through which the consumers are able to manage their appliances or the overall power consumption and to respond to the request of the utility, the central decision system or, depending on the scenario, simply control their power consumption following, for instance, price signals. The employment of such switches allows limiting peak load, implementing load-shifting actions, preventing a high energy price during the day, etc.

In the same context, another issue related to the interruption of the power circuits consists in the protection of the power system in which smart grid scenarios are applied.

The presence of many different actors, in particular DG systems, has completely changed the topology of the power systems, especially at distribution level, where local connection of RES plants, EV recharging systems, storage systems and various kinds of prosumers [43] are installed. It is clear how the typical way of managing, detecting and restoring grid faults does not fit anymore with the new features implemented inside a smart grid.

Smart circuit breakers [44] are now under investigation for many grid applications. The new characteristic of these components relies upon the possibility of creating a network of interconnected circuit breakers, where the breakers are able to exchange information about the fault, is typology, location, etc., and coordinate intelligently themselves for eliminating it or, at least, restoring a portion of the network that can be operated without affecting the power quality. These kind of approaches could modernise concretely the management of the distribution grid and improve significantly its reliability, while coping with all the others actors interacting with the grid itself. Today, many efforts are spent for improving the smartness of load and protection management: intelligent load control, smart fault location techniques, remote control of the switches, exploiting new communication means, such as power line communications, and so on.

2.1.8 Communication architectures and protocols

As stated many times during the previous sections, there is no intelligence without a proper communication framework allowing all the actors taking part in the smart grid concept to exchange information, coordinate themselves, monitor, control, send alarms, etc. In this view, the goal is to set-up smart communication architectures that allow all the actors to exchange the typology of data required for implementing their functionalities, taking care of all the related synchronization, cyber security, and reliability issues. Today, the design of a complete and integrated architecture able to handle all these topics is one of the greatest challenge of the research in the smart grid field. In this section, an overview on the main features of these communication solutions is provided.

The main classification addresses the different dimensions of the smart energy context in which the actors that exchange data are located [45]. Actually, three classes are here outlined: wide area networks, field area network, home/facility area network:

- Wide area networks: this architecture is the largest one and makes the connection of distributed small areas possible, even over large distances. This is the case of substations, buildings, or any kind of energy units located far from control centres: data have to be sent to the higher control level are received back from it in order to make effective the control decisions. Due to the great amount of information conveyed by this kind of network, high speed and bandwidth connections are required.
- Field area networks: this architecture allows the data exchange within the area of a distribution grid. The communications take place among the energy resources and the ICT devices inside the distribution context, so all the data coming from power system components, like feeders, substations, protection divices, etc., and the available energy resources, such as RES generation systems, storages, EV recharge stations, loads, etc., are collected for monitoring and management purposes by the EMS responsible of that portion of the system.
- Home/facility areas networks: this architecture is provided at customer and final user level for implementing the advanced functionalities envisioned in smart energy consumption, such as the real time monitoring of the appliances, AMI, DR actions, price signals following, etc. In this contexts, the communication occurs between the facility energy area and the local controlling and monitoring system as well as from/to utilities and retailer in order to receive market and prize data.

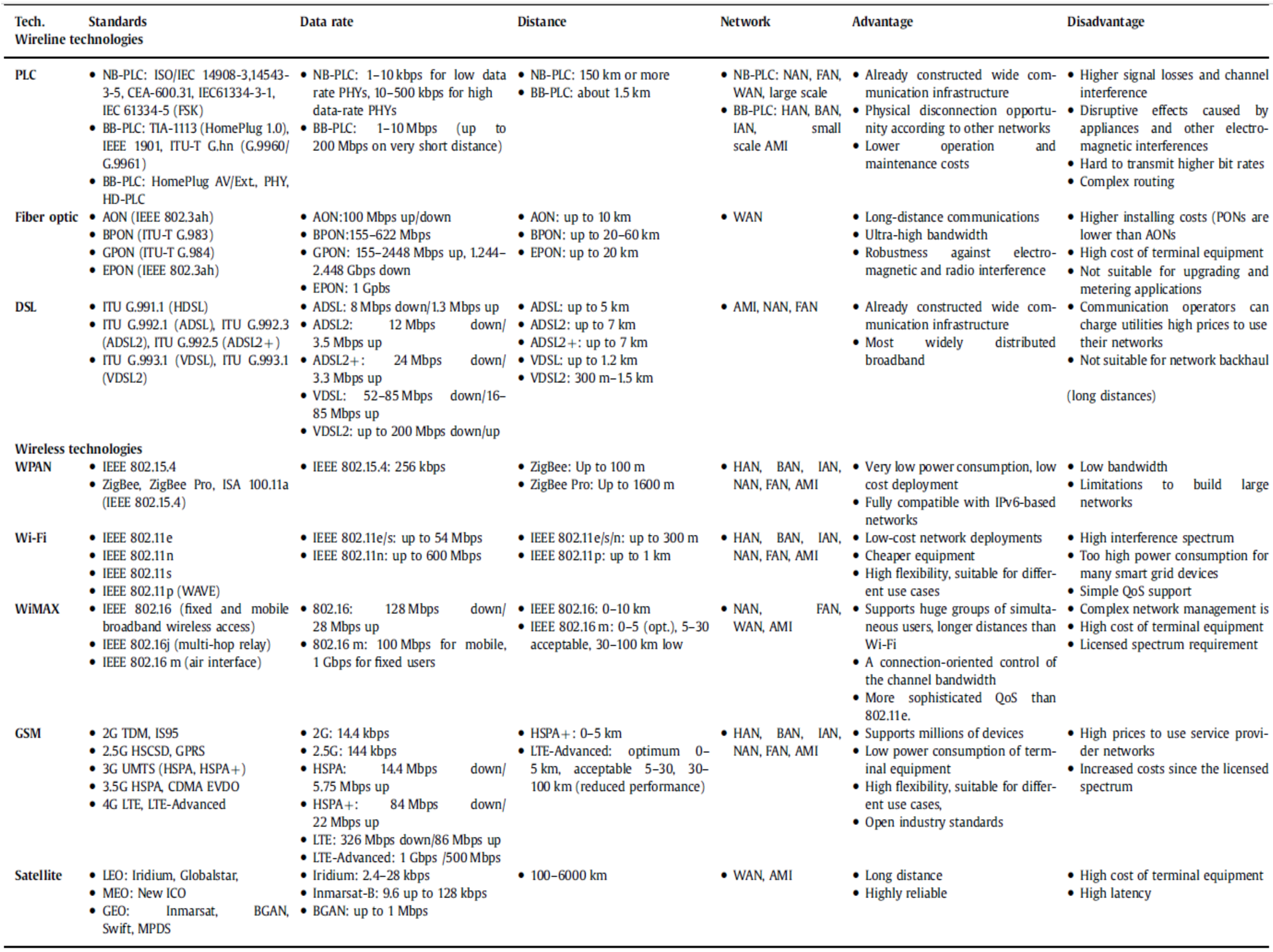
These different network frameworks allow to cover a wide range of distances within smart grid context: from some kilometres guaranteed by the wide area networks, from tens of meter covered by the home area networks.

Once the main architectures have been described, it worth detailing the technologies adopted for deploying such architectures. As far as the physical infrastructures are concerned, the main technologies for smart grids implementation are essentially three: (i) power line communication, that sends modulate carrier signals on power systems lines, reaching up to some Mbps. Due to its nature, it can be used only on a portion of the network, being unable to send information over the transformers. (ii) Wireline network employs cables for exchanging data, exploiting the existing network infrastructure or deploying new dedicated cables, with the related investments. This kind of solution offers up to hundreds of Mbps. (iii) Wireless networks are strongly enabled by the advancement in these technologies, and fit with many decentralised features of some of the described smart grid implementation. However, signals are subject attenuation and interferences; the date rate amounts to dozen of Mbps.

In the field of wireless network, it worth mentioning the great innovation brought by the fifth generation of cellular communication network, the 5G standard [46] [47]. It provides new high performances features on communication and decentralised management, especially in the areas of communication capacity, coverage, and energy efficiency.

Hand in hand with the development of tailored network technologies, research and standardization organizations have spent many efforts on identify the suitable protocol for performing the operations required in the smart grid scenarios [38]. Every technology tries to exploit its features by a proper communication protocol, tailored for a specific task. Going in the deep of details regarding protocols and their applications is out of the scope of this work; anyway, in Figure 6, a comprehensive list of communication technologies and features is provided [38].

Moreover, it worth mentioning that many standardization organizations, such as IEEE, the National Institute of Standards and Technology (NIST), the International Electrotechnical Commission (IEC), and many others are focusing on developing new standards for the implementation of effective, referenced, and interactive communication means in the smart grid context. For instance, the work done in this field by the IEEE Standard Association standards on smart grids is collected and reported in the website referenced in [48].



Tech.	Standards	Data rate	Distance	Network	Advantage	Disadvantage
Wireline technologies						
PLC	• NB-PLC: ISO/IEC 14908-3,14543-3-5, CEA-600.31, IEC61334-3-1, IEC 61334-5 (FSK) • BB-PLC: TIA-1113 (HomePlug 1.0), IEEE 1901, ITU-T G.hn (G.9960/G.9961) • BB-PLC: HomePlug AV/Ext., PHY, HD-PLC	• NB-PLC: 1–10 kbps for low data rate PHYs, 10–500 kbps for high data-rate PHYs • BB-PLC: 1–10 Mbps (up to 200 Mbps on very short distance)	• NB-PLC: 150 km or more • BB-PLC: about 1.5 km	• NB-PLC: NAN, FAN, WAN, large scale • BB-PLC: HAN, BAN, IAN, small scale AMI	• Already constructed wide communication infrastructure • Physical disconnection opportunity according to other networks • Lower operation and maintenance costs	• Higher signal losses and channel interference • Disruptive effects caused by appliances and other electromagnetic interferences • Hard to transmit higher bit rates • Complex routing
Fiber optic	• AON (IEEE 802.3ah) • BPON (ITU-T G.983) • GPON (ITU-T G.984) • EPON (IEEE 802.3ah)	• AON:100 Mbps up/down • BPON:155–622 Mbps • GPON: 155–2448 Mbps up, 1.244–2.448 Gbps down • EPON: 1 Gpbs	• AON: up to 10 km • BPON: up to 20–60 km • EPON: up to 20 km	• WAN	• Long-distance communications • Ultra-high bandwidth • Robustness against electromagnetic and radio interference	• Higher installing costs (PONs are lower than AONs • High cost of terminal equipment • Not suitable for upgrading and metering applications
DSL	• ITU G.991.1 (HDSL) • ITU G.992.1 (ADSL), ITU G.992.3 (ADSL2), ITU G.992.5 (ADSL2+) • ITU G.993.1 (VDSL), ITU G.993.1 (VDSL2)	• ADSL: 8 Mbps down/1.3 Mbps up • ADSL2: 12 Mbps down/3.5 Mbps up • ADSL2+: 24 Mbps down/3.3 Mbps up • VDSL: 52–85 Mbps down/16–85 Mbps up • VDSL2: up to 200 Mbps down/up	• ADSL: up to 5 km • ADSL2: up to 7 km • ADSL2+: up to 7 km • VDSL: up to 1.2 km • VDSL2: 300 m–1.5 km	• AMI, NAN, FAN	• Already constructed wide communication infrastructure • Most widely distributed broadband	• Communication operators can charge utilities high prices to use their networks • Not suitable for network backhaul (long distances)
Wireless technologies						
WPAN	• IEEE 802.15.4 • ZigBee, ZigBee Pro, ISA 100.11a (IEEE 802.15.4)	• IEEE 802.15.4: 256 kbps	• ZigBee: Up to 100 m • ZigBee Pro: Up to 1600 m	• HAN, BAN, IAN, NAN, FAN, AMI	• Very low power consumption, low cost deployment • Fully compatible with IPv6-based networks	• Low bandwidth • Limitations to build large networks
Wi-Fi	• IEEE 802.11e • IEEE 802.11n • IEEE 802.11s • IEEE 802.11p (WAVE)	• IEEE 802.11e/s: up to 54 Mbps • IEEE 802.11n: up to 600 Mbps	• IEEE 802.11e/s/n: up to 300 m • IEEE 802.11p: up to 1 km	• HAN, BAN, IAN, NAN, FAN, AMI	• Low-cost network deployments • Cheaper equipment • High flexibility, suitable for different use cases	• High interference spectrum • Too high power consumption for many smart grid devices • Simple QoS support
WiMAX	• IEEE 802.16 (fixed and mobile broadband wireless access) • IEEE 802.16j (multi-hop relay) • IEEE 802.16 m (air interface)	• 802.16: 128 Mbps down/28 Mbps up • 802.16 m: 100 Mbps for mobile, 1 Gbps for fixed users	• IEEE 802.16: 0–10 km • IEEE 802.16 m: 0–5 (opt.), 5–30 acceptable, 30–100 km low	• NAN, FAN, WAN, AMI	• Supports huge groups of simultaneous users, longer distances than Wi-Fi • A connection-oriented control of the channel bandwidth • More sophisticated QoS than 802.11e.	• Complex network management is • High cost of terminal equipment • Licensed spectrum requirement
GSM	• 2G TDM, IS95 • 2.5G HSCSD, GPRS • 3G UMTS (HSPA, HSPA+) • 3.5G HSPA, CDMA EVDO • 4G LTE, LTE-Advanced	• 2G: 14.4 kbps • 2.5G: 144 kbps • HSPA: 14.4 Mbps down/5.75 Mbps up • HSPA+: 84 Mbps down/22 Mbps up • LTE: 326 Mbps down/86 Mbps up • LTE-Advanced: 1 Gbps /500 Mbps	• HSPA+: 0–5 km • LTE-Advanced: optimum 0–5 km, acceptable 5–30, 30–100 km (reduced performance)	• HAN, BAN, IAN, NAN, FAN, AMI	• Supports millions of devices • Low power consumption of terminal equipment • High flexibility, suitable for different use cases, • Open industry standards	• High prices to use service provider networks • Increased costs since the licensed spectrum
Satellite	• LEO: Iridium, Globalstar, • MEO: New ICO • GEO: Inmarsat, BGAN, Swift, MPDS	• Iridium: 2.4–28 kbps • Inmarsat-B: 9.6 up to 128 kbps • BGAN: up to 1 Mbps	• 100–6000 km	• WAN, AMI	• Long distance • Highly reliable	• High cost of terminal equipment • High latency

Figure 6 – List of communication technologies employed in the smart grid and their features.

Besides the technological aspects of setting up an effective communication framework, there are many issues to be faced and solved for ensuring the best performance of the modern power systems.

Firstly, issues related to the communication time are addressed. In this context, the topics to be highlighted are: the latency of the information, concerning the maximum time in which a message is expected to reach its recipient, and thus time synchronization between this data exchange, as well as the assessment of the delay of the message sent between two or more networks, along with their own time requirements. Another issue concerns the reliability of the network. Playing an essential role in the smart grid implementation, the communications have to be as secure and reliable as possible, and all the countermeasures for avoiding their unavailability have to be taken. The main two countermeasures are to backup communication and the implementation of fast restoration of the communication network itself.

But the most important topic regarding modern communication systems for the power grid is about the cyber-security and the protection from this kind of attack. As a matter of fact, the information conveyed by these communication systems could be traced and leaked for many reason: access to sensible data, minor criminality, national interest, military strategic intervention on power system, etc. Because of these risks, the network designers pay great attention to ensure the highest level of cyber-security [45]. Besides the care of information authenticity, integrity, and confidentiality, the solution for improving cyber security of smart grid communication frameworks relies on denial-of-service defence, integrity protection and authenticity enforcement. Moreover, there are also physical requirements for cyber security definition [28], consisting in improving the security of all the electronics devices composing the nodes of the communication networks, such as PLCs, smart meters, and Phasor Measurement Units (PMUs).

2.2 Stakeholders involved

As a matter of fact, almost all the stakeholders of the power system benefit from the effects entailed by the services that a smart grid is able to provide [49]. So, each of them interacts with these services, implementing them, gaining benefits of different nature. In Figure 7, a simple representation of the stakeholders involved in the smart energy process is depicted.

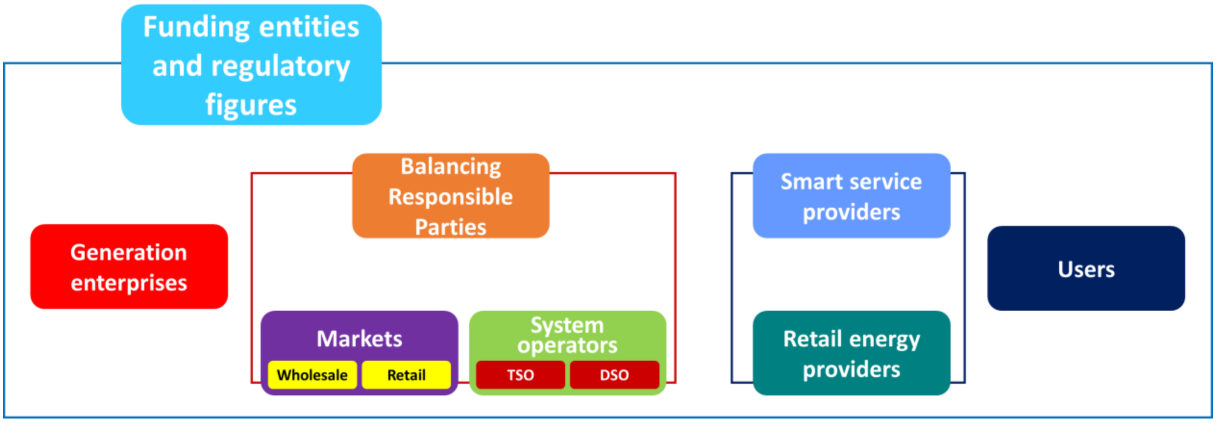


Figure 7 – Energy stakeholders involved on power systems evolution.

2.2.1 Funding and regulatory entities

The actions taken in the field of energy management and efficiency have a great impact on the human life. As a matter of fact, the usage of the energy resources is strictly linked to the environmental pollution and the sustainable development, aspects to be taken into account by the highest institutional figures and private, national and international decision centres. At the same time, the perspective solutions provided by the implementation of a smart grid concept aims at improving the quality of service provided to the users, whether common citizens or entrepreneurs, allowing them to have more flexible and exploitable systems, less supply costs and direct and indirect benefits from larger economic and social developments.

Thus, many governmental and non-governmental organizations focus their political and regulatory efforts on paving the way to these actions, promoting and fostering both the research and the easiness of implementation of energy efficiency and smart grid actions.

There are several institutions and organization whose main tasks is to create tailored framework for funding research projects on energy topics and support technical and regulatory issues by means of dedicated scientific committees. The main entity of this kind is the European Commission [50] that in the last 10 years has created several different opportunities to encourage and help research centres all over the Europe, gaining a very wide range of results and findings that has allowed the great development of smart grid solutions. The main results presented in this thesis have been achieved within the study carried out for two different European projects, as discussed in the next chapters.

Besides the necessary, and in some cases essential, funds that support the research and the implementation of energy efficiency and smartness programs, there is a significant need of update and renew some of the rules, laws and procedures in the energy area. Actually, lots of the most effective programs, such as establishing new market-places, control and communication infrastructure and so on, lack of a proper regulatory framework that can allow the easy implementation of these kind of actions. Furthermore, there are not enough entities appointed for the legal management, control and acknowledgement all the functionalities, operations and results provided within this modern energy context. Great effort is spent for creating this kind of entities, but there is not still a common framework to which univocally refer.

2.2.2 Generation companies

Today, the unbundling process that took place in the last decades in almost every country over the world has led to differentiate the electricity generation companies with respect to those that operate the grids or sell electricity. Today, the formers are companies participating to the electricity markets and pursuing their economic goas.

In addition, almost all of the new-born RES systems are owned by private parties, very often attracted by the possibility of gaining and achieving significant incomes from the sale of electricity and, above all, from the related incentives. It is clear how these stakeholders are able to influence and drive the evolution of the services provided by smart energy platforms implementation.

The business models related to the typical generation stakeholders are mainly driven by the fact that generation facilities achieve the best performances while following the scheduling production profile, otherwise they can incur in loss of revenues. Today, the deviations from the scheduled generation activities are likely to occur because of the great penetration of unpredictable RES systems into almost all the levels of the power system. In these cases, generation stakeholders can refer to the flexibility of smart grid users, in order to handle and smooth the high uncertainty caused by RES.

In this view, many programs are designed and aimed at flattening the consumption power profile of the final user, or smoothening the power injection into the grid by the unpredictable DG systems. Moreover, the ICT framework installed in these implementations allows a better communication between the generation stakeholders and all the other actors involved in the provision of flexibility.

2.2.3 Balancing Responsible Parties

The modern power system is widely interconnected in both distribution and transmission grid. This complex interconnection forces to coordinate in a proper way the power exchange for ensuring the balance of resources, taking into account several technical and operational factors. More in details, the main topic is related to security issues at the connection point of energy resources and among the connected networks, in order to safeguard their proper operations. Secondly, the possibility of interconnecting power networks allows to facilitate competition, transparency as well as efficiency in energy trading and to set up market-places. Last but not least, the management of the balancing phenomena across the power systems fosters a wider participation to energy efficiency programs, such as implementing DR actions and integrating RES systems or electromobility services.

In this context, the so called Balancing Responsible Parties (BRPs) [51] gain more and more relevance. Firstly, these bodies are in charge of meeting the requirements defined by the imbalance settlement between the interconnected systems and the grid operators. Moreover, it shall collect and provide all the information and data coming from the involved systems and send them to the grid operators in order to evaluate the balancing services needed as well as both plan and manage properly the power exchange. Finally, the BRP has to set up the procedure for handling the unbalance itself, in order to modify and stabilise the power exchange and the services provided.

It can be clearly noticed how the BRP comes between several actors in balancing power flows between interconnected networks. In case of implementing complex energy system management, in terms of scheduling, optimising, controlling, etc., the BRP plays a key role on addressing the energy phenomena in a smart grid or in an aggregated federation of them.

2.2.4 System Operators

The operators of the power systems, both transmission and distribution grids, are unquestionably some of the more relevant actors of the shifting from the typical conception of the electrical network to the newest smart grid architectures and implementations [52] [53]. Being in charge of the hardware reliability and of the operational management, the Transmission and Distribution System Operators (TSOs and DSOs) are involved in almost every phase of energy efficiency improvement by means of smart grid projects.

Firstly, many times they are the recipient and the beneficiaries of some typical service provided by the actions performed in a smart grid context: DR programs are often tailored on system signals coming from grid operators, RES injection smoothing goals focus on avoiding power peaks or power reverse flows, local storage helps on system balance, load profile flattening helps on delaying infrastructural intervention and grid extension or reinforcement.

Another aspect to be taken into account addresses all the issues caused by the presence of new devices connected to the grid. The installation of AMIs are very frequently performed in smart grid implementations, creating an interface layer between the hardware equipment of the users and the grid itself. Similarly, the adoption of local storage systems has often to be performed by connecting the storage to the grid, as the EV recharge systems and all the applications of this nature. Moreover, in many contexts, the installation of distributed automation devices is strictly necessary for making effective the decisions and setpoints evaluated at control level. It is clear how the operators are involved economically and technically in supervising and authorizing all these infrastructural interventions. On the other side, they are also forced to remodel their own equipment configuration, starting from protection devices and involving also lines, cables, transformers, and so on. As mentioned above, they could be also involved in reconfigurations of entire sections of the grid to be enlarged, reinforced, or modified.

Moreover, the ICT context in which TSOs and DSOs are asked to interact and exploit their operations are more and more innovative and require increasingly complex implementation, concerning both control logic and communication protocols. Initially, many smart grid or energy efficiency actions aimed at reusing properly the existing communication architectures for allowing the exchange of data among all the actors, for instance employing protocols such as the IEC61850 standards [54]. Today, many protocols and customized ways for exchanging information between grid operators and smart grid actors are proposed and tested in many contexts, in order to prove the best one in terms of efficacy, easiness of use and replicability. The grid operators are so asked to be compliant to these new communication means.

The local nature of the grid operators allows them to be fully involved in the topological aspects of smart energy actions. Many initiatives actually imply changes in grid topology, the federation of some energy resources, the connection of new generators and/or loads, as well as storage system; moreover, all of them are managed and equipped with their own control system to which grid operators have to interface. The complexity of such solutions force the utilities on modifying their usual operations patterns and evolve into smarter ones [13].

The above mentioned areas in which the grid operators are involved imply also the opportunity of setting up tailored business model, possibly supported by incentives schemas that drive the financial feasibility of many energy related projects. Even though there are no regulatory frameworks tailored on supporting grid operators on rewarding incentives to service providers, many researches are investigating on the economic viability of such solutions.

2.2.5 Retail energy providers

The retail energy providers are fully involved in the smart grid evolution taking place in these years, representing a service providers such as the energy retailers that, in the wider context of energy asset revolution, have been unbundled from the massive energy companies that in the last century were in charge of the management of all the aspects of the energy systems.

Many energy efficiency or flexibility actions, as well as DR and DSM programs, foresee the possibility of trading energy or offering energy-related services to the actors of the power systems, or offering discounts as well as different prices to encourage users to shift their loads, as shown in the past in many national contexts [55] [56]. This is driven by the fact that the energy retailers that do not provide the procurement to their customers are forced to buy the energy shortfall from the available markets, that are characterized by a significant price volatility. The energy flexibility provided by the above mentioned actions can cope with these phenomena by reducing, shifting and curtailing energy consumption, leading the retailers to accommodate business solution by means of this kind of services [57].

Moreover, they are very often involved in technological improvement and communication remodelling toward distributed energy resources. In many implementation of DR programs the retailers are asked to send price signals to the AMI of the participating customers, in order to allow them performing their energy actions. In the same way, DG system are often equipped with smart bidirectional meters through which the retailers are able to understand the amount of energy injected and/or self-consumed in order to pay or reward the system in accordance to the subscribed connection contract [58]. These aspects push the retailers to modify their equipment and to change their market tasks for properly ensuring the services agreed with customers.

2.2.6 Smart service providers and Energy Service Companies

The providers of smart energy services aim at supporting the business processes of all the main power system actors, from generation and consumption to market frameworks. The new business processes, besides traditional utility services such as billing, provide enhanced services such as management of energy use, the possibility of aggregating energy resources, home energy control, etc. [59] [60], while ensuring the quality and safety levels required by the smart grid scenarios. Besides offering new and innovative services exploiting the features of smart grid technologies, the key aspect of the services providers is that they make available also the interfaces between different domains. In particular, the main challenge is to achieve clear and integrated interfaces and standards for allowing actors from customer and grid operation domains to interact into tailored markets, in which the value of the services traded are rewarded to the service providers.

In some cases, the complex energy framework envisioned in this thesis, composed by such many actors and entailing such many actions to perform, requires the presence of tailored bodies asked to burden themselves of coordinating and easing the access to energy efficiency or flexibility services, such as Demand Response Providers (DRPs) [61], acting like an effective bridge between customers areas, grid operators requirements, and markets.

In this context, the energy resource aggregators [62] [63] can be seen as a typical DRP, playing a significant role in providing services to that users that cannot access directly to energy efficiency or flexibility programs. Actually, whilst the DR actions can be easily implemented in some industrial contexts, where it could be quite simple to manage in a centralized way the productive process for controlling load adsorption, it is not the same for many energy contexts, such as homes, offices, small enterprises, that does not have enough power to negotiate an effective service neither with grid operator nor with a market one. Moreover, the single end-user does not possess the required equipment for implementing such actions, for instance AMI or communication infrastructure, and does not know the legal and regulatory issues for undertaking such a complex initiative.

The aggregator has the role of interposing between a group of small energy resources, both consumers or DG systems, collecting their energy contribution to a certain service, that could address load shifting, profile flattening, reverse power flow reduction, etc., and propose this aggregated effort as an effective services to an actor of another domain. It also cares of installing the required smart equipment to users’ facilities and appliances. Once signed a contract with all the aggregated resources, the aggregator will exploit its management criteria in order to optimise energy impact [64], acting as a controller of the aggregated units. In this way, the users are rewarded, often through the aggregator itself, for the provisioning of energy services or by reducing the costs of energy supply, whilst the aggregator gains benefits from the user for the aggregation itself or gains from the transaction with the entities that request for a services, for instance a grid operator for technical aggregation programs.

The possibility of providing services like those described above is a booster for the introduction of innovative efficiency-oriented actions, like local market-places, the local exchange of energy flexibility, the interaction with new carrier distribution systems, and so on.

Another relevant actor of the smart energy context is represented by the Energy Service Companies (ESCOs) [65]. This private parties provide services related to the real implementation of a smart energy system by supporting, also economically, the interested customers of a smart grid. Indeed, an ESCO is involved in every phase of the implementation of a smart grid: it leads the design, coordinates the installation and deployment of the system, operates the smart energy management. Moreover, it often acts a significant role in financing all the related activities. The economic incomes of the ESCOs are directly connected with the effectiveness of the energy saving and efficiency actions performed by their systems. This can be considered a great leverage for the commitment of the ESCOs on providing such services.

The typical services delivered by these companies are listed in the following:

- provide an investment grade audit;
- engineer design tailored to the scope and size of the context;
- arrange project financing and assess financing options;
- procure and install the equipment;
- monitor and evaluated energy savings and efficiency;
- provide support on system operation and maintenance;
- prepare reports for the customer detailing energy behaviours.

2.2.7 Markets

The functionalities and the services provided by the implementation of a smart grid paradigm involve such many aspects of the energy process that is not possible to neglect the implications at market level. In this perspective, the most important regulatory entities have taken part in the definition of roles and market schemas for allowing the innovative technologies and services such as DR, reverse power flow reduction, RES generation and storage management, energy flexibility actions, to be accepted as effective phenomena in the market places. For instance, the two references in Europe and USA in this field are the European Union (EU) third package of energy market legislation [66] and the Federal Energy Regulatory Commission (FERC) Order 719 [67].

The impacts brought by the smart grid implementation could be recorded both in wholesale market [68] [69] and in retail one [70] [71], due to the fact that these actions involve a wide range of grid actors that are responsible of various tasks.

The contribution that a smart grid implementation can provide to the wholesale market is very wide and addresses many topics of network management. Firstly, it can participate actively in trading energy during market sessions, making bid and offers for selling and/or buying amounts of energy, in accordance to the features of the smart grid itself. This can be done by a unique energy unit managed in a smart way through one of the technologies presented, or by means of a resources aggregator, able to collect the energy capabilities of several customers (consumers, generators, or prosumers) and to give them such relevance, in terms of magnitude and contractual power, to be presented in the wholesale marketplaces. Another important possibility of smart grid realities is to trade ancillary services just like another typical ancillary services provider. Smart grid actions can provide services such as emergency demand response, increasing reserve margins, withholding generation capability, managing load consumption, starting fast start up units, etc.

Regarding the retail markets, the application are numerous, due to the fact that retailers are moved by both technical and economical drivers for allowing such kind of participation. From the technical point of view, grid operators, especially DSOs, are forced to maintain and ensure standardized level of service and quality, besides avoiding operating issues like overloads, reverse flows, and operating reserves. As economic aspects are concerned, the generators and the retailers can be subject to severe financial risks due to the price volatility in wholesale markets, so they prefer to set-up retails markets mechanisms with their customers by smoothen load supply instead to provide the energy from volatile markets. When technical issues are on the table, signals from grid operators act on interruptible load or in programs that allow to reactively respond to peak load reduction request. These are compensated to the customer with economic rewards, incentives, energy bill discounts, etc. In the case of economic led action, the most common refers to the usage of real time pricing or time of use pricing, based on the exchange of information between retailers and customers in order to gain economic benefits from supply energy at lower costs, besides possible rewards agreed in the service contract.

Despite of the many possibilities and advantages that the interactions with markets entails, there are still many challenges to be faced. First of all, there is no clear regulatory framework that assesses properly the rule of accessing, participating and managing the market operations. There is a great need of implementing a clear framework in this direction, especially in international view. For allowing and fostering this process, referenced and proved test concept for assessing the real effectiveness of such market implementations could be very helpful. Moreover, there are no affordable and standardized ICT infrastructure for managing and deploying the envisioned market infrastructure, so retailers and grid operators has to focus in creating a unique compliant technological solution for allowing all the actors to interact with marketplaces. Last but not least, great emphasis should be put on customer’s awareness and acceptance of such markets dynamics and the possibility of making a concrete resource from the flexibility that the smart management of their energy resources can provide.

2.2.8 Users

As largely discussed through this chapter, the end-users are interested in all the proposed smart grid scenarios; actually, the management of the energy resources passes through its actions. So far, the users have been taken into account only from technological point of view, for ensuring the correct operation of the devices installed in their premises, such the AMI or local storage device, or for creating tailored communication frameworks able to reach and exchange data with them. Now it is crucial to assess its commitment with respect the energy-related topics and its confidence in this kind of programs.

The key topic concerns the end-users’ awareness of all the issues connected with the complex framework of energy consumption and its management. Actually, in many cases there is a gap between the common understanding and the view on energy consumption that is far from the relevant modern topics, such pollution, dependency from other fuel supplier countries, possibility of managing energy in simple way, and availability of dedicated technologies for performing smart grid implementations. Today, many projects and public initiatives focus their work on sensitising citizens and, more in general, users of energy resources [72].

As a matter of fact, the engagement by the user in the energy topics led unequivocally to a better and more shared participation in many energy efficiency and flexibility programs, as well as in tailored markets frameworks, and push them to modernise also their equipment, for instance buying energy efficient appliances or controllable ones. It is crucial also to understand how the user can be committed and can believe in the really effectiveness of such actions: the motivation for changing its habits, to modify their load consumptions also affecting its own comfort, the employment of alternative technologies, or simply resigning to perform high energy-consuming activities, are at the basis of the success of new energy paradigm [73].

For allowing such a meaningful result, the user has to be confident on both technologies and actors taking part in this frameworks. This trust is not simple to achieve because many reasons, but there is a great effort in this direction, firstly for raising the awareness of the crucial topics of energy management and, secondly, for enlarging the basin of customers, loads, and prosumers, taking part actively in the smart grid paradigm. The performances of the implementation of such actions depend on users' trust and participation [74].

The issue of social acceptance by citizen and user is strictly connected to this topic, and will be discussed in the next section.

2.3 Social and economic impacts

Many studies about energy projects in the literature have assessed the social impacts of the actions aimed at promoting energy innovation and efficiency [75]. This is a key aspect for determining both the long-term and short-term outcomes on the social field, allowing to evaluate the benefits and the drawbacks in which various components of the society can incur once these kind of projects are implemented and made effective on a large scale [76] [77]. The approach employed for these analyses can be also an effective leverage for creating a comparison framework for governmental organizations and, broadly speaking, policy-makers: results from these studies can drive them to create an effective set of policy initiatives tailored for reducing obstacles to the development and spread of such technologies, as well as for regulating the legislative gap in the field of energy initiatives. Moreover, depending on the magnitude and the effectiveness of these actions on the society and the environment, various incentive programs can be shaped in order to foster the spread of such initiatives on national and, above all, local level. All the initiatives on energy innovation can pave the way to the spread of other energy related enterprises, most of which connected to the use of RESs. Thus, all the advantages on the social aspects carried out by RES actions can be considered part of the impact brought by energy efficiency and flexibility projects.

Strictly linked to the social topics, and to the possibility of obtaining incentives or similar forms of rewarding, the economic impacts of the implementation of the energy efficiency and flexibility initiatives have to be assessed. Actually, many areas of the community are affected by the presence of such initiatives, bringing a wide spectrum of benefits especially in the field of employment. Identifying and quantifying these benefits can be a key leverage for setting-up and proposing new incentive schemas and for structuring new business models related to the operations of a smart grid.

Firstly, this section presents an overview on the acceptance from citizens, small and medium enterprises and local authorities of the energy efficiency related projects that could be exploited and operated in their geographic area. Subsequently, all the social benefits related to the implementation of energy efficiency infrastructures are listed as well as briefly presented and evaluated in their prospective impact on community. In the second part, the economic benefits in the community are analysed and described in the European context, especially regarding Mediterranean area, and, finally, all the aspects analysed in this chapter are seen in the view of creating a proper incentive framework in order to foster the spread of energy efficiency and flexibility initiatives.

2.3.1 Community acceptance

Since the beginning of the discussion and research on energy related projects, great efforts have been spent on assessing environmental aspects on the infrastructure revolution proposed and envisioned by an astonishing number of initiatives. Nevertheless, in a few occasions the acceptance of these programs by the social fabric has been taken into account directly, so that many times apparent contradictions between the recognized environmental benefits and the social attitude have occurred. In this section, the elements characterising the features of the acceptance are assessed.

The first issue linked to the social acceptance is the lack of effective information and knowledge about benefits provided by the projects that implement energy efficiency and flexibility. As reported by many polls and interviews [78], there is a common shared positive view about the initiatives on the energy fields, but there is not a proper consciousness on what the problems are, regarding environment, energy balancing, market phenomena, etc., that should be faced by these initiatives. Moreover, there is also few understanding of what these actions imply, what are the responses expected by the energy users and the potential benefits achievable by the users themselves. In this direction, many projects focus on dissemination activities in order to provide the main stakeholders involved in these actions with proper knowledge.

Another key aspect affecting the acceptance of energy related initiatives is the unclear and unshared approach adopted by the policy makers on supporting such a kind of projects from various points of view, for instance by creating proper laws addressing the issues related to the deployment of energy infrastructure, taxes reduction, incentive schemas, dissemination and information activities at local level, landscape regulation, etc. Well defined and common national, as well as regional, regulation and law references in the topic of energy efficiency and flexibility will help on having a common shared view on the benefits and drawbacks of these actions and also on easing the awareness and the dissemination among the community. This is even more true when addressing the aspect of siting decision. Since these energy flexibility infrastructures are very often decentralized, due also to the medium/small-scale of their plant, a clear regulatory framework allowing a fair and transparent decision of the site where the energy plant have to be built and operated is crucial for the acceptance by the community.

In this context, some studies, like those referenced in [78] [79], have addressed the social acceptance of the energy related initiatives by creating a proper framework for assessing the different dimensions of social acceptance. As a result, three aspects have been highlighted:

- Socio-political acceptance: it addresses the acceptance of both technologies and policies by the citizens, the key stakeholders and the regional and local policy makers, and constitutes the broader kind of energy efficiency and flexibility initiatives acceptance, evaluating the mismatch between the actual feeling of these actors and the common thinking about energy innovation.
- Community acceptance: it refers to the acceptance of energy infrastructures by the inhabitants and the local policy makers in the site decision, taking into account various phenomena, such as different kind of protest movements, social barriers, NIMBYsm (from Not In My Back Yard), etc., evaluating also the dynamic change of the community point of view over the time, from the proposal of such an intervention to its physical deployment, ending to the management of its operation.
- Market acceptance: it analyses the social acceptance from customers, investors and firms-from the market point of view. As far as the customers are concerned, this topic is studied as the acceptance of a new product in the market by its users. Regarding the investors, the economic effort and the financial analysis of the energy projects are assessed. The intra-firms study addresses their market analysis on becoming active players in energy innovation projects.

In Figure 8 [78], the so called triangle of social acceptance is shown.

Figure 8 – The triangle of social acceptance of energy innovation initiatives.

2.3.2 Benefits on the community

The impact on social development due to the implementation of energy related projects has been assessed in several studies [79] [80], trying to detect the influences both at national and local level. As a result, many models and analytical frameworks have been developed in order to give proper means to analyse the main aspects that characterize the benefits on the community.

2.3.2.1 Demographic impact

In many areas of the Mediterranean basin, demographic issues have risen in the last twenty years because of intense migration flows, especially those from local and rural areas to greater city contexts. The deployment of energy innovation projects allows people finding new reasons for not leaving their home places, in the same way, the immigration phenomenon could be reduced, due to new economic and life-quality perspectives given by the energy infrastructure and all the benefits that it can provide.

Thereby, a greater share of young and working age people is expected to characterize demographic composition in the Mediterranean basin regions. This phenomenon, in addition to the potentiality provided by the improvement in the educational framework on energy topics, will generate a chain effect able to improve the economic and social development of those regions.

2.3.2.2 Social cohesion and human development

Access to modern forms of energy is essential for promoting human development in many aspects, such as supporting economic growth, increasing employment opportunities, improving quality of social services. A variety of socio-economic studies have addressed the topics of human well-being by evaluating some indexes, like the Human Development Index, and how they correlate with the quality of energy intended as the energy usefulness, thus the amount of work that can be performed by a unit of energy, directly or indirectly. This concept is strictly related to energy efficiency and flexibility.

Many of the above mentioned indices of human social well-being are well correlated with indices of energy availability and, as expected, Gross Domestic Product per capita. Moreover, these quality of life indices are as well correlated with a composite index of energy use and distribution developed in [81]. As a result, it appears that the quantity, quality and distribution of energy are key issues that influence quality of life.

Another aspect of great interest for the social impact is the gender issue; since the availability of cleaner energy options can free women’s time from survival activities (gathering firewood, fetching water, etc.).

Other impacts on social cohesion could be fostered by the will of different sectors of the society to cooperate, also economically, in buying, managing and addressing the choice of installing an energy infrastructure on their local area.

2.3.2.3 Energy impacts

Large-scale deployment and spread of innovative energy infrastructure can provide many solutions for allowing access to cleaner and modern energy options while ensuring long-term sustainability. As matter of fact, besides providing flexible availability of electricity, in particular generated by RES systems, the exploitation of other energy carriers as hydrogen, thermal energy, methane, etc. are often taken into account in these kind of energy initiatives. This will lead to more availability of energy resources not usually employed in typical energy systems.

2.3.2.4 Productive and occupational diversification of the area

A significant social impact can be found in the diversification of the productive activities and employment in the areas where such energy initiatives are implemented, installed and operated [82]. Actually, most of the energy innovation projects and actions require the support of variegated technologically advanced components, as several diversified professional expertise both for hardware energy infrastructure design and implementation as well as for energy management.

It is therefore expected a broadening in various areas, grouped in three large groups: technological development, installation/uninstallation, operation and maintenance [83]. As a matter of fact, all the activities linked to generation, distribution, transformation, usage and storage of any particular energy carrier are involved in the social and industrial changes triggered by energy efficiency and flexibility projects. This is due to the strong innovative character of these energy initiatives, leading to vary and enrich the productive and occupational asset of a region in order to cope with the technological development in that specific field.

2.3.2.5 Educational impacts

Great impact could be reported on the educational and training fields both at national and local level [84]. There is a very wide range of programs and activities that could be performed in the schools and/or during non-school training courses (incorporated into lessons in human, social and physical sciences as well as aspects of ethics) in order to improve the consciousness of the society on the energy projects and on the benefits they can bring to the community [85]. New energy technologies have to be presented and effectively explained to the society, above all to the citizens and final users in general, otherwise these technologies would have little effect if users cannot be convinced to use them.

The main goals of educational activities are:

- identifying the actions that can be performed by the citizens, entrepreneurs, SMEs and other community actors;
- raising awareness of the energy and environmental issues, as well as their background and all the related topics;
- explaining and underlining the benefits of that action and how they could affect all the stakeholders involved.

2.3.3 Economic impact on the community

2.3.3.1 Quantitative and qualitative impacts on employment

Among all the socio-economic impacts, great relevance has to be given to the effects on the employment, topic which is tightly linked to the social cohesion and human development, discussed in par. 2.3.2.2. Many studies and expert analyses [80] [86] [87] have demonstrated the positive effect on the occupational dimension.

Due to the intrinsic complexity of this issue, various aspects have to be taken into account, especially those related to qualitative and quantitative impacts [79], as well as their continuity over the life-time of the energy related projects. As a matter of fact, the number of employed people is expected to rise, especially at the beginning phases of the project, during the design as well as development and/or construction stages of the energy infrastructure. In the same way, for the dismantlement phase at the end of the project, or at the end of the plant life, these jobs are temporary. On the other hand, the creation of new occupation in the areas of operation and maintenance, surveillance, transportation, etc., and the satellite activities connected to that particular energy carrier is more durable and affects more significantly the job market.

2.3.3.2 Income generation effects and income distribution

One of the most significant economic impacts of these kind of energy related projects is connected to the increase of the incomes and their distribution among different sectors of the society [80]. Apart from the money for financing the local administration, the activities related to an energy infrastructure involve definitely a great amount of money for renting, hiring, buying or obtaining any kind of grant for the land in which the plant is to be erected. Moreover, money for supplies, authorization processes, etc., has to be considered as well. Secondly, the economic activities connected to the presence of at least one company in that area allows the increase of the taxes payed both to the local administration and to the contributory system.

Moreover, it is worth mentioning another crucial aspect when discussing about the income generation related energy innovation projects: the so called benefits payments. As reported in many socio-economic analyses [79], on several occasions the firms appointed for undertaking energy activities that affect the community create a program for rewarding the different parts of the society by means of economic payments, rewarded especially to facilitate the social acceptance.

If these economic mechanisms are structured in a proper way, besides simply generating higher and new incomes, they could allow to better distribute the richness within society, addressing also social and welfare aspects [88] [19].

2.3.3.3 Integration in the local economy and use of endogenous resources

The energy innovation projects are often related to distributed services, acting directly on the small-medium actors of the energy system for collecting their aggregated operation at a higher level [87]. This is often shown in distributed generation facilities, decentralized storage systems, smart district management system, etc. The features of these energy facilities allow a better integration in the local economy, being built, installed and operated in local areas. They typically exploit endogenous resources, either physical, human or capital. This is easily understandable for RES exploitation, strictly related to wind and solar conditions of the specific area, but is also true for the presence of industries in the area employing particular energy carriers, such as hydrogen, or education facilities creating professional profiles in that particular area.

This aspect is of great interest for the economic impact, both assessing the economic growth and above all exploiting resources in a smart and efficient way [79] [80].

2.3.4 Potentiality of incentives and possible schemas

As reported in the previous sections, both in Europe and in the rest of the world, all the main institutions and administrations are currently committed in the achievement of general objectives connected to the environment. In this way, the prosumer (consumer+producer) flexibility may be a powerful support also for the national general targets achievement in terms of environmental impact.

This is the reason why, also from the economic perspective, central governments should encourage the diffusion of projects supporting flexibility inside the regional and national grid, given the potential benefit they may bring for the whole citizenry. Strong political initiatives supporting both organizational and economic incentives would encourage more and more prosumers to become flexibility providers. The effectiveness of this solution can be compared to the success of a series of recent similar incentives for the widespread installation of PV panels and RES in general, also at domestic level.

In order to provide flexibility to the power grid, the firm or entrepreneur must afford an amount of costs, which can be grouped into two macro categories: CApital EXpenditure (CAPEX), thus all the initial investments for the acquisition, installation and setup of the new devices (storages, ICT equipment, etc.) enabling flexibility, and Operational EXpenditure (OPEX), thus all the periodic expenses needed to operate and maintain the system, once it has been built and started.

In order to support the acquisition of devices, and their maintenance, a great support may be given by the regulatory institutions by allowing these plants to participate to the flexibility market. National incentives may boost the adoption of the prosumer paradigm by most of the subjects having the potentialities to operate in such a way. Plant owners may be endowed with financial and legal resources in order to enhance, maintain, and periodically upgrade their existent systems. New entrepreneurs may be induced to enter this new business, attracted by the reward expectation and the incentives available to jump-start the new activity. Discounts on the electrical power and other resources may be applied by the suppliers, especially if they are motivated by congestion needs: as an example, replacing transformers with bigger ones, in order to adapt their network to higher requests from the grid, may be much more expensive than providing an economic incentive to foster prosumers flexibility.

The rewards to energy innovation and flexibility projects could be collected into three distinct groups: a fixed one awarded periodically, a variable one dependent on the flexibility degree, and the generic incentives coming from the authorities for the environmental, social and economic impact.

In this perspective, the fixed remuneration could imply a constant amount; it would be expected as a reward for the provision of flexibility services. The variable remuneration could be considered as proportional remuneration, when the amount of the total reward would be proportional to the degree of the flexibility services provided, as well as market follow-up and peak time-shifting, in which the pursuit of the energy market trends is expected. Regarding the public incentives, possible business model foresees the participation of central governments and public authorities in the remuneration of the flexibility provided by the new potential prosumers as a possible further opportunity for smart grid managers and owners.

2.4 Survey on smart grid projects

2.4.1 Research projects framework in Europe

The impetus for researching and improving the knowledge, confidence and reliability of the actions connected to the implementation of the smart grid concept relies upon national and international projects carried out and partnered by several actors. These belong to the classes of stakeholders described in this chapter: RES plant owners, grid operators, ICT service providers, retailers, and so on, participating actively on a great amount of initiatives aimed at funding, fostering and supporting the research in the energy field.

In Figure 9 [89], an outlook of the machine that stays behind this enormous effort is depicted; it reports the projecst in the European context, the one referred to in this thesis.

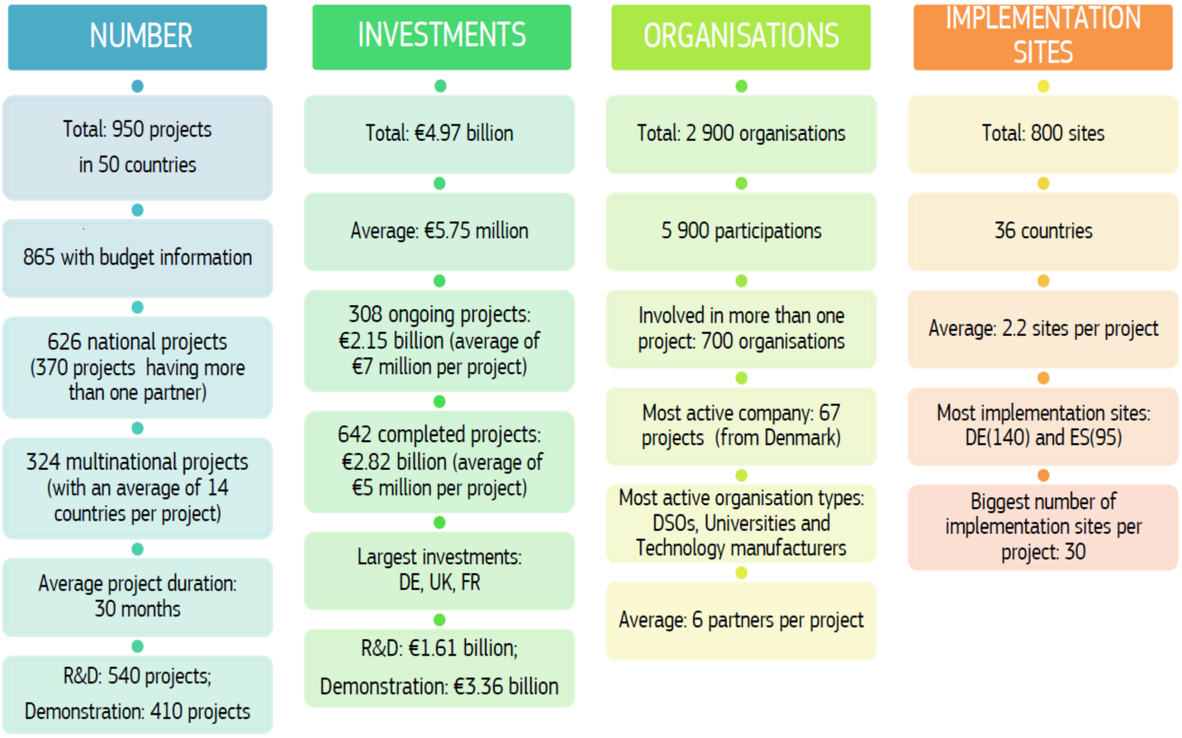


Figure 9 – Outlook on European projects by 2017.

It is well known that the process aiming at supporting these projects is based on funding mechanisms both from own or private investments, that represent the greatest share of funds, and from national or Community funds, or by a mix of both financial interventions. Even though private investment is the highest source of financing of smart grid projects, the number of projects funded by governmental actors is higher than the number of projects financed only by private capital. In this context, it is worth mentioning the great contributions of EC in creating tailored research programmes that cover all topics and crucial aspects of the challenges in the smart grid area; here are reported again the two most appointed programs: 7th Framework Programme [4] and the Horizon 2020 [5] funding programmes.

Moreover, in many cases, each country is strongly committed in creating a proper framework in which all the actors involved are fully supported and led to the effective implementation of smart grid projects. Thus, many competent national authorities, but sometimes private organisations, have adopted smart grid roadmaps and smart grid platforms. These tools are made available to ensure a clear and coherent national progress towards the main objectives in the energy field, providing all the involved stakeholders with a common understanding as well as shared and acknowledged means for conducting their activities.

2.4.2 Main projects on smart grids

In the present section, the most impacting projects in the European context are reported. They have been selected among those performed approximately in the last 5 years, in order to refer to the latest and most innovative technologies and approaches. The topics addressed by the proposed projects have been selected because of their relevance in the same smart energy field studied by this thesis in the next chapters.

Building Energy decision Support systems fOr Smart cities (BESOS) project: it aims at providing smart management of energy resources in city context whilst increasing the awareness of citizenry. The activities of this project involve mostly the utilities and the municipalities of the interested areas. The innovations brought by the project are tested in two demonstration sites, located in Lisbon (Portugal) and Barcelona (Spain). Duration: 2013 – 2016, closed project [90].

Combined Heat and Power Communication (CHPCPM) project: its goal is to create a standardized data communication platform based on IEC61850 and IEC62351 standards. The project is based on the employment of CHP and involves all the major stakeholder in its field, from CHP owners, to grid operators and market stakeholders. Practical demonstration will be performed by Danish CHPs. Duration: 2013-2016, close project [91].

Collaborating Smart Solar-powered Micro-grids (COSSMIC) project: this project aims at developing a smart management system for exploiting RES energy generation from PV system in a neighbourhood context that will be able to share and optimise the energy consumption with the energy district. Moreover, an ICT framework for coordinating the sharing of the RES generation is developed and tested in two test sites located in Konstanz (Germany) and Caserta (Italy). Duration: 2013 – 2016, project closed [92].

Distributed Intelligence for Cost-Effective and Reliable Distribution Network Operation (DISCERN) project: the aim of the project is to provide the distribution network with the level of intelligence required for seamlessly integrate RES generation, while ensuring reliable, controllable and observable operations of the system. The partnership of this project includes five of the major DSOs in Europe, through which the projects solution will be implemented and tested. Duration: 2013 – 2016, close project [93].

Energy To Smart Grid (E2SG) project: the target is to realise an architecture composed by a set of nodes that represent both the points of energy injection or consumption and, at the same time, of data exchange. The challenge is also to set-up a policy and industrial framework that support the evolution of such a technological solution aimed at increase the exploitation of RES systems. Duration: 2012 – 2015, closed project [94].

Balancing energy production and consumption in energy efficient smart neighbourhoods (E-BALANCE) project: this project proposes a comprehensive solution taking into account social, economic, and technical aspects for the sustainability of the power systems. Starting from available technologies, the solution is adapted to the social conditions, the economic and regulatory environment, and addresses the awareness of involved customers in integrating any kind of energy resource for the management of the grid. The proposed platform is deployed in demonstrators located in Portugal and Netherlands. Duration: 2013 – 2017, closed project [95].

Energy Positive Neighbourhoods Infrastructure Middleware based on Energy-Hub Concept (EPIC-HUB) project: it proposes a neighbourhood platform able to act as an energy hub for the optimisation of energy resources, exploiting existing ICT infrastructures in combination with innovative ones. Besides the energy management of the neighbours' resources, a trading platform is implemented. The effectiveness of the solution is proved in three test sites, Genoa (Italy), Belgrade (Serbia), and Bilbao (Spain). Duration: 2012 – 2016, closed project [96].

Development of methodologies and tools for new and evolving DSO roles for efficient DRES integration in distribution networks (EVOLVDSO) project: the research addressed by this project covers the field of technological improvement of DSO activities related to planning, operational scheduling, real-time operations and maintenance. Including some grid operators, the project aims at contributing in the transition to a more sustainable power grid increasing the reliability and security of distribution system in presence of high penetration of distributed RES. Duration: 2013 – 2016, closed project [97].

Future INternEt Smart Utility ServiCEs (FINESCE) project: it aims at proving the employment of future internet solution in the field of energy management. The main goal is to handle the management of energy usage in residential and industrial buildings, developing a new marketplace, integrating RES and using EV as a mean for DR implementation. The deployment of real-time smart energy services is teste in seven European countries in order to prove the performances of FI-WARE and Future Internet. Duration: 2013 – 2015, closed project [98].

Large-Scale Demonstration of Advanced Smart GRID Solutions with wide Replication and Scalability Potential for EUROPE (GRID4EU) project: it proposes the implementation of six, strongly integrated, large scale demonstrators to test innovative system concepts and technologies, highlighting and helping to remove some of the most important barriers to smart grid deployment. The main focus is on energy management of supply and demand oriented at the integration of RES and at involving consumers in active participation in aware energy consumption. Duration: 2011 – 2016, closed project [99].

Integrating Active, Flexible and Responsive Tertiary Prosumers into a Smart Distribution Grid (INERTIA) project: this project aims at providing an overlay network for coordination and active grid control running on top of the existing grid and consisting of distributed and autonomous intelligent Commercial Prosumer Hubs. Distributed Energy Resources (DER) will form dynamic clusters comprising self-organized networks of active nodes that will efficiently distribute and balance global and local intelligence. The DER self-organized overlay network will allow for seamless management and control of the active grid and the optimal exploration of single and aggregated prosumer capacity (generation and consumption) to participate in energy balancing and other DG related services. Duration: 2012 – 2015, closed project [100].

i-sare project: the goals of this project are to integrate effectively various kind of DER, both RES system or not, such as fuel cell, CHP, etc., and innovative storage technologies, such as super capacitors, flywheel, etc. All these technologies will be installed in a micro grid context, equipped with a proper ICT infrastructure, located in San Sebastian (Spain). Duration: 2014 – 2019, ongoing project [101].

Smart Grid Solar (SGS) project: the aims of this project is to improve the possibility of integrating RES, especially from PV system, into the distribution system. In this view, SGS focuses on developing better techniques of RES power management, in terms self-consumption or trading, and employing modern storage systems able to ease the management and consumption of the energy generated by the sun. Moreover, the smart grid context in which these services are implemented are analysed and simulated. The project performs demonstration into two test sites located near Frankfurt (Germany). Duration: 2013 – 2017, ongoing project [102].

Implementing smart ICT concepts for energy efficiency in public buildings (Smart Build) project: the targets of this project are to implement an effective smart ICT concept in different existing building located in different countries in Europe order to reach energy savings in annual and peak consumption. It is deployed by adopting an off-the-shelf ICT system, already proved and tested in energy context, for implementing smart grid paradigm. The researches address the analysis of the load features and the characteristics of the power system in accordance to the services to be implemented. The test sites are located in Germany, Italy, Slovenia and Greece. Duration: 2012 – 2015, closed project [103].

Smart Distribution System OperaTion for MAximizing the INtegration of RenewABLE Generation (SUSTAINABLE) project: the main goal of this project is to develop a cloud-based platform for allowing DSOs have the complete management of all the resources, smart metering, processing and evaluation of control criteria, setpoint decision and communication to all the actors involve, assessment of market strategies. This tasks are performed in the view of integrating distributed flexible and variable energy resources. Moreover, the project aims also at supporting the DSOs on managing the hardware infrastructure of their grids. Duration: 2013 – 2016, closed project [104].

2.5 Proposed smart grid solutions

The smart grid solutions proposed in this thesis consist in the results of the researches conducted over the last three years in two European projects in the field of energy innovation: the High-capacity hydrogen-based green-energy storage solutions for grid balancing (INGRID) project [105], funded within the 7th Framework Programme, and the Energy Local Storage Advanced system (ELSA) project [106], funded within the Horizon 2020 programme. The INGRID project ended in March 2017, whist the ELSA project is still ongoing. In both projects, the research, development and deployment activities have been focused on the realization of an ICT flexibility platform able to manage, monitor and control the energy resources installed in the demonstrator sites of the two projects. The choice of referring to these two projects has been made in order to highlight the approaches on designing an EMS in very different contexts: in the INGRID demonstrator, the EMS is in charge to monitor, optimise and control all the resources and the equipment of an industrial plant, responding to all the safety and operating constraints of the energy context, whilst the ELSA demonstrator aims at the implementation of an EMS for an urban district that has to be managed at district level for coordinating and optimising the operations in accordance with the requests of the DSO and the own control strategies of each energy unit of the district. The different levels of hierarchical control communication are managed differently and the features of the various units and, above all, of their communication system have been object of the ELSA project.

The cores of these two projects will be deeply discussed and presented in the next chapters; here, a brief description is reported.

Many different technologies of those proposed in the brief overview of this section have been adopted and successfully implemented, from the field of communication devices, to that of RESs, storages, EV programs, etc. The main feature on which these two projects relies is the provision of energy flexibility by means of the usage of storage systems installed inside the customer premises. The INGRID project employs an innovative hydrogen solid-state storage technology able to give flexibility between 400-1200 kW (by means of a Water Electrolyser (WE)) absorbing power from a Medium Voltage (MV) feeder and between 0-90 kW (by means of a Fuel Cell (FC)) injecting power to a Low Voltage (LV) line. The remaining part of the stored energy is sold to hydrogen customers or to a tailored gas market. The ELSA project exploits the availability of Li-ion battery that have been already employed for electromobility systems and considered exhausted for that purpose; this kind of technologies have been named second-life batteries. Actually, these devices can be reassembled in storage packages able to provide services that are suitable for local storage purpose in residential and low-power applications. In the ELSA demonstrator, the installed battery system reaches up to 96 kWh, ensuring 96 kW both in power absorption and injection. Such technology is employed to provide flexibility in a district consisting mostly of office buildings.

Another key technology characterizing the two projects under study is the RES system. Both the project demonstrators are located in areas characterized by a high penetration of RES system, especially PV and wind farms. In particular, the MV feeder providing the connection point to the INGRID demonstrator is subjected to a very high presence of PV plants injecting power in the MV grid, that sometimes is greater than the power requested from the loads connected to that portion of the grid, being that area a rural zone. The flexibility services provided by the INGRID plant allow the grid operator to smooth the generation profile and avoid reverse power flow phenomena. It worth noting how the INGRID plant constitutes also a DG on the LV grid, by generating power through the FC that reconverts hydrogen in electricity. In the case of the ELSA demonstrator, the RES system is part of the district itself: one of the energy resources managed and monitored by the EMS consists of two PV plants installed on the roofs of the facilities of the demonstrator. In this way, the proposed solution is able to optimise the usage of the energy generated by the PV system in accordance with the DSO requests, the power consumption of the loads and the flexibility provided by the battery system.

Also electromobility programs are addressed by these two projects, not only in the deployment of the EV facilities, but also dealing with the flexibility that the load absorption of EVs recharge can provide to the energy management of the demonstrator itself. In the INGRID system, the envisioned scenario foresees the supply of EVs by means of the power generated by the FC, handling charging requests by managing power and hydrogen flows. In the ELSA project, the electromobility program is managed throughout the process, from the booking system of the EVs recharging service of each car, passing through the power profile assessment and optimisation, up to the negotiation of the most suitable operational configuration to be implemented.

The EMSs developed for the two projects above discussed employ many ICT technologies integrated in a unique solution deployed in the real test sites. Firstly, all the computational and optimisation aspects have been dealt within MATLAB® [107] environment, by means of scripts and algorithm implementation developed on purpose. Subsequently, the main software environment employed is Java, through which the optimisation components have been exported and integrated, along with all the libraries for exchanging data with the other components of the architectures. The key components are indeed represented by the SCADA system for data monitoring and HMI representation, the data bases for data storage and backup, application server for running all the server-based and client-based application of the software solution, Representational State Transfer (REST) services for accessing the architecture from various point, the Open Platform Communication (OPC) [108] sever for exchanging data with the field equipment and the control components, the node.js platform for allowing the data exchange between the components of the architectures, and others that will be deeply explained and discussed in the dedicated sections of this thesis. Last but not least, a focus on the main protocols employed for the high level communication between the actors of the two systems proposed is provided: in the INGRID demonstrator, the interacting devices are industrial components, so the OPC protocol has been employed for allowing field communication between all of them, the SCADA, and the control system; in the case of the ELSA demonstrator, the communication process has been implemented by means of the OpenADR [109] standard, creating Virtual Top Nodes (VTNs), Virtual End Nodes (VENs), and the necessary communication infrastructure for ensuring the proposed information exchange between all the actors. In Figure 10 and Figure 11, the ITC architecture for the proposed solutions are shown.

Finally, in the two projects a similar approach has been chosen to implement the smart management solution. In both cases, a centralised management system has been developed, able to collect information regarding service requests, forecasted power profiles, operational conditions and constraints, flexibility availability, etc., for all the energy resources present in the energy context under management. This information is then used for performing the optimisation process: the framework adopted for the EMS under study is a multi-objective optimisation that allows to take into consideration many aspects of the system management, such as technical aspects, environmental one, economic one, operational one, and to address them simultaneously in the research of a set of optimal solutions. The developed algorithm is a genetic one [110] [111], from the class of evolutionary algorithm, and has been developed in MATLAB® environment. After the optimisation process is ended and the solution is chosen, also through a tailored Decision Support System (DSS), the optimal configuration is sent to the controlled devices and made effective. It could be possible, before the implementation of this last stage, the invocation of a negotiation process for rediscussing availability provision with the energy units involved.

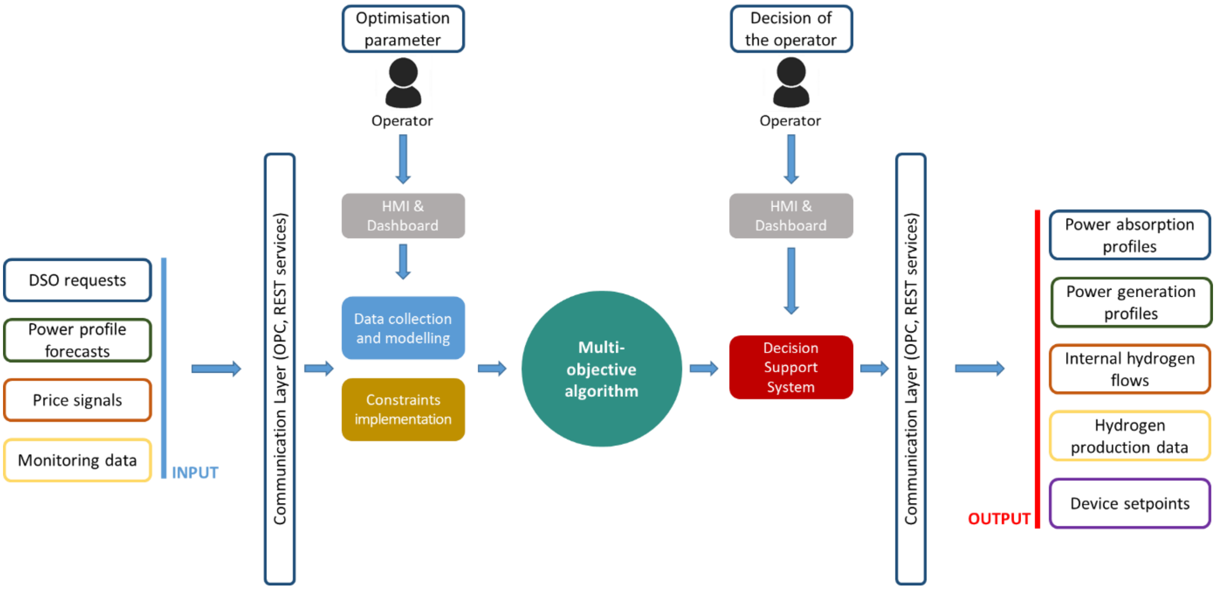


Figure 10 – Proposed architecture for the INGRID project.

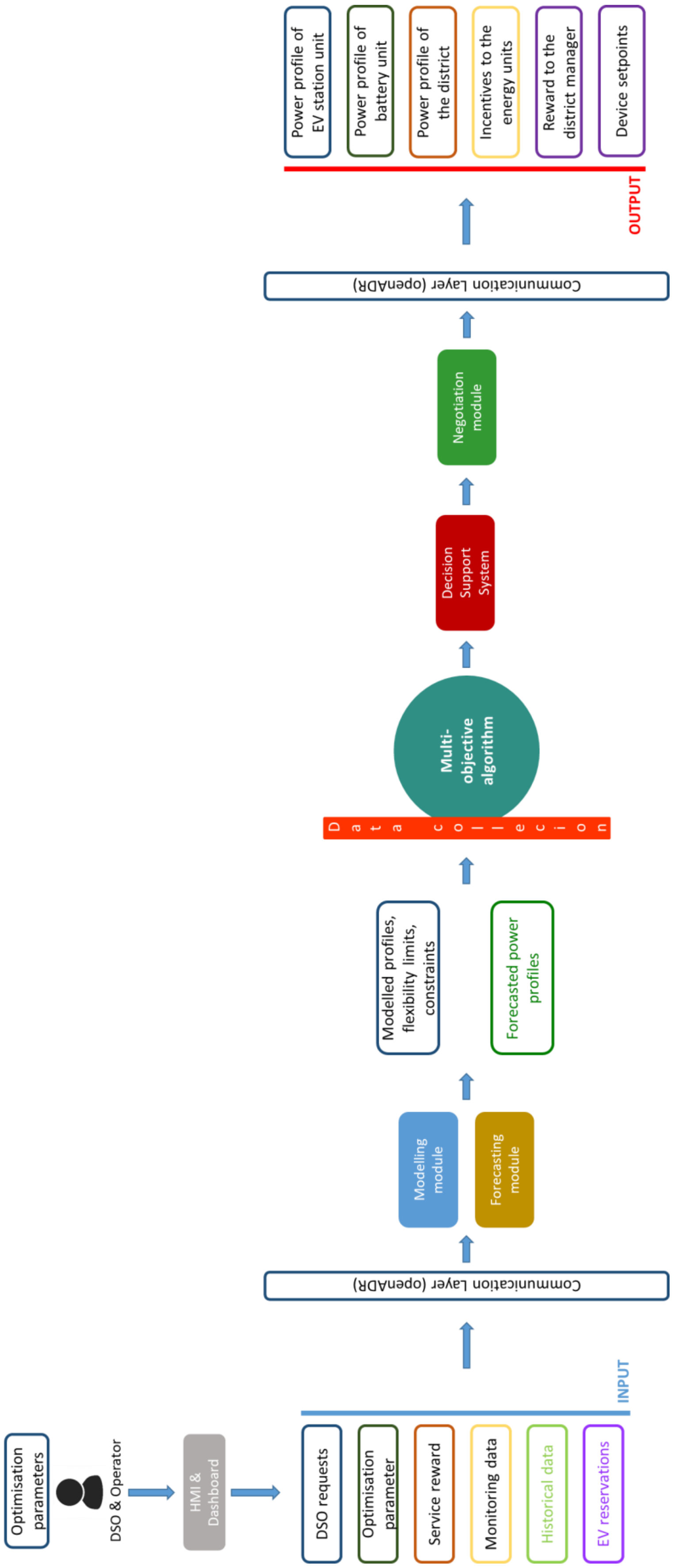


Figure 11 – Proposed architecture for the ELSA project.

Chapter 3

Smart flexibility in modern power systems

3. Smart flexibility in modern power systems

This chapter aims at assessing the exploitation of power flexibility in the context of smart power grids and its management. Firstly, a definition of the concept of flexibility is provided, along with an overview of the rationale and the causes of the rising of such services. There are many aspects and many stakeholders of the power system that are involved in the provision, employment, and exchange of flexibility. In this section, a comprehensive description of the need of flexibility services, the stakeholders able to provide them, and the market as well as economic values linked to the flexibility exchange are given. Moreover, the topics of policy and regulatory framework linked to the flexibility opportunities and exploitation are discussed.

In the second part of this chapter, flexibility platforms and the possibility of structuring them inside an EMS framework are analysed and detailed. The targets of an EMS in a context where different energy resources can provide flexibility are the drivers for the design of such a management tool, since many technical, economic, operational, and/or environmental topics can be addressed in the energy flexibility context, also in accordance with the actors involved. After that, the technological solutions concerned in the flexibility platform realisation are addressed, in terms of ICT architectures, control strategies, and communication means.

In the last part of this chapter, the optimisation approach for the management of the energy flexibility is described. After having provided the main reasons for the adoption of the appointed optimisation algorithms based on the mathematical formulation of the optimisation problem itself, the main solutions and management approaches are highlighted, along with a brief summary of the most common algorithms employed within the research in this field. Subsequently, the attention is focused on the heuristic methods, in particular those implementing evolutionary approaches. This choice has been done for explaining the features of the solutions presented in the next chapters; as such, the genetic algorithms (in particular the Non-Dominated Genetic Algorithm II) and the multi-objective approach are widely discussed.

3.1 Flexibility in smart grid contexts

The possibility of exploiting flexible energy resources is strongly leveraging the implementation of smartness in modern power grids and represents one of the most impacting services in terms of stakeholders, since the flexibility involves both generation and consumption stakeholders, as well as grid operators, BRPs, markets, etc. Many international regulatory and research entities, among the most relevant in this field [112] [113], have provided a definition for flexibility, which is reported here: “On an individual level, flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterise flexibility include the amount of power modulation, the duration, the rate of change, the response time, the location, etc.”.

The great changes under which the power system is going are reducing the flexibility of the systems itself and of the devices interacting with them. Since the key actions of system management have been assigned to large stakeholders so far, the management of flexible actions was coordinated centrally and was supported by a clear knowledge of the flexibility capabilities of the network, for instance the large traditional power plants in managing their ramping up and/or down capabilities.

Today, the features of the changing trends of the power system led to many uncertainties, especially because of the physical distribution of the energy resources over the geographic extension of the modern power systems, especially distribution ones, and the great diffusion of RES generation systems. The great amount of DERs, besides being a great opportunity for reshaping and modernising the grid, represents also a challenge in coordinating these resources and integrating them in safe grid operations. This concerns technical aspects such as voltage and frequency regulation, fault protection, demand-supply balancing, etc.

The possibility of coordinating and collecting flexibility in a smarter way relies upon the advantages that the DERs can provide to the grid in terms of control of their flexibility provision and exploitation, as well as aggregating their capacities. As the RESs are concerned, it is clear how the great penetration of RESs powered by the sun or the wind are characterized by partial unpredictability and poor flexibility as well as control capabilities [114]. In this view, the system loses a lot of its flexibility that has to be provided from other sources. In these cases, the struggle for enabling flexibility from other actors that can cope with the uncertain nature of the natural resources is crucial. This can be shaped in many energy applications, such as energy storage coupled with RES generation plants or DR and DSM programs.

It is clear how the exploitation of flexibility requires not only the availability of an energy resource but also its coordination and control for providing a flexibility service. In this view, the smartness of the modern power system paradigm helps to set-up an effective infrastructure able to allow the data monitoring and sensing, the data communication between all the actors involved, as well as the implementation of a control criteria. The ICT tool of a smart grid and the features of an EMS designed for handling flexibility requests and provisions as a tailored services for markets, grid operators, etc. represent the key enabling technologies for creating a framework in which flexibility platforms can help on managing many aspects on grid operations.

The users, seen as final consumers of energy, hold a decisive role in creating such a framework. As mentioned above, besides the generation stakeholders, many of the flexibility action are performed by the final users of the system, by changing their energy behaviour, modifying their consumption patterns, accepting to change their comfort perception, etc. The engagement and the awareness of the final user in putting in place such actions, sustaining all the economic and financial efforts derived from them, can be one of the most significant aspect of the success of such flexibility initiative.

3.1.1 Flexibility providers and flexibility typologies

As mentioned in the definition of the flexibility concept, a flexibility action can be performed by modifying energy absorption and/or injection patterns. Many stakeholders can provide this kind of operation using the features of their internal processes [115]. In this section, the different flexibility proposals are examined, assessing the different kinds of stakeholders providing flexibility and the features of the provided flexibility services [116].

3.1.1.1 Stakeholders providing flexibility

Generation: the generation facilities are fully involved in the provision of flexibility to the grid. Actually, supply-side flexibility has been always employed for balancing purposes in the traditional grid operations. Today, many other generation stakeholders are involved in this process and their contribution on flexibility is really effective [117]. As traditional power plants are concerned [118], the plants able to perform load following operations; for instance, Combined-Cycle Gas Turbines (CCGT), that is characterised by a high ramping rate, can afford many balancing tasks inside modern grid management, especially regarding highly fluctuating RES integration.

When DG is taken in to account [119], the possibility of controlling and managing locally these generation facilities gives great impact to supply-side flexibility provision on distribution system. Typical DG devices able to change their generation behaviour are Combined Heat and Power (CHP) plants, running simultaneously the generation of the two involved energy carriers for modifying their injection patterns. Moreover, the possibility of coupling them with both electric and thermal storages confers them more and more chances and complex scenarios for providing flexibility to the grid.

Another aspects to be addressed in the field of flexible generation is the curtailment of energy generation of those resources that are not controllable, such as many RES generation systems [120]. This technique refers to the operation of cutting down the power injection of a generator in case of significant unbalances or grid technical issues. Despite of this practice is common for the most spread RES systems, such as PV and wind plants, it is preferable to refer to other forms of flexibility, firstly because the curtailment means a direct loss of available green energy, secondly because it represents another cost for grid operator or BRPs that are committed to pay a reward to the plant owner that justifies the missed energy sale.

Storage: energy storage systems have always played a key role in the usage of electricity, but the deployment of such a system has never been consolidated due to many technical issues linked to storage operation. Today, the research on storage field is gaining more and more concreteness because of great advancements in the technologies of storage devices and, above all, thanks to the various applications in which storage systems have a significant role in providing smart services. Actually, storages offer the possibility of decoupling supply and demand, acting as a buffer between these two phases. This allows managing properly the energy resources in the view of implementing smart services to the grid or performing energy arbitrage, buying, consuming, and selling electricity in accordance to the varying market prices or to the requested injection/absorption services rewarding.

As reported in section 2.1.2, today, the most spread storage solutions employed in power systems are pumped hydro, compressed air energy storage, hydrogen storage, batteries, flywheels, superconducting magnets, and supercapacitors. These technologies are listed in such order for highlighting the time-scale of the services that they can provide: whist the features of pumped hydro, compressed air energy storage, and hydrogen storage are characterized by high energy storage and high time-scale, flywheels, superconducting magnets, and supercapacitors represents the fastest solutions for grid regulation services. Electric storage through batteries has hybrid behaviours, depending from the adopted equipment, consisting in a bridging technology in accordance with the application to be implemented. In Figure 12, a graphic representation of time-scale and energy availability for each technology is shown.

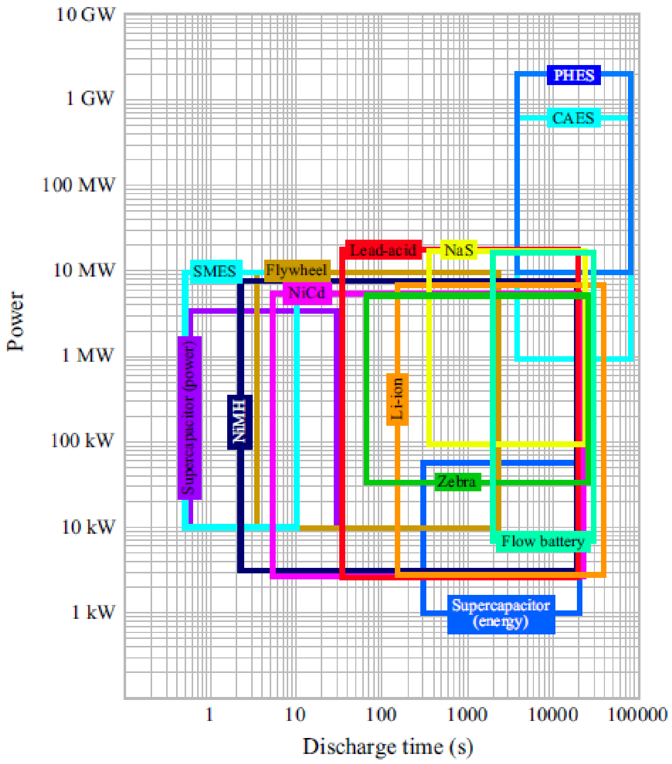


Figure 12 – Comparison of time versus power availability of the considered storage technologies.

Loads: the flexible energy behaviour achieved from power consumption is likely the most important aspect of the flexibility assessment of modern researches in this field. As matter of fact, an aware and conscious engagement from the final user of the energy resources is the key enabler for the most relevant implementation of flexibility and, in a wider view, of smart grid actions. The relevance of DR and DSM programmes is clear and attracts the attention of almost all the initiatives in the field of energy efficiency.

As widely addressed by the researches of the last decade of 20th century [121], loads can perform a wide range of actions to reshape their consumption profile [122]: load shifting, load shaving, consumption reduction, valley filling, etc. This can be achieved by a great penetration of both suitable technological equipment and awareness on customer side; its engagement, on both installing the required smart appliances and modifying its load consumption, is maybe the most important leverage for the effective implementation of many of the proposed scenarios.

Firstly, a classification based on the characteristic of the load is provided [123]. There are four main classes of loads that can provide flexibility: (i) optional loads, consisting in that load whose power absorption can be controlled in a range of fixed values from the maximum to the minimum one; (ii) deferrable loads, which power consumption depends on the users' decision of turning them on or not; (iii) controllable loads, that are totally manageable in accordance to users' choice or service request form the outside; (iv) storage loads, consisting in the possibility of exploiting storage capability as a load when needed of requested.

After this first classification, the main energy contexts in which users are requested to modify their load pattern can be used as a second criterion for evaluating the flexibility of this kind of actors. As the residential users are concerned [124], the home appliances and equipment are various and are characterized by very different load behaviour; most of them can be optional or deferrable loads, in accordance to the availability of the residents to adapt their load consumption. The offices and the workplaces have been often take as reference for the implementation of smart energy usage; they make use of massive optional and controllable loads and, above all, they are very often managed centrally. So the power absorption can be optimised and/or can respond to external signals. Industrial contexts have been the first facilities in which the most important programmes on energy efficiency and DSM have been implemented. Actually, most of the industry and factory have machineries whose processes are managed by tailored operational scheduling [125], that can be modified on purpose in order to meet technical request, which are very often rewarded inside a DSM or DR programme. These loads belongs approximatively to all the four classes listed above, so the industrial facilities can provide large amount flexibility, even if with high time-scale and in balancing transmission grid operation.

An emerging field that shows great chances of becoming a key player in flexibility field is the EVs programmes and their effects to the distribution grid [126]. Firstly, it has to be noticed that the diffusion of EVs all over the world, and the need of tailored recharging station, is a great infrastructural challenge for grid operators, because the need of charging point, both public/pooled or private, is increasing every year. At the same time, the recharge of these systems offers great opportunities of flexibility, as widely shown in the following chapters. Actually, taking into account the need and the satisfaction of the customer, that can be considered as constraints, there is very large flexibility on scheduling and planning the recharge of a fleet of EVs in accordance to several signals, technical and/or economical coming from other actors of the energy system.

Grids: the grids and their operators have a minor involvement in the provision of flexibility. In any case, some actions could be performed in order to change the status of the network and support the exploitation of smart operations. This is the case of improving the interconnection with the other grid for allowing a wide participation to the market places, allowing a more competitive energy trading. Secondly, if there are not technical constraints or security issues, the grid operator can increase the power exchange by uprating the power capability of sectors of the network under its management. Moreover, the flexibility capability can be enhanced by installing power flow control devices (like phase shifting transformers or FACTS devices) [127].

3.1.1.2 Typologies and features of flexibility

The aspects concerning the different typologies of flexibility as well as the quantitative and qualitative features of its provision have been addressed by many studies and reports by regulatory bodies. Here are summarized the main categorization adopted in the literature.

Firstly, the most referenced categories relies upon temporal classification of the response in providing the flexibility service [127] [128]:

- Regulation (real-time flexibility, up to seconds): it refers to the provision of services characterised by very high dynamics and need of fast response, such as voltage and frequency regulation. Usually, traditional power plants face by themselves these issues. Today, this kind of flexibility can be provided by the fastest storage technologies, for instance batteries or flywheels, or by tailored generation system exploiting their spinning reserves.
- Load following (short term flexibility, from minutes to hours): this kind of flexibility addresses the supply-demand balances by following the variation of loads behaviours, managed in relatively short timescale. The major source of this kind of flexibility are traditional plants and micro-CHP systems for short term response; another supply-side solution could be found in active power control of RES systems. DR can provide an effective flexible response accompanied by a proper ICT infrastructure for managing the coordination and the delivery of these actions, involving both loads and EVs. Moreover, storages can cope with load following; in particular, batteries offer the best features.
- Unit commitment (mid-term flexibility, from hours to days): the services in this category are aimed at evaluating the operational availability of the production units over days and their effects and movements on energy markets. The generation facilities able to provide such a service are gas and internal combustion engine plants; even CHP systems can provide them if properly managed. Anyway, in the smart flexibility context, the appointed sources of flexibility are the load shifting of both

industrial of small-scale users, if properly aggregated, and storage systems, as large scale battery installations.

- Seasonal variations (long term flexibility, from months to a year): the provision of this kind of flexibility is not common and is still under investigation, due to the lack of proper technologies and of a business framework for giving them a proper value. Seasonal variation can be addressed in order to shift the availability of huge amount of energy from a part of the year to another one; the appointed technology for these applications is power to gas, which reconvert the available energy in fuels to be reused for energy transformations, even though is characterized by very low round-trip efficiency. Power to gas technology is considered by many studies as an innovative storage solution.

After having described the main categories in which the provision of flexibility can be classified and assessed, the key features of the flexibility itself are provided [118].

Magnitude: it refers to the amount of flexibility that can be provided, both in term of energy or power according to its typology, and to the direction of this action, thus augmenting or increasing power/energy injection or absorption.

Ramp response: it quantifies the ramp of the flexibility provision in terms of time elapsed between the signal of request and the full availability of that flexibility resources. It has to be accurately matched with the services provided by the source for ensuring a correct response. Another key aspect of these features is the ability to respond to events that have been forecasted or not, since the ramp response can by different in these two cases.

Frequency: this feature addresses the number of events per unit of time that a flexibility source can afford with the same rated features of magnitude and ramp response. The frequency of flexibility interventions can affect significantly the performance of the service provision.

Available flexible resources: it reflects the availability of the deployed flexibility source in providing different features in accordance to the requests received. This is achieved by enriching the deployed solution with different flexibility technologies that can be installed and managed in a unique solution.

Besides distinguishing between time and energy flexibility provision, many other categories and features can be derived and referred by combining the above mentioned elements, in order to create a flexibility source that matches in a closer way the operational requests [129].

A careful analysis of both available flexibility typologies and their features allows choosing and implementing the proper and most effective technology in accordance to the energy context under study. Beside of this overview, many researches are improving technological features and are studying for innovative services, so this framework is arguably going under some changes in the next few years.

Figure 13 recaps in a unique graphic representation the aspects addressed in this section: all the outlined flexibility sources interacting in modern power systems are reported along with their most employed technologies and they are furthermore structured in order to give a general view of the typology of flexibility they can provide.

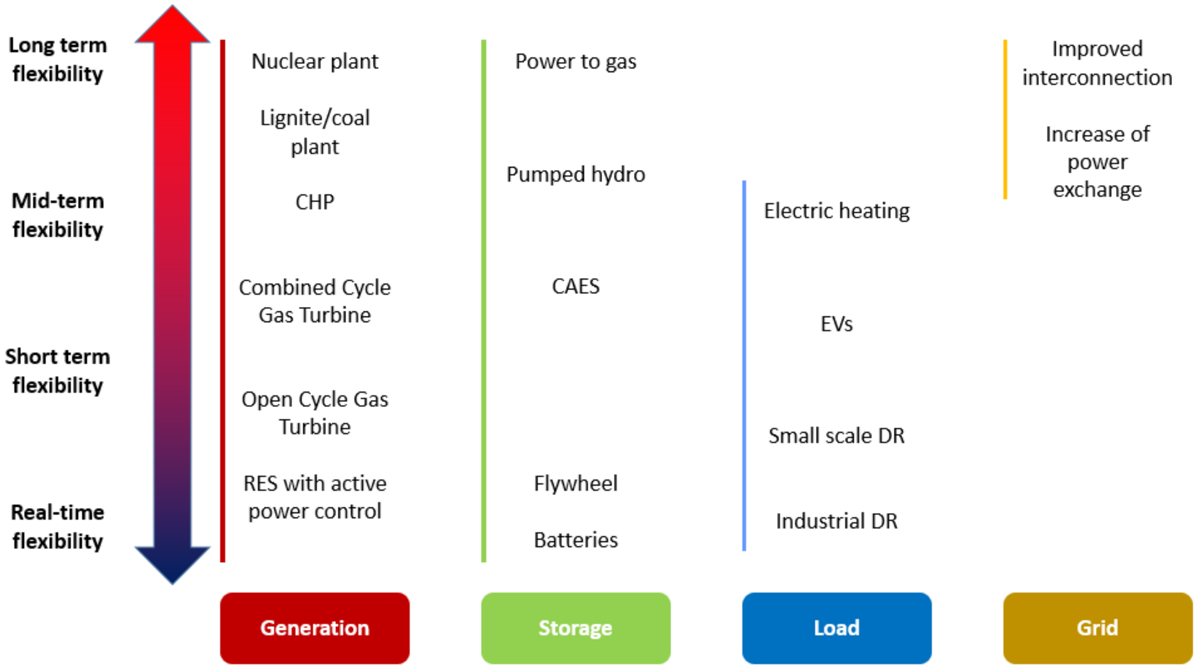


Figure 13 – Sources of energy flexibility in modern power systems and their common used technologies in comparison with the flexibility categories depicted.

3.1.2 Flexibility users and benefits

In this section, the services entailed by the provision of flexibility are presented and explained, along with their main users/recipients and the benefits achieved from them. Moreover, the main reference strategies for the management and the exploitation of these services are mentioned and reported too.

3.1.2.1 Stakeholders exploiting flexibility

The key stakeholders of modern grids requesting for flexibility services are BRPs, TSOs and DSOs.

BRPs: as briefly presented in 2.2.3, the BRPs are central in the usage of flexibility, since all the balance responsibilities of small users, residential, small and medium enterprises, offices, etc., and of aggregated clusters of energy units are committed to the BRP (through the trading activity of the users' suppliers). Thus they have to fulfil all the unbalance activities and provide all the necessary flexibility for addressing them. In the contexts of portfolio optimisation tasks, the BRPs have to perform short term planning; the principal envisioned source in this field can be the flexibility.

The main actions required by a BRP are the adjustments of power demand and/or injection. As a matter of fact, the portfolio optimisation needs both user demand management, mainly in reducing power consumption, and generation control, especially in contexts of high RESs penetration. In this case, BRPs have to ensure an adequate generation capacity in terms flexibility and its dynamic exploitation.

TSOs: the operators of the transmission grid make real use of the energy resources under their control for handling very relevant grid services to the entire power system.

One of the most important services is the control of frequency: as known, this control is performed by managing very rapidly the unbalance variations between demand and supply. In this view, TSOs exploit the flexibility provided by the fastest actions from generation facilities, storage systems and DR actions.

The other control service carried out by TSOs concerns reactive power provision for the management of voltage profiles over the network infrastructure. For this purpose, flexibility from traditional generation facilities are mainly employed, even though many power electronic applications have shown the possibility of supplying reactive power also from RES, for instance from wind turbines, and storage units.

The other commitments of TSOs regarding flexibility concern the congestions of the grid devices, and the grid loss reduction. Actually, the possibility of reducing power consumption for the former case and the possibility of using power generated locally, for the latter one, address both of these grid issues.

DSOs: the owner and manager of distribution grid can gain many advantages from the provision of flexibility services because most of the flexibility providers are directly connected to the distribution grid.

Firstly, DSOs have to ensure the grid connection to all users that make request for it. Exploiting flexibility capabilities of both generation, load and storage devices, stand-alone operations can be deployed, avoiding to incur in very high grid investments. Moreover, in this view, the possibility of varying and managing both power injection and demand could smooth the power flow in entire distribution grid areas, where reinforcement actions are strongly required. Exploiting flexibility can lead to defer great financial efforts for modifying the network infrastructure.

DSOs are also in charge of voltage control; this task has become more and more complicated to be performed due to the great amount of DG units connected to MV and LV feeders. The possibility of regulating both demand and supply provide DSOs with effective tools for ensuring high power quality level to the final user. The same approach can be used for addressing reverse power flow phenomena: the high amount of uncontrollable and unpredictable generation from RES units causes power flows going from the distribution network towards transmission systems, implying several issues in balancing and operating the grids (protection devices, transformers, etc.). The flexibility provided at distribution level, for instance by storage systems, allows to avoid these phenomena, as widely shown and proved in this thesis.

Table 1 [113] shows the direct links between the stakeholders providing flexibility and the ones exploiting it, accompanied by the services and the functions that has to be performed for implementing the flexibility actions.

Table 1 – Links between flexibility providers and flexibility users detailed with services and grid functions implemented.

Service that can be provided	**System user providing this service**	**Function that this service can fulfil**	**Flexibility user requiring this service**
Peak shifting	Aggregated (or individual) industrial and commercial users Aggregated domestic customers	Long term congestion management. Portfolio optimization Generation capacity adequacy	DSO BRP TSO
Demand adjustments – manually/automatically	Aggregated (or individual) industrial and commercial users Aggregated domestic customers	Short term congestion management Portfolio optimization Generation capacity adequacy	DSO BRP TSO
Frequency balancing services	Aggregated or individual industrial and commercial users Aggregated distributed generation	Frequency control	TSO
Generation adjustments	(Aggregated) distributed generation	Short term congestion management Grid losses reduction	DSO TSO
Curtailment products	(Aggregated) distributed generation	Short term congestion management	DSO TSO

	(Aggregated) industrial and commercial users Aggregated domestic customers		
Reactive power (mandatory)	(Aggregated) distributed generation	Voltage control DSO	TSO

3.1.2.2 Benefits and values of flexibility

Many benefits rise from the flexibility services employment among the modern power system actors [113] [123] [112] and they are related to many aspects of the energy production, distribution and utilisation chain. Here, these benefits are categorized in four main classes.

Supply and demand balancing: as mentioned previously in this section, one of the most effective contributions of flexibility services relies upon the improvement of balancing operations. As a matter of fact, the availability of these services enlarges the BRPs solutions for portfolio optimisation, in order to avoid the purchase of unbalance supply from very volatile markets. Moreover, the investments for installing and operating generation systems able to cope with the unbalances is significantly reduced.

Grid operation: from the grid infrastructure point of view, the advantages brought by the flexibility services are numerous. Firstly, the possibility of modifying the load patterns and the power flows of the grid devices allows the grid operator to defer the most impacting grid reinforcement actions, as the installation of peak power plant, being able to cope with the peak needs by means of flexibility services; this entails the temporary delay of grid investments. The availability of these services affects significantly also the operation of the grid itself: flexibility can be requested for avoiding power generation curtailment of exceeding RES systems, can prevent many fault conditions and, above all, can be employed largely for the provision of grid ancillary services. Moreover, the flexibility employed by energy resource can lead to a relevant reduction of grid losses for transmission and distribution by encouraging and optimising the local supply from the great diffused DER systems. In an advanced scenario of grid collaboration among the interconnected countries, the flexibility can be effectively used in cross-board balancing services.

User engagement: the users are strongly encouraged and supported by many initiatives aimed at increasing their incomings or reducing their energy bills. Firstly, the user participating in a flexibility program, like a DR one, are often rewarded, as a financial compensation, for the availability on modifying their consumption habits and arguably their comfort; this payment is made by grid operators or intermediate actors, such as aggregators. Users can gain economic benefits also by reducing their energy bill: the adoption of real-time pricing of time-of-use tariffs allows them to manage their power consumption in order to allocate it in the cheaper time zones. Moreover, they can benefit indirectly from grid performance improvement, by the reduction of grid charge in energy bills.

<u>Emissions</u>: the flexibility provision allows the reduction of polluting emissions on the environment by helping on decarbonising the power system. Actually, the possibility of employing flexibility by many actors led to the displacing of high-polluting peak load generation system, as those for the provision of ancillary services. Furthermore, many flexibility services allow the integration of higher number of RES systems, augmenting the share of green energy.

<u>Innovation</u>: since a great amount of studies have highlighted and envisioned the relevant chances of improving many aspects of power systems through the implementation of flexibility services, an enormous boost on innovation in many technological areas has occurred in the last decades. In this view, many ICT solutions and services have been proposed and studied, and all the results achieved by these works have enlarge the knowledge on the performance of these systems. Besides the technological aspect, many projects have created effective demonstration test benches for deploying and proving the effectiveness of the flexibility provision. In this thesis, two of these innovation actions are discussed and their results are shown.

As clearly outlined through this section, the exploitation of flexibility services is strictly linked to economic values given by the stakeholders involved in the energy exchange, that are committed in creating tailored business models. In the next sections, the impacts on market dynamics will be discussed.

3.1.2.3 Strategies for flexibility management

The complexity of the context in which flexibility services can be employed and of their features can be an effective obstacle for the management of a smart grid implementing flexibility resources. As such, it is clear the importance of arranging a strategy aimed at allowing a seamless integration of flexibility providers in smart grid environment and the aware acceptance by flexibility users. Three steps for facing the management of the flexibility resources are proposed:

1) Integration to the existing energy context: the first aspect to be addressed is the study of the energy environment in which the flexibility solution is going to be deployed. As mentioned in the previous sections, the main features of the flexibility source, in terms of time scale and magnitude of the services provided, have to be matched with

the requests of the existing energy units, in order to provide the most effective services. In this view, another relevant aspect to be taken into account is the analysis of energy issues occurring in that context, such as load congestion, RES curtailment, etc., in order to detail the requirements of the system [130]. After that, the integration with the installed ICT tools of the energy units is necessary, in order to exploit as better as possible the existing technologies, such as forecasting tools and state estimators, and choose compliant equipment and communication means. Moreover, a key aspect of this phase is the evaluation of the flexibility that can be provided by the other energy units and the perspective users that will exploit the provided flexibility services.

2) Market and business opportunities analysis: in this phase, the opportunities of giving an economic value to the provided flexibility services are addressed [131]. As highlighted above, there are many source of revenues when implementing such services. In this view, the stakeholders that set-up the business models upon this flexibility have to be evaluated. Firstly, the opportunity of participating to a flexibility market [122] has to be investigated; as such, the solution offered by retail energy suppliers, in terms of tariffs and rewards, are key topics. Moreover, also the presence of energy resources aggregator can be of great interest, as the possibility of creating an aggregation solution *ex novo*. After that, the possibility of gaining incentives for green energy actions or grid supporting ones has to be examined in order to evaluate the sustainability of the proposed flexibility solution and its best business model.
3) Operational assessment: the operational features of the flexibility to be implemented are essential to shape correctly the provided services [126]. In accordance to the features of the service itself, its operations are designed to cover all the stages of energy flexibility management: planning, performed offline in order to evaluate approximatively the availability of the energy resource interacting with the flexibility source; scheduling, performed online aiming at coupling the provision of the flexibility service with the actual energy configuration of the systems; real-time operation, regarding the execution itself in terms of sending and making operative the optimal setpoints evaluated at scheduling-time; settlement, performed offline for storing and analysing the electrical and economic data related to the executed operations. All the data exchange has to be properly tailored for each stage with the correct stakeholder.

3.1.3 Aggregation

The concept of energy resource aggregator has been appointed many times through this thesis. In this section, a formal definition is formulated and an overview of its features, as well as of its main functionalities in relation to the services that it can provide is given.

The aggregator is defined as an entity in charge of collecting and pooling the flexibility resources that can be provided by a large number of individual customers, both in generation or consumption field, in order to achieve as much relevance to be offered to several energy contexts or flexibility stakeholders, that otherwise could not be reachable by the single user [132] [112]. An aggregator can be also a retailer as well as a public or private third party. It acts as an intermediary between the customers providing flexibility and the flexibility procurers, managing the flexibility aggregation and the creation of tailored flexibility products to the procurers.

This entity is a very relevant boost in energy contexts, giving chances and weight to the customers that, even if interested in contributing in energy management operations, would not be able to bring enough energy services, in terms of power and/or energy, to be relevant in modern energy contexts. Moreover, the aggregator plays a key role in forming the flexibility resource: all the small flexibility contributions by highly decentralized energy units has to be coordinated in a proper way in order to provide an effective flexibility service, in terms of grid impact but also in terms of economic value.

In this view, the main classification of the aggregator activities are based upon its technical or economical nature.

The concept of technical aggregation [132] relies upon the provision of flexibility seen as grid service to the systems operator. Actually, both generation and demand sides can give a serious contribution on coping with congestions, fault restoration, voltage regulation, etc., providing the short term flexibility services discussed above. The role of technical aggregator, collaborating and exchanging information with the DSOs and TSOs about the network status, contingencies, and topologies, can provide tailored services for restoring grid operations.

The commercial aggregation [133] [134] is instead based on creating a business value to the flexibility provision, that can be achieved in many contexts, such as ancillary services markets, balancing markets, etc. In this view, the aggregator acts as a market operator making bids and offers into the market places, being in contact with suppliers and intermediating their operations (the role of the aggregator can be also played by a supplier itself). They interact also with the

BRPs for the trading of the services to which a proper business value has been assigned. The markets dynamics in flexibility field will be explored in depth in the next sections.

In Figure 14 [133], a representation of relations among the actors dealing with an aggregator is provided. The diagram a) shows the connections between the aggregator represented by a BRP or a supplier and the other stakeholders involved whilst, in the b) diagram, the same connections are reported for an aggregator operated by a third party.

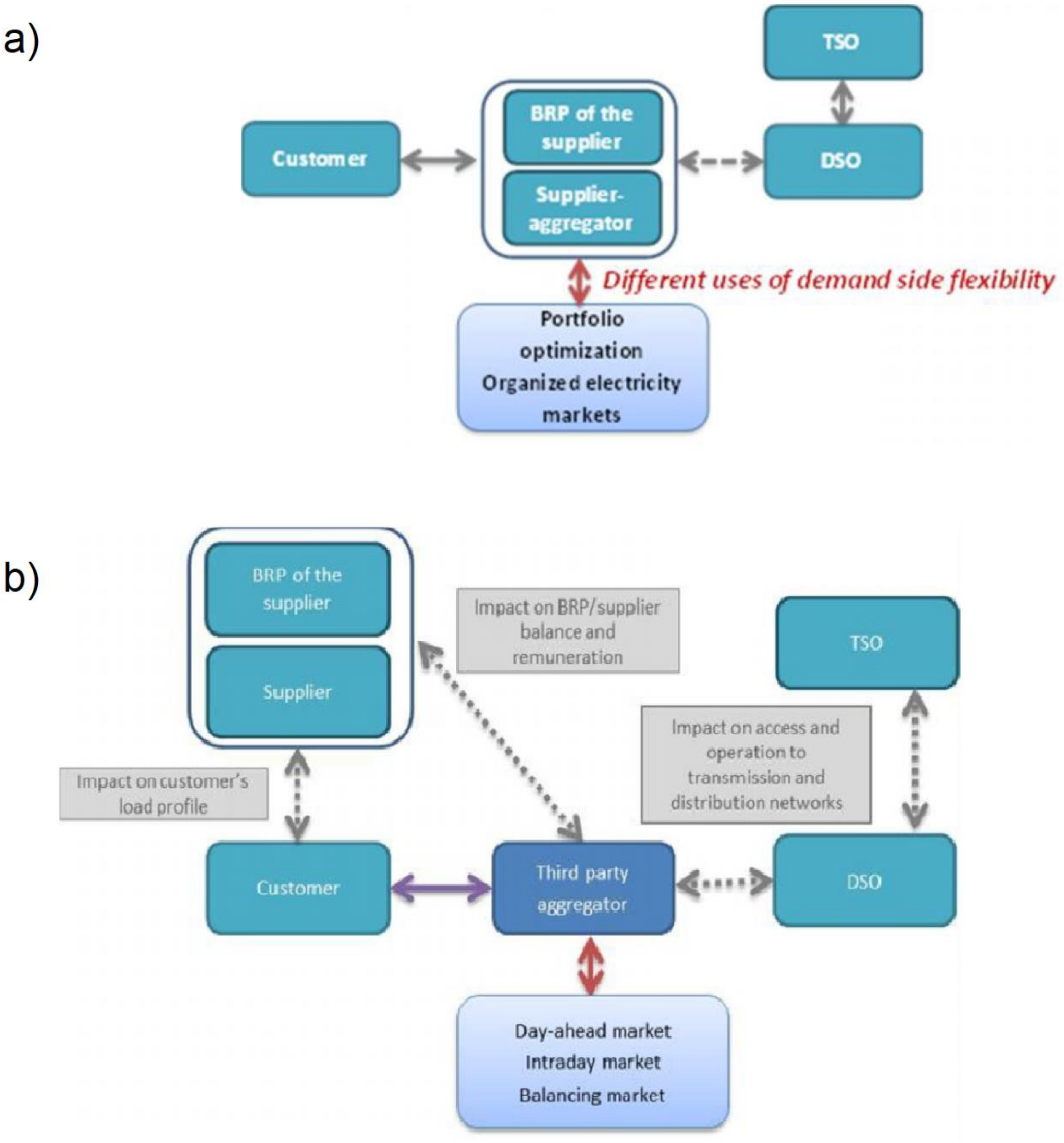


Figure 14 – Relations among the actors dealing with an aggregator consisting in a BRP/supplier (a) or a third party (b).

3.1.4 Flexibility markets

One of the most attractive and perspective exploitation of flexibility services is the trading of such products into energy market places. As mentioned many times, the benefits brought by the implementation of flexibility are several and can be seen in many fields; the possibility of attributing them a business value and purchase/sell them in tailored, even though visionary, markets or in the existing ones is clear. In order to create such a market framework, many efforts have to be performed and many changes have to take place. Firstly, a mechanism able to reward properly these services as the same quantity of power/energy provided in any markets context has to be structured, taking into account different prices and/or rewarding mechanisms in accordance to the different flexibility features of the services provided. Secondly, the grid operators have to foresee and design new practices, operations and technological solutions for incorporating the flexibility resources and enable their access to the market places. Thirdly, the entities in charge of defining the legal and contractual aspects of flexibility provision and relationships between the parties have to create a proper regulatory framework to ease the exchange and the trading of flexibility products [135].

In this view, the access to the markets has to be guaranteed to all the flexibility providers, both as single customers or mediated by a supplier as well as an aggregator. Not only the flexibility providers has to be recognised and provided with the suitable means to participate to the market operations, but they have to be put at the same level of all the other actors, giving them the same relevance and the same economic reward to the product they trade. This is even more true in the case of flexibility provided from demand side: the flexibility procedures from supply side are known and well established so the smart DG systems are in some way facilitated in their recognition; the customers flexibility actions are new in these contexts so there are still some obstacles in viewing them as an effective flexibility resources. This change has to be accompanied by a strong policy action, in order to allow a regulated access to the market places. In this view, all the European countries are driven by many reference such as the Third Energy Package [66], the Energy Efficiency Directives [136], and the Network Codes [113] [132].

Another topic related to the access to the markets is the easiness and clarity of the procedures to be accomplished for entering in such trading. Both users and aggregators should have direct access to detailed energy bills, tailored educational programs, interoperability of their systems and easiness in controlling them. Moreover, they should be always able to monitor accurately data about power flows and related tariffs, and, above all, the cyber security and the possession of these data has to be ensured. Also the contracts arranged and signed by the involved parties have to be clear, simple and have to explicitly mention all the responsibilities and risks from all sides [137]. As the contracts are concerned, great attention from policy entities has to be spent on them: due to the high number of entities involved and of economic exchanges between them, there is the risks of conflicting agreements; for instance the same flexibility resource sold to two different entities. In order to avoid this, a strong and transparent regulatory framework has to be set up.

In this section, the role of aggregator is mentioned as a key role for enabling markets possibilities [123] [138]. Firstly, many of the small-scale resources gathered by the aggregators could not be able to participate to any markets if not properly managed and intermediated by these figures; this aspect is relevant because most of the market features to be addressed in smart grid contexts are due to the presence of the flexibility of these actors, especially from demand side, that until the last years were not able to participate actively in the energy management process. The importance of an aggregator and its role as key actor has to be highlighted also for fostering the proper legal recognition from all the stakeholders of the energy market, by providing the flexibility market with all the means of a typical one. The aggregator allows also to integrate the small-scale innovative technology representing emerging stakeholders of the smart grid, such as DGs, EVs facilities, and local storages that until now cannot participate to the markets [117].

The BRPs are required to pay a great attention on managing the flexibility transactions [113] [133]. In order to ensure consistency of imbalance settlement and grid management, the BRPs has to be provided with accurate data for evaluating the actors that caused the unbalance itself. A great contribution is given also by the grid operator: TSOs are neutral markets facilitators, in charge of managing in the most transparent way the provision and the trade of flexibility; DSOs are involved in the technological smart shift of all the grid equipment that enables flexibility participation to the markets and, above all, have to be provided with a comprehensive view of the status of the network in order to assess if the flexibility trades are in conflict with secure grid operations. In Figure 15 [113], a representation of the possible relations among the actors in smart flexibility market domain is provided.

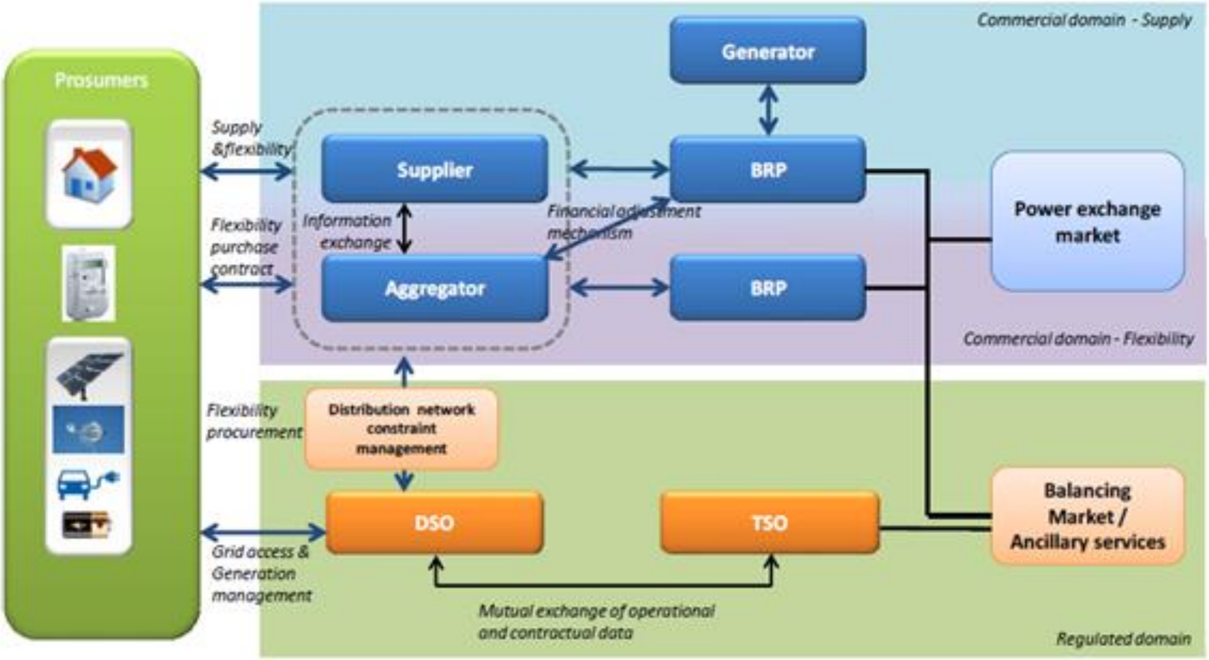


Figure 15 – Possible relations between the actors in smart flexibility market domain.

The markets involved in the participation of flexibility resources are various, depending mainly from the nature and the features of the flexibility service and from the economic convenience in participating in one or another market. Currently, capacity, forward, day ahead, intraday, and balancing markets are interested by flexibility in various forms. The main changes to be performed for allowing an easy integration and the best exploitation of flexibility provision into the market address some features of market operations and the opening of new branches of market-places [135] [119]. Firstly, the change of pricing intervals is necessary. In such a way, many fast services that are provided by flexibility can be traded in the market; the mismatch between the market features and the operational requirements could led to the impossibility of exploiting flexibility services. If modifying the pricing intervals is not possible, new service exploiting shorter intervals should be set up. In this view, another market opportunity consists in opening the market of frequency control services also to the flexibility ones, or, in contexts of great penetration of RES systems, in addressing the ancillary services market with the flexibility products. The markets could be also subject to the trade of ramping services, allowing flexibility to participate to the provision of ramping up and/or down capability to the system operators. Finally, some emerging flexibility services could allow the trading of long term services over multi-hour periods.

3.1.5 Policy and regulatory framework

The field of flexibility implementation and its deployment is by its own nature very complex and involve a wide range of actor and interests. Moreover, most of its features, actors involved on its implementation, and technologies are innovative and there is no a clear and agreed way of properly operating them in all the energy related contexts. Despite the great contribution that the flexibility services can bring to these contexts, there is a concrete risk of not being able to exploit them at their full potential if their employment is not properly regulated and managed. Therefore, in the last years, many entities have focused their effort on modelling and proposing a clear and comprehensive regulatory framework able to accommodate and suitably integrate the flexibility services in the complex and dynamic world of modern energy system.

In this view, the European Union (EU) is really committed on fostering the introduction of energy flexibility as a leverage for achieving the challenging energy objectives of this century. The well know targets of 2020 Energy Strategy [139], tackling GHG emission reduction, RESs share and energy efficiency, have been already updated by means of new targets for 2030, consisting on the same objectives of the 2020 strategy to be achieved bindingly plus the target of creating a European internal energy market characterized by high interconnection features. As already discussed, benefits brought by the flexibility services perfectly match the targets defined by the EU, since flexibility: allows a better integration of unpredictable RES generation systems, is used for optimising the behaviour of energy resources impacting on polluting emissions; represents a set of key actions for improving efficiency in all energy domains, and can be an active player in several markets and also can foster the design of new market frameworks.

In particular, the topic of energy efficiency is strongly addressed by the EU by means of the Energy Efficiency Directive, proposed on 2012 (Directive 2012/27/EU of The European Parliament and of The Council of 25 October 2012 on Energy Efficiency) [140] [141]. This directive consists in a series of binding measures concerning energy savings that have to be performed in the view of achieving the above mentioned targets. In particular, these measures involve all the main actors of the energy chain that are fostered, even by advices on available technologies, to save energy: grid operators, users from private and public sectors, energy retailers, industries, government on providing incentive measures. For adapting these actions to the new challenging targets set for 2030, a new proposal for this directive has been submitted in 2016, named “Clean Energy for All Europeans” [142]. This proposal aims at offering more competitive tools for performing this enormous energy transition: the focus is put on efficiency, RESs, and, above all, on customers' commitment. As clearly outlined in this chapter, the most innovative features of the flexibility smartness relies upon the possibility of exploiting the energy engagement of the final users for affecting the energy phenomena. The design of innovative electricity markets in which the customers can participate and through which are able to perceive an economic value to their actions is today one of the main challenge of the regulatory actors.

The Third Energy Package [66] is one of the actions undertaken by the EC for giving its regulatory contribution to the creation of modern European market domains. The main field addressed concerns: the unbundling of the generators and the suppliers of energy, for allowing a fair competition among the actors; the design of an internal market, where all the actors access openly and fairly, and the related independent regulators, aimed at controlling neutrally the market operations and ensuring equal opportunities for all participating countries; cross-border cooperation for ensuring the next means for the management of the entire interconnected system.

The regulatory framework is enriched by the work and contribution of other actors that are in charge of supporting the EC on making as effective as possible their decisions. Two main roles are underlined here, the Agency for the Cooperation of Energy Regulators (ACER) and Council of European Energy Regulators (CEER): they aim at complementing and coordinating the national and international regulators in the field of energy, for helping their cooperation in achieving the wider objectives set at EC level. Their tasks are similar: whilst ACER focuses on legislation requirements, CEER addresses all the other topic of energy regulation; very often, their conjunct effort leads to clear recommendation and guidelines for facing the innovation required by the energy transition envisioned by EC. Their contribution in the field in energy flexibility is significant, as the contribution of these services can enable many energy efficiency task. In the white paper reported in [143], the emphasis is put in giving a feedback to the European proposal for Energy Efficiency Directive, addressing a wide range of topic: ensuring and clarifying the roles of all the actors, as well as market framework design and their safe implementation; avoiding the barriers and providing tools for overcoming the existing ones; creating innovative solutions for balancing demand and supply, also through the flexibility, that has to be fostered at regional and national level in order to integrate new role as EV systems, local storages, DR implementations, etc., and give the opportunity to provide effective contribution. In particular, another work written in cooperation between ACER and CEER [144] addresses directly the possibility of facilitating the integration and exploitation of flexibility services: “European Energy Regulators consider that a high level, harmonised, principles-based approach to underpin the regulatory framework in relation to facilitating flexibility is the optimal way to deliver a more affordable, secure and efficient electricity system”. Two main topics are underlined, the importance of structuring a holistic market framework to support market participation of flexibility and the support that flexibility services can provide to the grid operations management. As the market regulatory issues are concerned, both ACER and CEER address the avoidance of market barriers, in particular to the extent that all the users able to provide flexibility have the right and the possibilities to access markets, also in accordance to the requirements of market places and the features of the flexibility itself. Moreover, great emphasis is given to the regulation of balancing responsibility to properly assign financial and technical duties. As far as the technical aspects of system management are addressed, these recommendations concern the actual access by the grid operators to the flexibility services for facing their technical issues, their commitment on equipping the grid infrastructure with suitable ICT devices as well as the comparison of these investments with those requested by grid reinforcement projects, and, finally, the establishment of an unique European DSO.

Besides the decisions taken by the European governmental body, many studies address relevant aspects of the policy and regulatory efforts needed to pave the way for the implementation of effective and valuable flexibility solutions. Here are listed the main categories of regulatory actions required that have been collected from the evidences reported by many studies [113] [145] [146] [147] [148].

- Market design: the set of clear and transparent rules for allowing and facilitating the access to the market places to every actors, for trading as much as smart services as possible, and the design of new markets able to receive and exploit the contribution of innovative services.
- Direct regulation: all the political decision aimed at directly support and foster the deployment of smart energy activities, such as directive for physical infrastructures for energy systems.
- Fiscal policies: actions influencing the economics of a country such as taxes and spending, that indirectly affect the consumptions and employments of energy resources, such charges on fuel and CO_2 taxation.

- Support schemes: these means aim at supporting the financial effort for the installation of smart equipment and innovative systems, such as the RES generation systems, rewarded by feed-in-tariffs, or investment grants.
- Incentive programmes: are proper regulatory schemes that aims ad rewarding an actor for allowing it recovering their costs, in order to incentivise it in undertaking risky and unpredictable business activities.
- Research and development: this actions are aimed at proving and testing both new technological solutions and innovative services implementation, mainly through the deployment of real demonstrations and business analyses in new unexplored sectors.

These actions, in their complexity and variety, refer to almost all stakeholder domains of the energy environment [149]. In particular, supply side, demand side, grid operation and environment are the main domain addressed by tailored policy tools. On the supply side domain, many initiatives have been designed for enabling both generation technologies advancement and awareness, as well as acceptance by the community and citizenry; entities from public and information sectors, as well as research centres and universities, have been involved in this tasks. The demand side, being at the centre of many innovative customers engagement initiative, has witnessed a great number of interests from both public entities and governments, offering contractual arrangements and technological solutions, and from commercial figures aiming at providing to the customers the suitable means for participating in markets and for giving economic value to their perspective flexibility capabilities. The entities responsible for grid operations, DSOs and TSOs, have been pushed by many figures to modify their assets, their grid management criteria and to enlarge their interconnection capabilities. Many research centres, as well as associations and energy involved stakeholders, have proposed significant changes regarding grid operators responsibilities in market-places, infrastructural intervention for allowing flexibility, and, above all, the management and control criteria of their networks. As the environment is concerned, the main efforts have been spent by governmental actors: through taxation, political measures and legal regulation, a concrete framework for assessing and modifying the causes of environmental impacts has been set up, focusing on the heath aspects and public consultation, the environmental constraints and planning new taxation and tools for reducing actual polluting emissions.

After the overview of regulatory framework in Europe, a brief description of the same contexts of the two largest political and geographical players is given, thus USA and China [135] [147] [149]. In the USA, despite the very intensive usage of electricity, the power system infrastructure is dated, unreliable and do not ensure the necessary flow capabilities. There is no long-distance power transmission network and the permissions for constructing new lines are not easy to be obtained. In this context, the implementation of smart and flexible energy usage could improve the modernization the power systems equipment from many points of view and the possibility of managing the power consumption, as well as its flow over the network, could led to enormous savings in deferring and avoiding infrastructural reinforcement. Most of the actions have been undertaken by the US government, driven also by environmental concerns, exploiting scientific and technical development, financial actions, political efforts and the participation of public enterprises. In China, the main boost for improving smart grid and energy efficiency relies upon the great Chinese demographic expansion in relatively rural non-electrified areas, the great spread of RES generation and the low attention and awareness on energy consumption by the final users. The central Chinese government is in charge of the deployment of smart grid actions and of all the tasks related, exploiting the efforts of public enterprises, scientific and technical development, and binding legal regulations.

3.1.6 Drivers and related barriers

Along the sections of this chapter, many elements representing enablers and drivers of the flexibility solutions implementation are discussed and contextualised, as their barriers. Here, an organic overview is given [113] [145].

Firstly, the technological advancements required by the smart grid paradigm is an essential enabler for the provision of flexibility services. The ICT infrastructure is the backbone of an effective intelligent grid. The are several drivers of this transition, from the development of complex EMSs able to control and supervise all the operations of the grid to the deployment of tailored communication protocols that can enable the data exchange between all the actors involved. Strictly connected to this topic, the deployment of smart appliances and smart meters has a key role for integrating smartness in customers' facilities, through energy efficient appliances, that can also be controlled, and data communication. The main barriers of the technological development [123] are related to the lack of a unique an integrated solution for the implementation of EMSs, of their control criteria and the resources managed, as well as communication protocols able to convey all the information needed for the smart management of energy units. Moreover, the implementation of such technological solution is expensive, and no certain financial assessment on the return of these investments has been performed. Finally, the commitment and the awareness of the customers on energy topic, and the direct and indirect benefits achieved, is crucial for installing and operating smart appliances and smart meters.

The main commitment of grid operators and retailers in providing drivers for flexibility implementation relies on the possibility of setting up tailored grid tariffs and products aimed at increasing the attractiveness and the feasibility of customers-side actions, such as DR contracts, curtailment ones, installation of smart devices, etc. Some financial reward mechanisms can be represented by restructuring the usage of system charge or critical time-of-use tariffs by DSO, whilst the retailers are involved in the proposal of time-of-use tariffs and other dynamic pricing programs. Moreover, the grid operators are committed in innovating and equipping their networks with smart devices whose economic potential are not certain, as seen above [150]. The main barriers to this transition, besides the engagement of the customers, relies upon the opponent actors that have conflicting interests in implementing it, for instance those utilities that own traditional generation plant whose businesses can be affected by the provision of flexible services by other stakeholders.

As widely discussed in the previous section, markets can represent great enablers for the diffusion of the flexibility services implementation. Allowing the access to the several market-places able to trade flexibility products for all the actors and the entities involved in the provision of these services is the first step towards the deployment of an integrated market framework. Moreover, the clarity and the simplicity of the contracts to be proposed to the providers, especially the small scale one that often do not have the knowledge of trading contracts details and other related aspects, is a key enabling factor. The main barriers to the integration of flexibility services to the energy markets is represented by some distorted mechanism in handling the market participation of traditional plant, especially with regards to the flexibility provided by RESs [127]. Actually there is a strong mismatch between the costs incurred for building and operating base load power plants and the high volatility of the price formed into the market places, causing some issues on the financial involvement of the traditional plant owners and their contribution on system operation.

Finally, the regulatory and policy framework are essential for fostering and driving the transaction towards modern grids, especially in the field of flexibility. Firstly, the regulatory entities have direct influence to national and international governments for supporting them in the implementation. Secondly, these entities have great impacts on community and their action manage to commit and involve actors from almost every stakeholders. The driving factors of the regulatory and policy actions have been widely addressed in the previous section, from markets regulation to financial and taxation intervention, passing through user engagement as well as research and development funding. The main barriers consist in the pressures that the regulatory bodies can receive from entities with vested interests on performing smart energy transaction [123], aimed at hindering the proposals of innovative mechanisms. Moreover, the number of actors involved in the flexibility context is very high and the regulatory actions to be taken in order to address and coordinate effectively their operations are very complex; there is actually an issue on mixing the policy approaches [148] for creating a coherent and fair regulatory framework.

3.2 EMSs and flexibility platforms

This section focuses on the tools and ICT components in charge of managing the flexibility resources and the provision of the flexibility services to the numerous stakeholders requesting for them. The proper integration of these tools consists in a flexibility platform, that is a framework able to manage simultaneously all the aspects of the flexible energy behaviour, from the assessment of flexibility capabilities to the reward of the services provided [151] [152]. These platforms can be considered as an advanced functionality of the typical EMSs, allowing these systems to deal with resources that can provide flexibility, or as a new kind of integrated enhanced solution in grid management technologies.

The features of such a platform allow to entirely manage the flexibility capability of an energy unit and the energy context in which it is installed. The flexibility of energy resources has to be firstly assessed and evaluated in order to quantify it and properly choose the service and the stakeholders to which it can be provided. This task foresees the possibility of forecasting and/or modelling the typical energy behaviour of an energy unit, or accessing to its historical data, in order to compare it with the availability of in terms of both power and energy consumption/injection of that unit. Once that the flexibility of all the resources under the control of the platform are known, the functionalities provided by this ICT infrastructure have to properly collect and handle it in order to be structured in one or more services to other smart grid stakeholders. Actually, the provision of flexibilities has to be coordinated for responding to a dynamic price program, for instance adapting to the price signal of a retailer, or to technical requests from grid operators, such as request for reducing or increasing power consumption, etc. This kind of coordination is driven by a control technique, as will be described later in this section. In a context where each energy unit providing flexibility possesses an own management criteria, the possibility of negotiating the flexibility services has to be taken into account and the tailored means and protocols for performing it have to be put in place. When the flexibility platform has calculated the solution that fits the control criteria and all the energy units confirm their commitment in providing the flexibility they dispose of, a set of sensors and actuator has to be employed for making this solution effective in the energy context managed, along with the setpoints, as well as working configurations deriving from them. Moreover, the flexibility platform is in charge to deal with all the other actors involved in the provision of flexibility services, such as aggregators, retailers, or DSOs. In this view, the proper communication tools and trading mechanisms have to be provided, such as OpenADR implementation.

Besides all the aspects proper of a tool that addresses the management of flexibility, these platforms have to make available all the functionalities that characterise an EMS [153]: the monitoring infrastructure, equipped with its own data storage system, forecasting tools, sensors and actuators, a simple access to all the resource requesting for connection, a cyber security layer, a Graphic User Interface (GUI) and all the related tools for human operators, etc.

In the following sections, an overview on the main features of flexibility platforms is provided. Firstly, the goals of the flexibility managers are shown and discussed. Subsequently, the description of architectures and their classification is provided. Finally, the control strategies and the techniques adopted for designing the flexibility platforms are depicted and briefly reported.

3.2.1 EMS purposes in flexibility platforms

The flexibility management platforms are key elements in providing smartness in modern grid contexts. As a matter of fact, the possibility of providing flexibility by itself is not enough for ensuring smart grid scenarios, as such these services have to be coordinated following a management objective in order to provide a wide range of benefits to the stakeholders involved in flexibility provision, as well as in its exploitation. Here are summarized the most relevant goals and purposes pursued by flexibility management platforms [124] [138] [154] [155] [156].

- Economic benefits maximization [124] [154] [155]: one of the main referenced and addressed aspect of flexibility exploitation concerns the economic advantages derived from these services. The actors providing flexibility are very often driven by the possibility of gaining incentives [157] in the form of reward for the service provided, for instance giving economic value to the variation of the power adsorption or injection, or in the form of price based initiative aiming at indirectly reward flexibility by reducing energy supply costs in the energy bills. In this view, many approaches in flexibility platforms address the maximization of customers’ economic benefits. Other cost aspects are related to indirect effects of further flexibility goals, such as reductions of grid losses, polluting emission related costs, and social welfare.

- Control of DG, RES, and storage [156]: the flexibility provision coming from DG and RES [158] systems is gaining more and more importance due do the fact that a coordinated management of power injection can give a great contribution on balancing demand and supply and, above all, it allows to prevent all the issues derived by unpredictable and intermittent power injection. Moreover, the possibility of integrating such generation systems with local storage devices increases significantly the flexibility capabilities of distributed energy units. In this view, the flexibility platform are in charge of forecasting the energy behaviour of the generation system, especially when weather data have to be taken into account, to assess the flexibility and exploit it in accordance to price signals or technical contingencies coming from other stakeholder. The maximisation of energy sale into tailored market-places is another key target of the flexibility manager.
- Power profile improvement [154] [155] [156]: in many circumstances, the actors connected to power grids are requested to modify and modulate the shape of their power profile, both in case of demand or generation, with the aim of coping with grid technical issues. The main goals are lowering peak of power demand during critical hours in order to avoid congestion and overload issues, smoothing the entire power consumption profile in order to avoid recurring at expensive and polluting peak power plants, reducing production excesses in distribution grid coming from unpredicted RES injection in order to avoid disturbing reverse power flow phenomena. The implementation of such actions is triggered by signals sent by DSOs or TSOs, in form of critical peak hours report or requested/suggested power profiles or by penalties agreed contractually in case of high load consumption during peak hours.
- Emission reduction [124] [154] [155]: the reduction of polluting emission in the environment can be achieved by both integrating green energy generation and avoiding the employment of high CO2 emitting power plants [159]. The exploitation of power flexibility support both these tasks, as seen above, allowing the an higher share of RES generation in the energy mix and supporting load shifting by moving the load consumption from critical peak hours to low demand hours or to periods of the day characterized by high generation from RES sources.
- Energy efficiency [154] [155]: improving the efficiency of modern energy systems is a relevant aspect of the smart grid transition. In this view, the availability of some

users to modify their energy behaviour is a suitable support for increasing efficiency. Firstly, the loads commit themselves in reducing their power consumption, so the flexibility can be exploited in order to avoid or modulate the employment of some appliances, such as illumination and Heating, Ventilation and Air Conditioning (HVAC) systems. These kind of actions obviously need the engagement of the users on impacting slightly on their comfort for a virtuous goal. Moreover, the service provided by a set of flexibility provisions could led to optimise the local usage of the energy resources, reducing the losses on the grid and improving significantly grid performances [160].

- Market participation and price stabilization [138] [154] [155]: the provision of flexibility, especially that coming from small-scale energy resources, has be to properly managed in order to participate to the market-places discussed in the previous sections. The coordination of flexibility resources and the interface with other actors, such aggregators or BRPs, is essential for offering effective trading bids in the market and for gaining the proper economic value. Moreover, the presence of various actors into the markets led to great volatility and instability of the energy prices, especially in wholesale markets; in this view, flexibility platforms are in charge of handling price stabilization techniques [161].
- Power quality and grid parameter regulation [124] [156]: in many cases, the energy management tools of grid controllers are responsible of the power quality of the electricity service provided and they are equipped with voltage and frequency regulation devices in order to ensure reliability and safety requirements. In the context of flexibility, the platforms can exploit these services in order to avoid overload and demand-supply unbalances that affect the grid parameters. The possibility of employing power electronics allows to perform also fine regulation tasks from devices that can provide fast responses in modifying their power injection/absorption.
- Deferral of grid investments [124]: the management of the flexibility provision focused on the technical grid issues has the important role of helping the grid operators in deferring or delaying the interventions and the related costs for empowering as well as enlarging network infrastructure with new lines, uprated transformers, etc. The availability in modulating the power profiles exploiting the flexibility of the involved energy resources could solve peak phenomena by shifting or reducing the power consumption and/or generation profiles of the managed users.

> In this way, the related overload and congestions phenomena, as well as reverse power flow ones, are avoided and DSOs and TSOs are not forced to design new infrastructural solutions for providing the required quality levels.

3.2.2 Hierarchical levels and architectures

3.2.2.1 Hierarchies

As far as the hierarchical architecture of an EMS is concerned, the main classification relies upon the physical layout level of the different components over the energy system structure and, at the same time, upon the different systems addressed [124] [156] [162]. In this view, the ANSI/ISA-95 standard [163] is a relevant reference for addressing this kind of level definition since it aims at modelling the interfaces between all the actors in control systems, providing suitable definitions, as well as terminology, and addressing the technological aspects of control system design. In the context of flexibility platform, the multilevel hierarchical control structure proposed from this standard has been adapted to the management and performance requirements of energy systems. In Figure 16, a graphic representation of this hierarchy is depicted.

The lower level (Level 0), the closest to the energy usage, addresses the monitoring and control of each single energy units, intended as a device or a sub-system seen as a black-box, handling its control as well as monitoring task, and implementing the setpoints coming from the upper control level. The second level (Level 1) carries out the control of grid performance in terms electrical parameters and quality of the services provided. At this stage, voltage and frequency regulation are performed by means of various techniques. Moreover, this level takes care of the technical feasibility of the data evaluated by the upper control level. The third level (Level 2) performs the energy management of the system, integrating all the information about monitoring data coming from the lower levels in order to bring smartness to the energy system and manage the flexibility provided. This occurs implementing the control criteria set for the management of the energy resources, able to address technical, economic, environmental, etc., aspects of the system itself and of all the stakeholders involved. The fourth level (Level 3), is in charge of managing the interface with all the other energy actors the smart grid is connected to. These actors are in charge of synchronization issues, supply-demand balancing, power flows regulation, and all other tasks for allowing the seamless integration of the smart grid in the electric networks as well as the provision of smart services to the grid operators and BRPs.

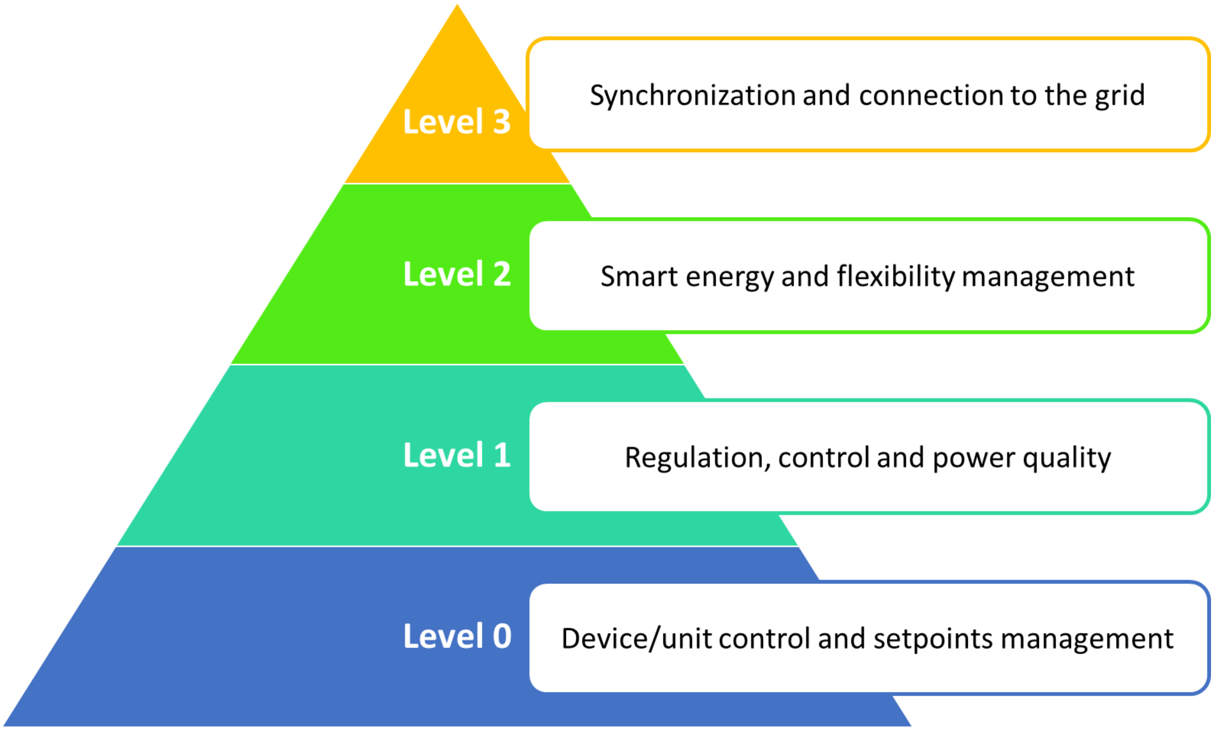


Figure 16 – Hierarchical structure of energy management for smart flexibility contexts.

Another classification concerning these aspects of smart EMS is based upon the time scales of the operations discussed above. Actually, these levels operate over significantly different time scales [164]:

- the first one acts very quickly for following the devices dynamics, between 1 and 10 ms;
- the second one depends on the responsiveness of the sensors in charge of detecting parameters violation and the implementation of the regulation action, between 100 ms and dozens of seconds;
- the third one, mostly limited to the speed of communication means and computational efforts, occurs between 1 s and few minutes;
- the fourth one, addressing the scheduling and the planning of the system operations, takes from some minutes up to 1 hour.

3.2.2.2 Architectures

The architectural solutions of such a flexibility platform address many technological and operational aspects. Here a brief overview of the most common approaches is given.

The clearest architecture regards the definition of different layers addressing the main functionalities of the platform itself [165]: one layer is appointed to integrate all the communication means from the components under the control of the grid in order to seamlessly collect the information from all the involved actors. Other layers, strictly related to first one, handle the smart core of the system, where the gathered data are elaborated. Using the information about the energy behaviour of the controlled systems, this layer is able to properly manipulate them in order to evaluate forecasted data, provide input data to simulation models and monitor the system operation. After that, proper management criteria are implemented in order to detect the best operational configuration that fits the targets of the system manager, for instance maximizing revenues, participating to DR programs, reducing polluting emissions, etc. The third layer concerns the interface with the external users: it provides the necessary HMI and GUI, equipped with data analytics tools, to the users in order to graphically show the results of the energy management process and to allow the operators themselves to interact with the functionalities provided by the platform, for instance starting the management process, choosing an energy plan, etc. The last layer addresses the data management: a set of data bases and related tools have to be deployed for storing the information, creating reports, as well as Key Performance Indicators (KPIs), and ease the data exchange among all the internal and external actors of the systems. In Figure 17, a graphical representation of such an architecture is shown.

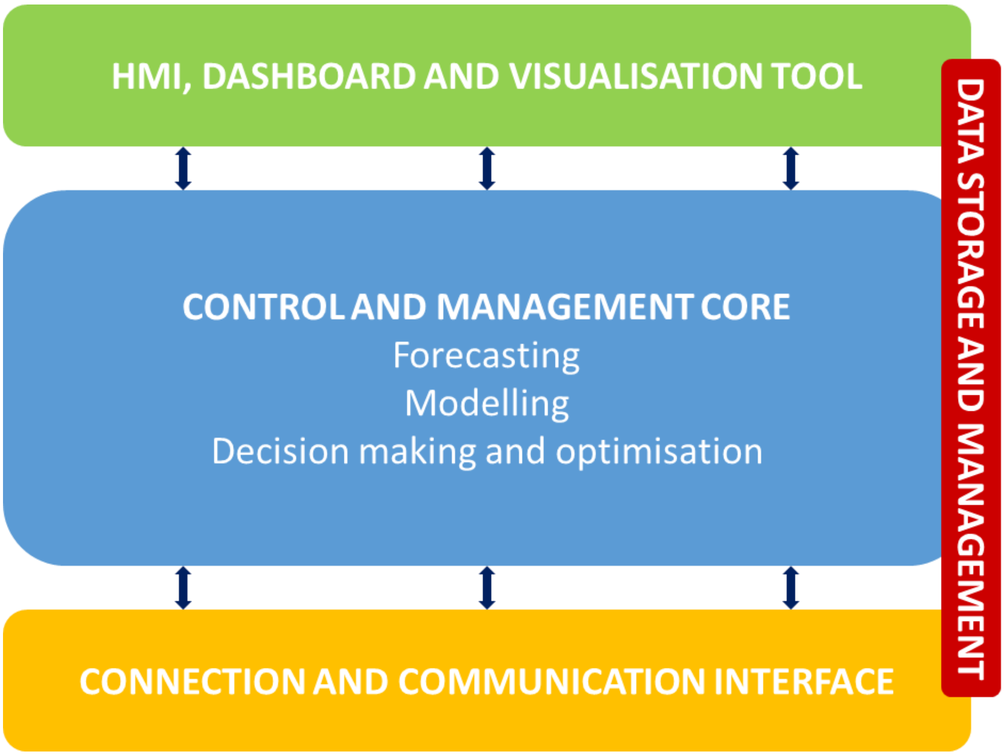


Figure 17 – Typical architecture solution for a flexibility platform.

Besides the proper structure of the architecture, another aspects in hierarchical structure topic regard the approach through which the flexibility platform can be deployed in an energy context [124].

A first classification addresses the displacement of the intelligence implemented by the platform itself, tracing two main options, a centralised or decentralised management [166]. In the case of centralised management, all the smartness is located in a unique centralized entity that is in charge of exchanging data with all the devices of the system and coordinating their operations in an optimised way. As such, the evaluation of the best strategy is complex and committed to a unique centre but allows to take into consideration several management criteria and an easier communication with external actors. In the case of decentralised management, the smart control is entrusted to several small actors that address local parts of the management criteria, coordinating their approach by exchanging data among themselves. In this case, smaller parts of the management are performed in parallel reducing the complexity and the execution time, but the evaluation is not as complex as the one performed by the centralized control. The strength and the smartness carried out by this approach relies therefore in the interaction among the decentralised actors. In accordance to the management criteria, the use cases to be implemented, and the technologies available, the centralised or decentralised approach could led to best performances. In any case, in many smart grid and smart micro grid contexts, the distributed control techniques are appointed to be the most effective for managing modern power grid operations.

A second categorization can be found in the different usage temporisation of the management tools. Actually, the process can be designed in order to be invoked once only before the start of the interested time period, providing all the scheduled setpoints and profiles for all the energy resources involved. In this case, the process can be expensive from the computational point of view and very long, taking into account a plenty of information for very wide time horizons. Another solution can be seen in repeating simpler management process in a multi-stage approach, in order to have shorter assessments nearer to the time when they will be effectively implemented into the system. In this way, a quasi-realtime management of the energy processes is achieved. The choice between these solutions depends on the complexity of the management to be implemented, the behaviour of the controlled resources, the services to be provided, and the technological devices adopted.

3.2.3 Solution methods and approaches

In addressing the design and development of EMS architectures, many techniques for solving and handling the management of energy resources have been studied, tested and implemented in real life demonstrators. In this section, the most common methods are listed and addressed along with the energy solutions that better fit the methods.

- Linear programming [167] [168] [169]: this method is employed when the objective function and the related constraints are linear and deterministic. Actually, it is not suitable for addressing studies where high unpredictable parameters affect the management of the system, such as RES generation devices. There are many proven and well-established methods that relies on linear programming.
- Convex optimisation [170] [171]: this kinds of approach are employed when both objective functions and constraints are convex. By means of methods like least squares, conic programming, Lagrange multiple methods, and geometric optimization, these cases can be handled as in the case of linear contexts.
- Heuristic optimisation [172] [173] [174]: this approach on addressing the management criteria is strongly used where uncertain elements are involved in the solution of the optimisation problem, for instance in the case of RES assessment. By means of heuristics, the study of global properties of the objective function are not needed, as well as there are no constraints on objective function complexity. In many cases, it emulates natural phenomena for optimising the energy resources, like the biological process of evolution in the case of genetic algorithms.
- Dynamic programming [175] [176] [177]: this techniques is based on Bellman's principle of optimality and consists in considering the management problem as a series of multiple stages to be solved one by one. This perfectly fits some smart energy contexts when the energy behaviour changes over time.
- Stochastic optimisation [178] [179] [180]: the stochastic approach is utilised when several parameters of the context under study are strongly uncertain, for instance when RESs, price variations, and human behaviours are taken into account simultaneously. Most of the times, the problem is structured as a multi-stage methods, consisting in a probabilistic scenarios tree. The techniques usually employed for solving this problems are Markov Decision Process, Lyapunov optimization, and Model Predictive Control.

- Robust programming [169]: this technique has the advantages to ensure strong robustness to the management process in exchange for uncertainty that can be handled as deterministic variability of the parameters and of the solutions. This approach is therefore widely used in modern energy contexts.
- Machine learning [181] [182]: this methods consists of creating a system able to evolve autonomously relying upon the data taken from historical observation and empirical data. This can be employed for estimating price variability, impacts on the grid performance due to the adoption of a technology, etc.
- Game theory [183] [170]: the game theory approach fits many aspects the modern power system structure, since it foresees a strong and dynamic relationship among the actors involved in the management of the grid itself, each of them seen as the player of the management “game”. In this view, two kinds of approach can be envisioned:
    - cooperative [184] where the single players of energy units play in order to achieve a common and shared objective to be optimised;
    - competitive [185] where the maximisation of the objective is reached by letting all the players pursuing their own goal.
- Multi-agent systems [186] [187] [188]: this approach consists in providing the intelligence to several agents that interact among them implementing a decentralised management criteria. Multi-agent systems are basely capable of autonomous actions, intended as capability of deciding by themselves their best, and implements complex cooperation and coordination tasks among the involved actors. The main advantages of this method is its high flexibility and responsiveness to the environment, allowing to solve problems that cannot be handled by means of a centralised approach.

3.3 Optimisation of energy resources

3.3.1 Problems addressed

The structure of a smart grid is inherently very complex and consists of a large amount of actors interacting with different aspects of the energy chain and pursuing several different goals. The heterogeneity of the systems composing a smart grid is indeed extremely high [189]. There are some actors that are responsible of the physical infrastructure whose presence spans over several kilometres that cares about technical issues and power quality goals over quite long time horizons. Other actors that are only virtual ones and address financial and market aspects, as well as entities dealing with regulatory and policy topics. Many entities are concerned about the generation and injection of power into the grid, taking advantages of the sale of the produced energy and/or the incentives related to the exploitation of RES energy. The load figures of the power system are very different from each other, in terms of absorption features, flexibility, control capability, dynamic services provided. Moreover, storage devices, smart metering systems and other technologies are changing the typical energy consumption patterns and features, along with other load typologies such as the EVs connecting to the grid for recharging. It is clear how the enormous differences among the objectives, time scales, ICT infrastructures, spatial distribution, etc., increase significantly the complexity of the power system seen as a whole. Moreover, as shown several times in the previous sections, the operations and the dynamic features entailed by the implementation of smart energy actions require an high level of interdependency between the actors, in coordinating the generation and absorption phases, in managing grid operations, in addressing economic aspects, etc.

The high complexity of modern power grid forces the management systems to deal with very large and not easily identifiable problems. In this context, the implementation of optimisation frameworks allow addressing most of the issues concerning the management of modern power systems. As a matter of fact, in many circumstances the optimisation is seen as the core of the smartness provided by modern power grids [190].

All the optimisation problems are based on a mathematical formulation, through which the energy environments are properly modelled by means of objective functions and constraints. The most general definition of such a problem is as follow [191]. A general optimisation problem is defined as minimizing (or maximizing) the function $f(\mathbf{x})$ subject to inequality constraints, expressed by the functions:

$$g_i(\mathbf{x}) \leq 0, \qquad i = \{1,\ldots, m\}, \mathbf{x} \in \Omega$$

and equality constraints, expressed by the functions:

$$h_j(\mathbf{x}) = 0, \qquad j = \{1,\ldots, p\}, \mathbf{x} \in \Omega$$

where m is the number of inequality constraints, whilst p is the number of equality ones.

A solution minimizes (or maximizes) the scalar $f(\mathbf{x})$, where $\mathbf{x}$ is a n-dimensional decision variable vector $\mathbf{x} = (x_1,\ldots, x_n)$ from some universe Ω.

It worth noting that that $g_i(\mathbf{x}) \leq 0$ and $h_j(\mathbf{x}) = 0$ represent constraints that must be fulfilled while optimising (thus minimising or maximising) $f(\mathbf{x})$. Ω contains all possible $\mathbf{x}$ that can be used to satisfy an evaluation of f($\mathbf{x}$) and its constraints. Of course, $\mathbf{x}$ can be a vector of continuous or discrete variables, as well as f($\mathbf{x}$) can be continuous or discrete.

Starting from this formulation, a proper optimisation process is addressed. Taking into account the purposes in managing energy flexibility resources discussed in the previous sections (see 3.2.1), one or more objective functions are set up in order to quantitatively assess the fitness to the goals to be pursued, for instance the function evaluating the cost terms of an economic optimisation, the function calculating the power losses over a grid portion, the function parametrising the distance between a service request and the actual energy behaviour, etc. Subsequently, a deep analysis of the energy context allows to define the solution space of the problem. The technical constraints of the equipment installed in that energy environment, intended also as rated values, provide a first boundary assessment, accompanied by the constraints coming for operational aspects, related to the working phases of the energy system. Moreover, other constraints can be derived from final users' comfort limits, contingency analysis, market rules, etc.

3.3.2 Optimisation solutions and management criteria

The optimisation approaches carried out in the researches in smart energy field are several and address the most of the technical, operational, economic, and environmental issues of the smart grid management. The Optimal Power Flow optimisation techniques are some of the most addressed topics in the study of smart grid since many decades. Relying upon the physics of the power grid, described by the Kirchoff voltage and current laws, the Optimal Power Flow computation aims at optimising both electrically and economically the usage of grid resources through highly complex mathematical formulation [190]. Unit commitment is an optimisation process that addresses the operations of the generators connected to the grid under management and aims at coordinating their scheduling in order to achieve some common goals, such as matching the energy demand at minimum cost or maximize revenues from energy production, over a fixed period of time, usually 24 hours [192]. One of the most economically effective approach on smart grid context is the optimisation driven by market led DR program [193]. As a matter of fact, this approach aims at modifying the generation and/or absorption profile of the customers in order to achieve economic benefits. These can be brought by the reduction of the cost of energy supply, for instance due to the adoption of time-of-use tariffs, or by the economic reward, in terms of incentives, payed to the users that are able to follow properly the DR request. Since today the RES based generation system are extremely spread all over all the levels of the power system, many optimisation approaches address the exploitation of such energy sources

[194]. In this view, the optimisation can be driven by several goals: avoiding power generation curtailment, shaving production peaks and avoiding reverse power flow phenomena, gaining economic benefit from market participation, improving grid power quality, etc. Another issues related to RESs and DERs in general is the proper allocation of such systems over the power grid infrastructure [195] [196]. Actually, RESs, storage devices, EV recharging stations, and CHP systems impact significantly the normal operations of both transmission and distribution grids. The possibility of choosing the connection point of such systems allows to address issues like grid losses reduction, voltage and frequency regulation, fault prevention techniques, etc. The provision of ancillary services to the grid operator is a very relevant topic in modern energy systems, and the possibility of structuring a dedicated market for them has driven many researches in this field [197] [198]. The optimisation of the operations of the systems able to provide frequency regulation capability, spinning and non-spinning reserve is therefore a great driver for energy management research. Moreover, the economic and price-stabilization benefits carried out by an ancillary services market is under investigation by many optimisation studies. In the context of multi-carrier systems, the optimisation of the energy flows among the different devices of an energy hub is a key aspect for exploiting the advantages of integrating different energy carriers [199]. This optimisation has to handle several decision variables and parameters, often from different energy fields, and complex objectives functions, related to many features of the hub itself, and several constraints coming from the complex interfaces between the carriers involved. The economic aspect in managing grid operation and energy losses has always been a key topic in optimisation researches [200] [201]. These methods can be addressed by managing power flows both in terms of active and reactive power or managing properly energy resources, such us storages or RES systems operation. Moreover, great emphasis is given to the possibility of modifying the topology of the grid in order to avoid losses and other management costs. The last aspect on optimisation context proposed in this brief overview concerns environmental issues [202]. The optimisation objectives in this field are various: reducing energy consumption, fostering the usage of green energy system, curtailing load peak in order to avoid high polluting plants to be turned on, prioritising the employment of low-carbon impact appliances or devices, etc., and many of them have been effectively proved and implemented.

In evaluating the optimisation processes, this approaches classification has to be matched with the different levels of the smart grid in which such a solution is going to be implemented [189]. The lower level is the closest to the final consumers; in this case the approaches will address the optimisation of building or factory energy consumption and/or usage, storage exploitation, market led DR implementation, and environmental issues. When the higher level of distribution systems is concerned, the optimisation approaches to be held are different and are oriented to topological assessments, RESs and DERs exploitation, ancillary services provision, and technical as well as economic benefits provided by the implementation of DR actions. Finally, the transmission and traditional generation level employs the optimisation processes mainly for unit commitment purposes, Optimal Power Flow, wholesale markets participation, power reverse flow phenomena, and large-scale RES integration.

Due to the wide range of possible optimisation approaches and the extremely high diversity of the energy contexts in which such solutions can be implemented, a very careful preliminary study about the energy environment under study has to be performed in order to choose the proper optimisation framework. Firstly, the objectives to be pursued has to be clear and well-established between all the stakeholders acting in the smart grid context, so as the most effective optimisation approach can be adopted. Secondly, on the basis of the selected approach, the solution method should be chosen from those outlined in section 3.2.3, in accordance to the typology and complexity of the goals, in terms of objective functions, constraints, models, etc. Finally, the correct energy parameters have to be chosen for being adopted as decision variables of the problem to be optimised, as well as the constraints have to be set, both equality and inequality ones. Once all these steps are performed, the optimisation framework can be designed and developed.

3.3.3 Heuristic optimization algorithms

In this thesis, heuristic algorithms are studied and addressed in order to solve complex energy management tasks for smart grid and smart micro grid contexts where the energy resources are able to provide flexibility.

The heuristic techniques are based on the concept of research and discovery, as its name itself claims (from the Ancient Greek: εὑρίσκω, "find" or "discover"). They implement non-exact procedures for addressing the solution of many complex problems, for the nature of the problem itself, for the mathematical complexity of the function related to the problem, for the great amount of variables involved, for the uncertainty of some parameters, or for the extension of the solution space. Even though there is a loss of exactness in adopting these methods, the heuristic algorithms allow addressing a wide number of problems that could not be solved otherwise, reducing the complexity of the mathematical models (they do not require strong mathematical assumption on the features of the function or information about its gradient) and computational time of the evaluation process itself. The employment of such techniques is very common in computer science, artificial intelligence, and mathematical optimisation. Another important feature provided by this kind of heuristic approach is the possibility of implementing multi-objective optimisation by slightly modifying the structure of the method itself, as will be shown and explained in the next sections.

The implementation of a heuristic methods is based on the usage of simple, intuitive, and natural mimetic rules in an iterative way for exploring the solution space in a direction supposed to be the one that provides the optimal solution [203]. As such, these techniques try to iteratively improve the solution step by step, implementing sophisticated techniques for ensuring the best research over the solution space.

There is no a unique referenced classification of the heuristic algorithms, due the wide range of different features characterising their algorithms. Some of them are classified in accordance to the search strategy, that could be global or local with respect to the solution space. Another criteria is referred to the number solutions addressed in performing the algorithm actions: single-solution based methods act on only a solution trying to improving its fitness with respect to the objective function, whilst population based ones manage multiple candidates simultaneously exploring larger portion of the solution space. The nature of the rules that drive the algorithm is often employed for distinguishing different heuristic techniques, for instance referring to biological phenomena, animal world behaviours, chemical processes, etc.

In the present study, the adopted classification is based on two main classes: swarm and evolutionary approach [204]. Even though a complete review of these methods is not in the scope of this thesis, some of the most referenced and employed algorithms for both these two classes are listed below:

- evolutionary algorithms:
    - Genetic Algorithm [205] [206];
    - Differential Evolution [207],
    - Evolution Programming [208];
    - Simulated Annealing [209] [210];
    - Tabu Search [211] [212];
- swarm algorithms:
    - Firefly [213];

  - Shuffled Frog Leaping [214] [215];
  - Particle Swarm Optimization [216] [217];
  - Artificial Bee Colony [218] [219];
  - Ant Colony Optimization [220];
  - Whale Optimization [221];
  - Cuckoo Search Algorithm [222].

In the following sections, an overview on evolutionary algorithms is provided, in order to give specific information about the optimisation algorithm adopted for the researches reported in the following chapters.

3.3.3.1 Evolutionary algorithm in optimization

The evolutionary algorithms aim at mimicking the natural phenomena of Darwinian evolution theory for seeking and searching individuals that fit the goals of the algorithm itself in a fixed solution space [191]. Indeed, generation by generation, the individuals of a population improves their characteristics because only those that adapt better to that particular environment manage to reproduce themselves and give birth to a childhood population that fits better that environment, relying upon the “survival of the fittest” concept derived from natural selection. At the same way, an evolutionary algorithms uses the fitness to the selected objective function for performing this selection, trying to improve the features of the population at very generation implementing techniques for exploring the largest part of the solution space [223].

The analogy is based on the following links: in both cases there is a population, which, in the case of the evolutionary algorithms, is a set of possible solutions. The single element of the population is an individual, corresponding to solution of the addressed problem. An individual consists of several chromosomes, which represent the decision variables of the context to be analysed. Each chromosomes is composed by a set of genes, on which evolutionary phenomena, like mutation, recombination, and selection, act for creating new child generations; this are represented by tailored mechanism that are performed on the decision variables in order to generate new solutions [191]. In Figure 18, a graphic representation of the steps performed by an evolutionary algorithms is provided.

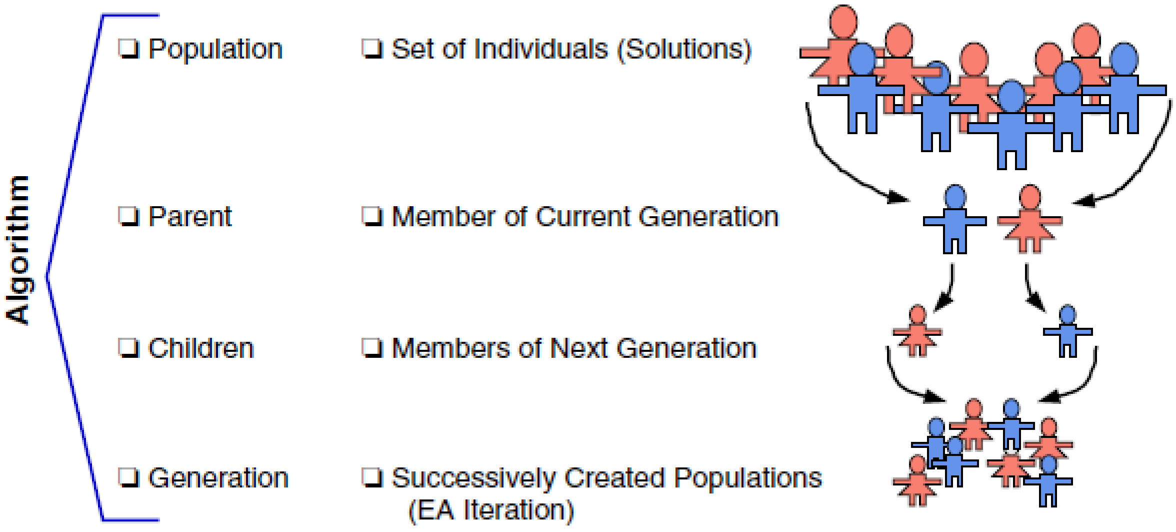


Figure 18 – Main steps of an evolutionary algorithm.

3.3.3.2 Multi-objective approach

As stated in the previous sections, heuristic algorithms fit well with the possibility of creating multi-objective optimisation framework. The complexity of the smart grid infrastructure and the presence of several actors driven by heterogeneous goals force the tools responsible of the management of the grid to assess simultaneously different objectives, modelled by different objective functions, and characterized by significantly different nature, as such economics, environment, technical operations, etc. In such context, the multi-objective algorithms allow to handle different management criteria and pursue them at the same time.

The mathematical formulation of these kind of techniques has been provided by the Pareto-optimality theory [224]. Due to its nature, the multi-objective optimisation approach do not provide a unique solution, but a set of Pareto-optimal solutions. Then, the user dealing with the optimisation process has to choice among different solutions the one that fits better its goals, selecting the one that offers the best trade-off conditions among the different criteria implemented. For this reason, this frameworks are often accompanied by a decision support tool in order to simplify this choice and make it more intuitive. These concepts are mathematically explained in the problem definition.

The multi-objective optimisation problem is formulate as follows [191]. Assuming that $f_z(\mathbf{X})$ are k different objective functions, the multi-objective problem is defined as minimizing the vector of functions:

$$\mathbf{F}(\mathbf{X})=[f_1(\mathbf{X}), \ldots, f_k(\mathbf{X})]^T$$

which is subject to a set of inequality constraints, defined as:

$$g_i(\mathbf{X}) \leq 0 \qquad i=1,\ldots, m$$

and a set of equality constraints, defined as:

$$h_j(\mathbf{X}) = 0 \qquad j=1,\ldots, p.$$

The decision variables are the numerical values which are expected to be chosen, as solutions, by the multi-objective optimisation. They are the independent variables of the objective functions and are used to minimise them; they are represented as the vector:

$$\mathbf{X} = [x_1,\ldots, x_n]^T \qquad \mathbf{X} \in \mathbf{\Omega}$$

where $\mathbf{\Omega}$ is a n-dimensional vector space and represent the set of the feasible region of $\mathbf{X}$.

As already mentioned, the multi-objective optimisation algorithms are based on Pareto-dominance and Pareto-optimality. A solution $\mathbf{X} \in \Omega$ is said to be Pareto-optimal with respect to Ω if and only if there is no $\mathbf{X'} \in \Omega$ for which

$$\mathbf{v} = \mathbf{F}(\mathbf{X'}) = [f_1(\mathbf{X'}),\ldots, f_k(\mathbf{X'})]^T$$

dominates

$$\mathbf{u} = \mathbf{F}(\mathbf{X}) = [f_1(\mathbf{X}),\ldots, f_k(\mathbf{X})]^T.$$

A vector

$$\mathbf{u} = [f_1(\mathbf{X}),\ldots, f_k(\mathbf{X})]^T$$

is said to *dominate* another vector

$$\mathbf{v} = [f_1(\mathbf{X'}),\ldots, f_k(\mathbf{X'})]^T$$

(denoted by $\mathbf{u} \preceq \mathbf{v}$) if and only if $\mathbf{u}$ is partially less than $\mathbf{v}$, i.e.,

$$\forall\, i \in \{1,\ldots, k\},\ u_i \leq v_i \wedge \exists\, i \in \{1,\ldots, k\}: u_i < v_i.$$

Therefore, the Pareto-optimal Set, $\mathcal{P}^*$, is defined as:

$$\mathcal{P}^* := \{\mathbf{X} \in \Omega \mid \neg\exists\, \mathbf{X'} \in \Omega: \mathbf{F}(\mathbf{X'}) \preceq \mathbf{F}(\mathbf{X})\}.$$

3.3.3.3 Non-dominated Sorting Genetic Algorithm II

In order to manage the control issue of the EMSs reported in this thesis, the appointed algorithm is the Non-dominated Sorting Genetic Algorithm II (NSGA-II) [110]. This algorithm is based on Pareto-dominance and Pareto-optimality and many recent papers [225] [226] [227]

[228] have proved that the NSGA-II is quite efficient, especially in the field of power distribution operation and planning.

This genetic algorithm separates and orders the population (the set of all the individuals) following a criterion based on non-dominance: individuals which are not dominated by any other individual are labelled with a higher rank; individuals that do not dominate any other individual have a lower rank. Another sorting criterion is implemented within each rank, based on the concept of crowing distance, which is an index evaluating how an individual of the population is close to the neighbour elements in the solution space. By means of a Binary Tournament Selection, individuals with the best rank are chosen to be the parents of the offspring generation. Following the analogy with the biological phenomena, crossover and mutation actions are performed on the selected elements, through Simulated Binary Crossover and Polynomial Mutation mechanism. Now, the parent and the child population are mixed and only the best N individuals are chosen for the next generation, where N is the population size. This is one of the most innovative features of the NSGA-II, called elitism, which avoids possible losses of valuable solutions. After having repeated these steps for a prefixed number of generations, the algorithm results are an entire population of Pareto-optimal solutions.

In Figure 19, the flow chart of the algorithm and the elitism concept are shown.

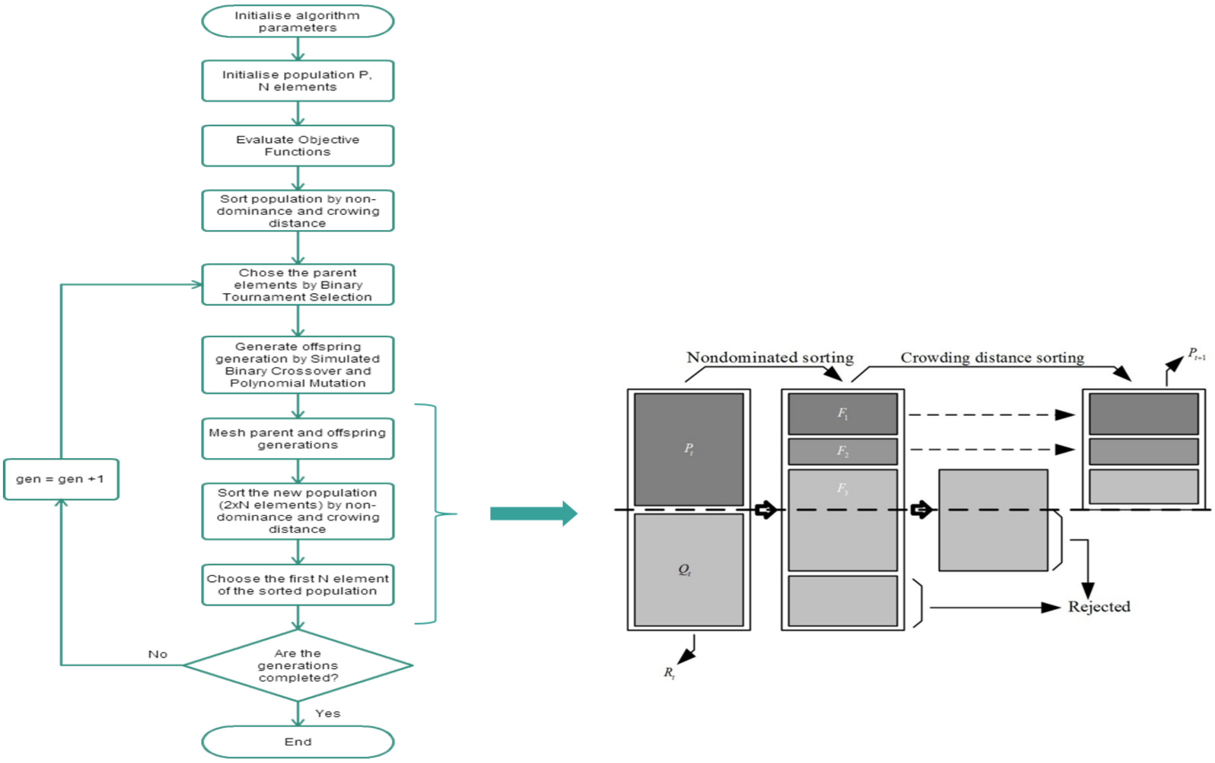


Figure 19 – Flow chart of the implemented NSGA-II algorithm and elitism block representation.

Chapter 4

The EMS of an industrial context developed for the INGRID project

4. The EMS of an industrial context developed for the INGRID project

This chapter shows the researches performed within the High-capacity hydrogen-based green-energy storage solutions for grid balancing (INGRID) project funded by EU, addressing in particular the implementation of a flexibility platform in the shape of the EMS of the Project, as well as the real instantiation of the EMS itself inside the Project real life demonstrator.

Firstly, the INGRID project is presented: its goals and the main approaches for achieving them are shown and explained, the frameworks implemented and the ICT solution envisioned for controlling the energy resources are described, the test site of the demonstration phase is shown and described. Subsequently, the features of the optimisation platform itself are described in depth: how the adopted algorithm is tailored to this energy context, the auxiliary tools integrated for creating the ICT framework composing and supporting the platform and the graphic visualisation means towards the final users. Finally, the results of the tests performed on the real life demonstrator are shown and discussed.

4.1 The INGRID project

4.1.1 Goals and overview

4.1.1.1 Concept and objectives

The INGRID project proposes a multi-carrier energy system able to provide supply and demand balancing services to the transmission and distribution grids by exploiting high availability of RESs and innovative hydrogen-based storage technology for modern smart power system solutions. As such, this Project tackles some key challenges of modern smart grid paradigms: the management of strongly penetrated RES generation systems, allowing to employ the energy harvested from solar and wind energy at its best; the solution of more and more recurrent technical issues such as congestions, overloads, and reverse power flow phenomena within the infrastructure of HV and MV grids; the improvement and optimisation of energy resources employed inside an industrial plant taking into account the provision of services to MV grid exploiting the employment of different energy carriers.

These ambitious and challenging topics are pursed through four main Project objectives:

- the usage of innovative hydrogen solid-state storage technology based on a cutting-edge magnesium hydride absorption process that offers several technical and operational advantages [229] [230];
- the exploitation of DER generation systems by smart managing the integration of fluctuating and unpredictable RESs and employing generators like a fuel cell for providing services to the grid;
- the development and deployment of an advanced ICT platform in the shape of an EMS in charge of monitoring, controlling, simulating the usage of energy resources and exchanging data among the available devices;
- the implementation of a small-scale electro-mobility system in order to assess the potential benefits of such of a program in the smart grid context integrated with a multi-carrier plant.

The concept proposed by the INGRID project for addressing these challenges consists in a multi-carrier hub system able to handle and manage the processes related to two energy carriers, electricity and hydrogen, and it is ideally connected to three different energy distribution grid, acting as a smart interface between these three systems: the MV distribution grid, the LV distribution grid, the gas distribution grid. The above mentioned multi-carrier hub is composed by:

- a WE which is in charge of converting electricity into hydrogen; it is supplied by a distribution grid to which the envisioned INGRID plant is connected;
- an Hydrogen Solid-state Storage (HSS) system where the produced hydrogen is stored and properly conditioned. The HSS system forms two different channels:
    - the Open Loop (OL) channel, where the hydrogen is stored for being injected in a gas distribution network or for being sold to a tailored market and/or an hydrogen customer;
    - the Closed Loop (CL) channel, where the hydrogen is stored for being retransformed in electricity and injected in the LV grid distribution grid in order to provide grid services;
- a FC which is in charge of converting the hydrogen coming from the HSSs installed in the CL channel for injecting electricity to a LV distribution grid.
- an EV recharging system that can be supplied by both the LV distribution grid or directly from the electricity generated by the FC.

Both the WE and FC systems are equipped with their own power electronic converters for conditioning the inlet and the outlet electricity. In Figure 20, the scheme of a typical INGRID plant solution is shown.

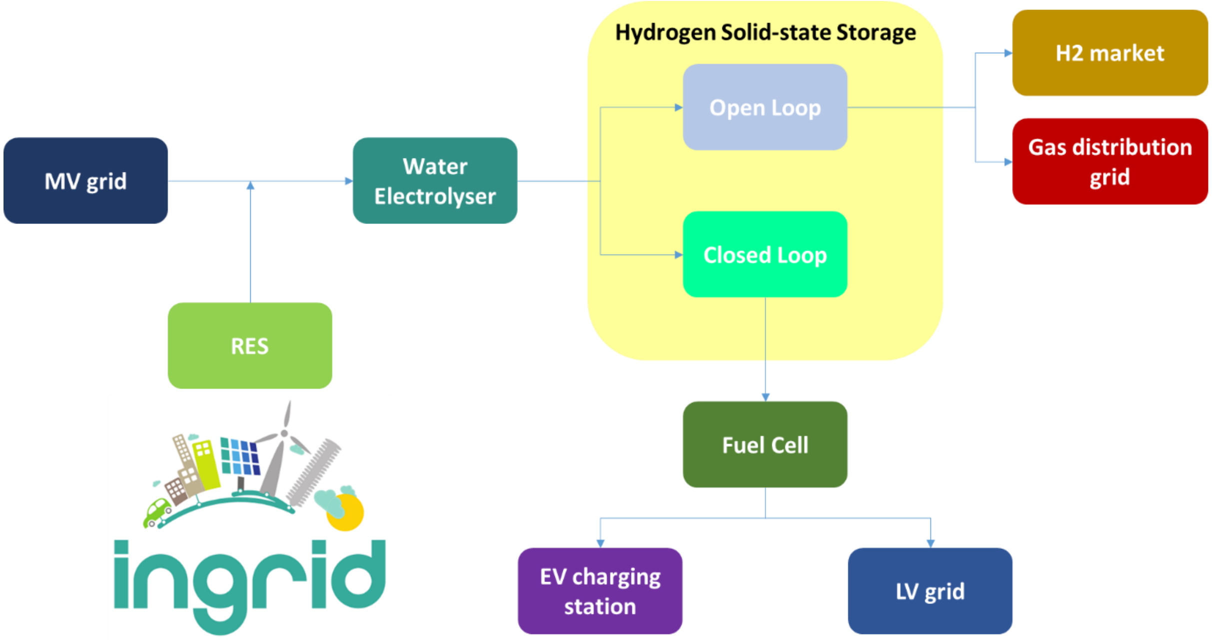


Figure 20 – Scheme of the general framework of a perspective INGRID instantiation.

The proposed concept allows a series of energy related operations: the WE absorbs electricity from a MV feeder that is characterized by a great amount of power generated by RES systems flowing upstream towards the HV voltage system; the load contribution of the WE allows avoiding or reducing the reverse power flow phenomena. The hydrogen produced by the WE is conveyed through a gas panel where the hydrogen flow is split into two channels, the OL and the CL ones. The HSSs installed in the OL channels stores hydrogen to be sold to the hydrogen market, for instance an industrial or public entity interested in buying hydrogen, or to be injected into the gas distribution network, before being properly conditioned. The HSSs employed inside the CL channel are instead involved in reconverting the hydrogen in electricity: after the storage phase, the desorbed gas is sent to the FC. In its turns, the FC produces electricity at LV level: this power can be injected to the LV distribution grid or used locally for recharging EV by means of the recharging station installed inside the plant. This tasks represent the provision of load balancing services to the distribution system. It worth noting that an instantiation of an INGRID plant is able to provide different services to the DSO, whose entity and effectiveness are strictly related to the performances of the equipment, in terms of rated power, time responsiveness, dynamic behaviours, etc. The availability in providing such services gain more and more momentum since the ICT infrastructure responsible of the management of the plant aims at enhancing the employment of the energy resources taking also into account the requests from the DSO.

The key technology breakthrough of this solution is represented by the solid-stage gas storage system based on magnesium hydrides. Metal hydrides are chemical compounds generated by the reaction between gaseous hydrogen and certain metals, such as magnesium. For a given temperature, if the pressure is above the equilibrium pressure, the metal absorbs hydrogen to form a metal hydride; instead, if the pressure is below the equilibrium pressure, hydrogen is desorbed, and the metal returns to gaseous state. The equilibrium pressure varies directly with temperature. Among the investigated materials, magnesium hydrides (MgH2) are particularly suitable for mass storage because they offer a large range of benefits, such as: (i) totally reversible storage approach, (ii) loading and unloading operations at typical pressures of the available interfacing equipment, (iii) minimum time for complete loading/unloading operations, (iv) unloading at fuel cell/H2 gas turbine inlet pressure, (v) no need of compression, implying relevant energy, cost and maintenance savings, (vi) high cycling stability, that is high reliability.

The ICT management tools are responsible of several tasks related to the operations of the plant. Firstly, the monitoring system is in charge of the measurement and graphic visualisation of all the relevant data coming from the field devices; besides this system, the ICT tools are also responsible of the control of the plant, in terms of sending setpoints and communicating with the low level control system of each device. Moreover, the EMS is the tool designed for evaluating the optimal usage of energy resources, making decision and allowing the operator to properly choose the operational configuration. These aspect, that are those related the flexibility platform concept, will be deeply investigated in the next sections.

Finally, the researches conducted within the INGRID project have been deployed and tested in a real site demonstrator, located in Troia (FG), Italy. In this demonstrator, all the devices have been commissioned, installed and tested, all the software deployed and integrated. A series of test campaigns has been performed and many data about the working phases of the system have been collected, as a proof of concept of the proposed results.

4.1.1.2 Details of the Project

As already mentioned, the INGRID project has been funded within the EU Seventh Framework Programme for the topic "Storage and balancing variable electricity supply and demand". The Project lasted 57 months, from the 1st July, 2012 to 31st March, 2017.

The participant partners of this Project were seven, from Italy, Spain, France, and Belgium. The entities composing this partnership are:

1. Engineering Ingegneria Informatica S.p.A. (Italy), a leading provider of advanced ICT systems and services to diverse commercial and governmental customers, with a particular attention to the energy and smart grid sector. It is the coordinator of the project and responsible of the ICT framework in all its parts, from the development to the deployment in the demonstrators plant.
2. McPhy Energy S.A. (France), committed in carrying out the industrial development of the storage technology process developed by the National Centre for Scientific Research and the Université Joseph Fourier in Grenoble. It is responsible of the HSS systems and all their auxiliaries, from the design to tests and the commissioning of the devices in the plant.
3. Hydrogenics Europe N.V. (Belgium), committed to satisfy the hydrogen needs in the industrial energy and renewable sectors by designing and manufacturing electrolysis gas generators and hydrogen fuelling stations. It is responsible of the WE and the FC and all their auxiliaries, from the design to the tests and the commissioning of the devices in the plant.
4. Fundacion Tecnalia Research & Innovation (Spain), forms a private, applied research centre of international excellence with a great impact on local industry, representing a centre that attracts people and organisations in the field of smart energy. It is responsible of the development of the forecasting, modelling and the simulation tools of each device and of all the entire plant.
5. Ricerca sul Sistema Energetico S.p.A. - RSE (Italy), is a research centre located in Milan to take over funded research activities of national and international interest in the energy sector, especially RESs, smart grids, and regulatory aspects. It is responsible of the study and the investigations about the environmental impacts as well as the current policy and regulatory conditions in such an energy context.
6. e-distribuzione S.p.A. (Italy), is the largest power company in Italy and Europe, second listed utility by installed capacity; it ensures the electric power distribution service over its owned distribution networks. It is responsible of the electrical interfaces between the INGRID plant and the MV and LV grids, as well as the deployment and test of the EV recharging station.

7. Agenzia Regionale per la Tecnologia e l'Innovazione Puglia - ARTI (Italy), is a public body whose primary mission is that of promoting and consolidating the regional system of innovation. It is responsible of the communication aspects and the dissemination of the Project, especially at the local and regional level.
8. Studio Tecnico BFP S.r.l. (Italy), is a dynamic and flexible engineering company with several years of experience in the energy sector for the production, transmission and supply of electrical energy, in particular from renewable sources such as sun and wind, and also in the oil sector. It is responsible of the civil works related to the demonstrator plant, the authorisation processes and the plant erection.

In Figure 21, the partners of the INGRID project are listed and geographically located over the Europe.

It is clear how the expertise and the know-how brought to the Project by each partner-has been a key components for the success of the Project itself and for the achievement of all the objectives. A strong collaboration has characterised the Project over all its duration, driven by many meetings, audio conferences, test sessions, etc. In particular, the erection and the operation of the demonstrator plant is a clear and evidence of the effectiveness of the proposed solution.

Figure 21 – Partners beneficiaries of the INGRID project.

4.1.2 Multi-carrier hub approach

The INGRID system is a hybrid structure involving two energy carriers and can be considered as an integrated multi-carrier energy hub. A multi-carrier energy hub is defined as a “hybrid energy system which interfaces between energy producers, consumers and the transportation infrastructure” [231]. G. Andersson et al. [231] [232] [233] have proposed a matrix modelling approach for the entire hybrid system, even with storage devices inside. This model can represent generally and comprehensively the conversion and storage stages of multiple energy carriers. Accordingly, a model of the INGRID hybrid system using this approach has been developed: the final aggregate instantiation is a multi-carrier energy system that involves both electricity and hydrogen. This model also permits dealing with storage devices, and so it is perfectly suitable for the system purposes. In Figure 22, a graphic representation of the multi-carrier model is depicted, reporting all the devices working in the INGRID system.

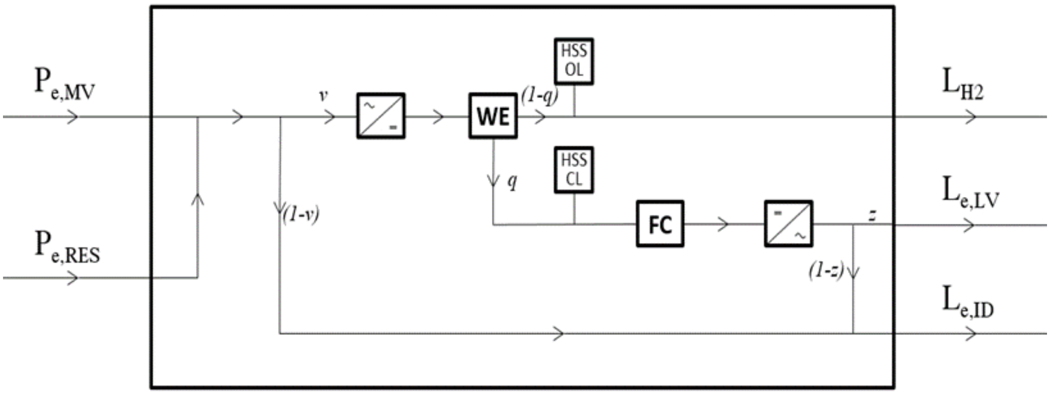


Figure 22 – Block diagram of the proposed multi-carrier model of the INGRID concept.

In this block diagram, the input energy carriers of the system are the electric energy coming from the MV grid ($P_{e,MV}$) and/or the RES connected to the MV feeder supplying the plant ($P_{e,RES}$). The output energy carriers, in their turn, are considered as loads; these are: (i) the hydrogen flow toward the specific market (L_{H2}), (ii) the electric energy sent to the LV grid ($L_{e,LV}$) and (iii) the electric energy used for supplying the Electric Vehicle Recharge System (EVRS) ($L_{e,ID}$). The WE and the FC are considered, respectively, with their AC/DC and DC/AC conversion devices. Finally, the HSSs, for both OL and CL channels, are modelled by their own blocks. This diagram presents dispatching factors whenever a flow line splits in two different paths (see “v”, “q” and “z” in Figure 22). These factors allow the definition of the amount of energy sent to one process or another. All of them can assume a value between 0 and 1.

The relationships between different energy carriers can be directly deduced by the flow chart and can be expressed through a matrix equation:

$$\begin{bmatrix} L_{H_2} \\ L_{e,LV} \\ L_{e,ID} \end{bmatrix} = \begin{bmatrix} v\,\eta_R\,\eta_{WE}\,(1-q) & -v\,\eta_R\,\eta_{WE}\,(1-q) & e_{OL} & 0 \\ v\,\eta_R\,\eta_{WE}\,\eta_{FC}\,\eta_I\,z\,q & -v\,\eta_R\,\eta_{WE}\,\eta_{FC}\,\eta_I\,z\,q & 0 & e_{CL}\,z \\ \begin{array}{c} v\,\eta_R\,\eta_{WE}\,\eta_{FC}\,\eta_I\,(1-z)\,q+ \\ +(1-v) \end{array} & \begin{array}{c} -v\,\eta_R\,\eta_{WE}\,\eta_{FC}\,\eta_I\,(1-z)\,q+ \\ +(1-v) \end{array} & 0 & e_{CL}\,(1-z) \end{bmatrix} \cdot \begin{bmatrix} P_{e,MT} \\ P_{e,RES} \\ \dot{E}_{OL} \\ \dot{E}_{CL} \end{bmatrix}$$

In this matrix equation, each device is represented by its instantaneous efficiency η_i; the storage system contribution is represented by the parameters e_{OL} and e_{CL}, which can be seen as the energy efficiencies of the whole storage system, depending on their working state. These parameters will be multiplied by $\dot{E}_x$ (where x could be OL or CL) that corresponds to the internal flow of the device, assumed to be the time derivative of the stored energy.

The relationships expressed by this matrix equation allow to derive directly the equations for each single energy carrier:

$$L_{H_2}= \left(P_{e,MV}+P_{e,RES}\right) v\,\eta_R\,\eta_{WE}\,(1-q)+\dot{E}_{OL}\,e_{OL}$$

$$L_{e,LV}= \left(P_{e,MV}+P_{e,RES}\right) v\,\eta_R\,\eta_{WE}\,\eta_{FC}\,\eta_I\,z\,q+\dot{E}_{CL}\,e_{CL}\,z$$

$$L_{e,ID}= \left(P_{e,MV}+P_{e,RES}\right)\left[v\,\eta_R\,\eta_{WE}\,\eta_{FC}\,\eta_I\,(1-z)\,q+(1-v)\right]+\dot{E}_{CL}\,e_{CL}\,(1-z).$$

So, taking into account all the above shown equations, the inlet and outlet parameters of the multi-carrier model are strictly put in relationship with the values that are interested in the optimisation process criteria, in particular the electrical power absorbed from the MV grid by the WE, the electrical power injected to the LV grid by the FC, the electrical power supplied to the EV recharging system, as well as the hydrogen flows:

$$\left(P_{e,MV}(t_i)+P_{e,RES}(t_i)\right)=(P_{WE}(t_i)+P_{IDgrid}(t_i)+P_{RES}(t_i))\cdot\Delta t$$

$$L_{H2}(t_i)= \left(P_{e,MV}(t_i)+P_{e,RES}(t_i)\right)(1-q)v\,\eta_R\eta_{WE}=P_{WE\text{-}HSS\text{-}OL}(t_i)\cdot\Delta t\cdot K_{WE}$$

$$L_{e,LV}(t_i)=\left[\left(P_{e,MV}(t_i)+P_{e,RES}(t_i)\right)\eta_R\eta_{WE}\eta_{FC}\eta_I vq+\dot{E}_{CL}e_{CL}\right]z=(1-\beta)P_{FC}(t_i)\cdot\Delta t$$

$$L_{e,ID}(t_i)=\left(P_{e,MV}(t_i)+P_{e,RES}(t_i)\right)(1-v)+\left[\left(P_{e,MV}(t_i)+P_{e,RES}(t_i)\right)\eta_R\eta_{WE}\eta_{FC}\eta_I vq+\dot{E}_{CL}e_{CL}\right](1-z)=$$
$$=P_{IDgrid}(t_i)\cdot\Delta t+\beta\cdot P_{FC}(t_i)\cdot\Delta t$$

where:

- P_{WE} is the total power absorbed by the WE, [kW];
- $P_{WE\text{-}HSS\text{-}OL}$ is the part of the power absorbed by the WE used to feed HSS OL, [kW];

- K_{WE} is the WE conversion factor between electricity and hydrogen, [Nm^3/kWh];
- P_{FC} is the electric power produced by FC, [kW];
- P_{IDgrid} is the forecasted power demanded by ID (for EVRS), [kW];
- P_{RES} is the forecasted power produced by RES system, [kW];
- Δt is the duration of time slot;
- t_i is the time stamp.
- β is a real coefficient between 0 and 1 which defines the part of the power produced by the FC absorbed by EV recharging system (instead,(1-β) is the part of the power produced by the FC used for ancillary services).

The reader is invited to note that the input terms of the multi-carriers hub are labelled with $P_{i,k}$ and $L_{z,v}$ even if they define energy values, while the terms of optimisation algorithms uses P_j defining power flows. This set of equations has been employed for defining the equations that have been shaped into the objective function of the optimisation process, since they are able to model the energy behaviour of all the devices inside an INGRID plant instantiation.

4.1.3 ICT-based EMS solution

As explicitly prescribed in one of the Project goals, the INGRID concept foresees the supervision of an ICT-based framework which is responsible of many of the management tasks inside an INGRID plant through the EMS. This framework has been developed and deployed as an effective flexibility platform able to perform all the management and control operations as well as to allow the data exchange among the actors inside the plant and between those actors and external ones. Firstly, the core application of this EMS addresses the actual management operations related to the optimisation of energy resources, the accommodation of the data coming from different devices and actors, their storage, as well as providing the tools allowing the control of the process. This part is strictly linked to the one providing GUI and HMI to the human operator, in order to monitor the current data of the plant, visualise the results of the management process and interact with the plant itself. All the information coming from the devices of the plant are collected and handled by proper integration and monitoring tools, represented by a complete SCADA solution. Finally, the connection with all the external actors, intended as both physical entities and software tools is addressed by proper means realised on purpose.

This description is at the basis of the INGRID EMS architecture designed after a deep investigation and analysis of the requirements of an INGRID instantiation, which is not in the scope of this thesis. In Figure 23, the overall EMS architecture is shown.

Figure 23 – The architecture of the INGRID EMS solution.

As depicted in the figure above, this architecture consists of four layers: (i) the Application layer, (ii) the Core layer, (iii) the Integration layer, and (iv) the Link layer. In the following, these layers are described in depth.

4.1.3.1 Application layer

This layer is composed by all the user interfaces and dashboards adopted for human operators, maintenance workers, and supervisors, along with software counterparts belonging to other layers, e.g., the EMS Federation Connector. The tools inside this layer allow all the external interactions with the plant by directly visualising the all the relevant information about the plant status, such as the operational phase as well as the power and hydrogen flows, the requests from the external actors, the forecasted power profile, and the scheduled data coming from the optimisation core.

In this layer, the EMS Federation Connector is also included. This component is shared with the Core layer because the connector is intended as an end point for output coming from the EMS towards the EMS Federation and also as an inputs which may trigger the optimisation phases. This is a possible evolution of the EMS in terms of collaboration with a future network of federated EMSs which can work together, following high level criteria to achieve a global optimisation.

4.1.3.2 Core layer

In this layer, the core elements of the EMS are merged all together to provide the functionalities of the EMS.

The central component of this layer is the Energy Supply & Demand Matcher (ESDM), which is the engine of the EMS and of the entire INGRID platform. It receives energy requests from loads and energy offers from sources and, on the basis of its optimisation strategy, finds the best INGRID system configuration. In order to perform its optimisation tasks, this component takes advantage of the data collected by the lower layers, translated in a common format and eventually stored into an Integrated Data Base (IDB) for persistence. Its key functionalities are largely described in the next sections.

The ESDM is accompanied by several tools in order to fully cover the functionalities provided by the EMS. It is supported and integrated by some modules which complete the real core of the EMS: the Decision Support System, the Strategic Planner, and the Security Module. These modules provide all the operational information to be taken into consideration during the optimisation once received all the required input data.

4.1.3.3 Integration layer

This layer is totally dedicated to the advanced monitoring and actuating functionalities provided by the EMS. It is directly connected to the lower Link layer, by means of an Integrated SCADA Layer which collects all the incoming data and creates a single unique end point for the monitoring activities as well as for the control of the underlying machinery.

The Advanced Monitoring Tools and the Advanced Acting Tools are directly connected, via the Integrated SCADA Layer, to the adapters of the lower layer: whilst these adapters are all monitored, since there are always a read facilities provided by the SCADA associated to each specific component, the acting tools are usable only on those components which are controllable.

The Integrated SCADA Layer will provide to (and receive from) the upper layer of the architecture a set of data about the consumption and generation profiles the components intend or request to follow, according to the nature of the component itself. The prices associated to the profiles to follow, intended either as generic constrains or a particular profiles are provided to the Core layer in order to implement a particular strategy (typically economically based) imposed by the supervisor of the EMS. These costs or prices comes from the lower layer.

Provided that not the whole data coming from the components may be part of the optimisation process, however some kinds of data can be further processed and recorded. This is why this layer is also tightly connected to the Data Integration functionalities, provided by the upper layer.

4.1.3.4 Link layer

In this layer, several components external to the EMS itself are reported, along with a series of adapters and managers. This is the lowest layer of the architecture, the one connected to the hardware, the sensors and all the equipment composing the INGRID platform itself. This layer is also connected to those external systems which interact with the EMS. The entities external to the EMS but included in this layer of the architecture are hardware components (the EV system, the WE, the HSSs, the FC, the RES) and their software systems, such as the Distribution Management System (DMS) employed by the DSO for monitoring and data exchange purposes.

In order to make hardware and software external systems interact with the rest of the INGRID platform, a set of integration managers are integrated: each manager will be in charge of linking together all the information that the component provides and needs in order to implement the protocols and the interfaces managed by the upper levels of the architecture. The main target is to create a shared data model which all the components must implement and use to interact with, and a common communication system which can be used to convey all the information. All the data coming from or directed to the Link layer are managed internally by the SCADA level specific for each component.

4.1.4 Demonstrator test site

4.1.4.1 Demonstrator location in Troia, Italy

All the researches, the studies, the design and the manufacturing efforts performed during the Project has been successfully deployed in a demonstrator test site located in Italy. Tests related to its operations have been conducted and analysed within the scope of the Project.

The demonstrator test site is located in Troia (FG), Italy, close to the Industrial Settlement Plan zone of the municipality of Troia. The plant and the necessary infrastructure have been built in lands owned by the municipality of Troia. In Figure 24, the demonstrator site is georeferenced in the map of Italy and a satellite view of the site is shown.

Figure 24 – Geographic location of the INGRID demonstrator and a satellite view of the site.

Troia is one of the municipalities in Europe with the highest rate of energy produced by renewable sources. For this reason, the choice of Troia municipality is also symbolic for the development of this new initiative. In particular, the INGRID demonstrator is connected to a MV grid portion that is characterized by an extremely high penetration of RES sources, especially PV plants, whose power injection cannot be always be matched by the load requests of the consumers of that area, since it is a rural zone of the Apulia region. The excess of power generated by RESs causes particular stress conditions for the electrical systems, such as overload, thermic damage, and, above all, power reverse power flow phenomena. Figure 25 shows clearly how the increase of these phenomena is getting more and more impacting for distribution and transmission grids: during Saturdays and Sundays, the excess of power generated by PV plants is conveyed upstream towards the HV network.

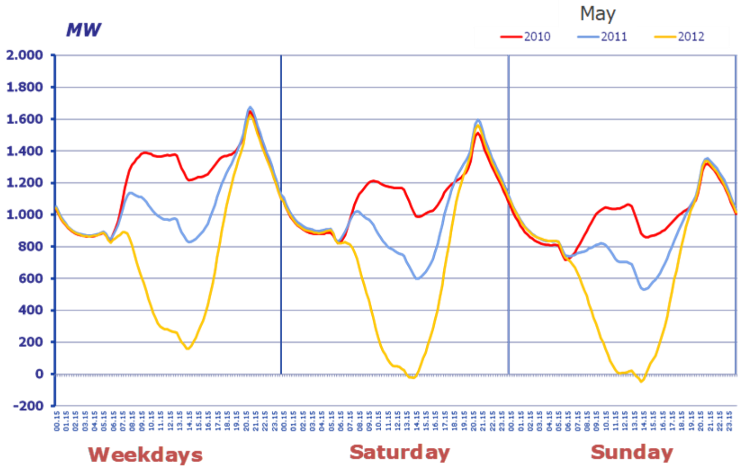


Figure 25 – Power flows from the distribution grid (owned by e-distribuzione) and transmission one (owned by Terna) in the Apulia region.

The demonstrator plant is supplied by a MV feeder pertaining to a HV/MV primary station, whilst it is connected to the LV grid for injecting the power generated by the FC. In Figure 26, the electrical scheme of the grids and the connection with the INGRID plant is depicted.

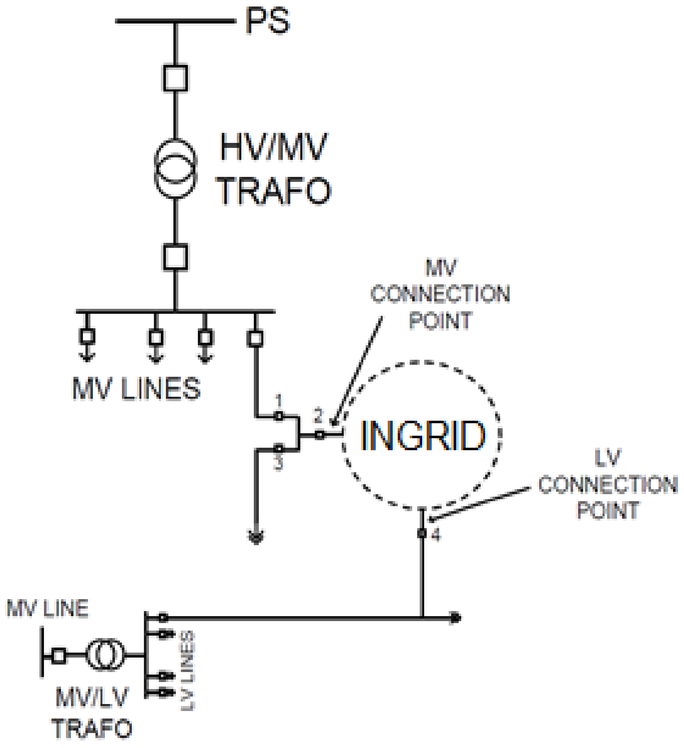


Figure 26 – Electrical scheme of the connection between the INGRID demonstrator and the MV and LV lines.

4.1.4.2 *Technological equipment*

The real life instantiation of the INGRID concept installed in the demonstration site presents the physical deployment of the equipment provided by the technological partners. In the view of the real operation, the rated values and the features of each device has been tailored on the services to be provided in the Apulia region context. In the following, the specifics of the installed equipment is reported.

- WE: this devices is brought by Hydrogenics. It is an alkaline WE, able to reach up to a production capacity of 180 Nm^3/h of hydrogen. This is realised with 4 prototype cell stacks, Figure 27. Each of these cell stacks has been thoroughly tested in Hydrogenics test facility.

Figure 27 – One of the four cell stacks installed inside the WE.

The WE is designed according to a modular production unit whose different subparts are all housed in a stand-alone container; in Figure 28, the container installed in the demonstrator site is shown. The unit consists of:

- a control panel, which is Siemens PLC that controls the unit and is monitored by means of a HMI;
- a power rack that converts the tri-phase incoming AC power to DC, required to activate the electrolytic dissociation of water;
- a water purification system, where a reverse osmosis process is completed to avoid impurities and loss of conductivity;
- a hydrogen generator and gas separator, that takes care of the production of hydrogen;
- a cooling system where the electrolyte and the produced hydrogen gas are cooled down after the gas separation;
- a hydrogen purification system, where a drying system is considered in the gas-liquid separating vessels in order to purify the hydrogen.

Figure 28 – The complete set-up of the WE deployed inside the INGRID plant.

The central part of the process container contains the cell stacks, with the gas liquid separator on top. On the left end of the process container, the general purpose room is located, which contains the reverse osmosis system and the control panel. On the right end of the process container, the hydrogen purification system and break-tanks/demisters skid are located. Basically, the reverse osmosis system is used to purify the water coming to the WE and make it ready for the following stages. The gas generating system operates the electrolysis process, by means of the cell stacks, and separates the gas from the liquid: an AC/DC converter is used before this stage. Finally, the hydrogen purification system is responsible for drying the H2 from the residual water, passing from rapid cooling and heating phases, to reach up to 99,999999% of purity.

In Table 2, some of the most significant parameters of the WE are shown.

Table 2 – Specifics and parameters of the WE installed inside the INGRID demonstrator.

Water Electrolyser parameter	Note
Nominal power	4 x cell stacks of 243 kW each = 970 kW BOL (Beginning Of Life).
Recover from standby	• From 60 s to 90 s when starting pressure > 8 barg.

	• From 120 s to 360 s when starting pressure is between 0,5 and 8 barg. About 1000 s when starting pressure < 0,5 barg.
Max power production	It can be set and ramp-up is applied. No external control function. It has been set to 870 kW for the duration of the tests (90% of its nominal power).
Min power production	It can be set so as lower setpoints are interpreted as min allowable setpoint as long as there is hydrogen consumption. It has been set to 300 kW for the duration of the tests (30% of its nominal power).
Ramp up and ramp down in normal conditions	Max ramp rate = 40 kW/s. 25s to ramp up or to ramp down between 0% and 100% of its capacity, with a precision of 95%.
H2 flow (production)	• 300 kW (min) = 4,98 kg/h H2. • 870 kW (max) = 14,45 kg/h H2. The proportionality is basically linear. About 1 kg/h is used for regeneration in the purification system.

- FC: it is brought by Hydrogenics. The type of fuel cell considered is a Proton Exchange Membrane (PEM), composed of a proton exchange membrane (polymer) between two catalyst-coated carbon papers (platinum and/or similar types of noble metals are used as the catalyst material).

  The entire FC system consists of several parts that support the electricity generation process:

  - FC rack, on its turn composed of 4 water based cells, Figure 29, for the reaction of H_2 with O_2 in air generating the DC electricity and;
  - DC/AC inverter system to allow grid coupling;
  - cooling system;
  - outdoor housing.

Figure 29 – The cells rack installed inside the FC.

The fuel cell rack with an installed power of 120 kW is a modular build with four fuel cell power modules (30 kW each), one FC heat exchanger whose general purpose is to evacuate excess heat and one air delivery system. Electricity and water are the result of the reaction inside the power modules. The power module includes the associated subsystems and control software required to produce electricity. The control system will automatically control the auxiliary equipment plus the cells rack. The integration of FC in a very compact rack is a Hydrogenics novelty that allows to install substantial FC power on a limited footprint (roughly 120 kW/m²), which is shown in Figure 30. To enable coupling to the grid, conversion to AC power is required, which is performed by an inverter. This inverter was selected carefully in order to comply with Italian standards, more specifically with the standard CEI 0-21.

Figure 30 – The FC container set-up installed inside the INGRID demonstrator.

In Table 3, some of the most significant parameters of the FC are shown.

Table 3 – Specifics and parameters of the FC installed inside the INGRID demonstrator.

Fuel Cell parameter	Note
Nominal power	4 x modules of 30 kW each = 120 kW.
Recover from standby	• From 2 to 4 minutes from hot standby. Up to 15 minutes from cold standby.
Max power production	It can be set and ramp-up is applied. No external control function. It has been set to 70 kW for the duration of the tests (58% of its nominal power).
Max power production	Technically there is no limitation. It has been set to 20 kW for the duration of the tests (17% of its nominal power).
Ramp up and ramp down in normal conditions	Max ramp rate = 30 kW/min.
H2 flow (consumption)	• 20kW (min) = 1,57 kg/h H2. • 90kW (max) = 5,48 kg/h H2. The proportionality is basically linear.

- HSSs: they are brought by McPhy. The HSS units are based on metal hydride technology. By using different temperatures and low pressures, hydrogen is either absorbed or desorbed by the metal. Magnesium hydrides (MgH2) has been selected for mass storage because they offer a large range of benefits as:
    - a totally reversible storage can be realized because of reversibility of reaction;
    - hydrogen can be absorbed and stored at typical electrolyser outlet pressure;
    - hydrogen stored can be reversibly desorbed at pressure typically adopted into fuel cells and H2 gas turbines;
    - no intermediate compression stages are required (compression and maintenance costs are saved);

- high cycling stability.

The type of storage chosen for the INGRID system is a non-adiabatic one, called High Density Series system. The gaseous hydrogen, coming to the storage, is absorbed with an exothermic reaction, by the composite which is contained into hydrogen vessels. This heat released during the absorption step is evacuated by a fan outside the shelter. During the desorption step, the heat is given back to the hydrogen vessels by the fan with air heated through electrical elements.

The HSS systems are able to store up to 150 kg and are composed of different units:

- the transportable hydrogen module, composed of 30 hydrogen vessels, piped together and connected to downstream hydrogen piping by means of a quick connect plug with isolation valve, Figure 31;
- the stationary filling/unloading station, constituted of a thermal module in which the hydrogen block is inserted, a gas module with hydrogen piping and valves as well as an electrical module (electrical cabinet with PLC).

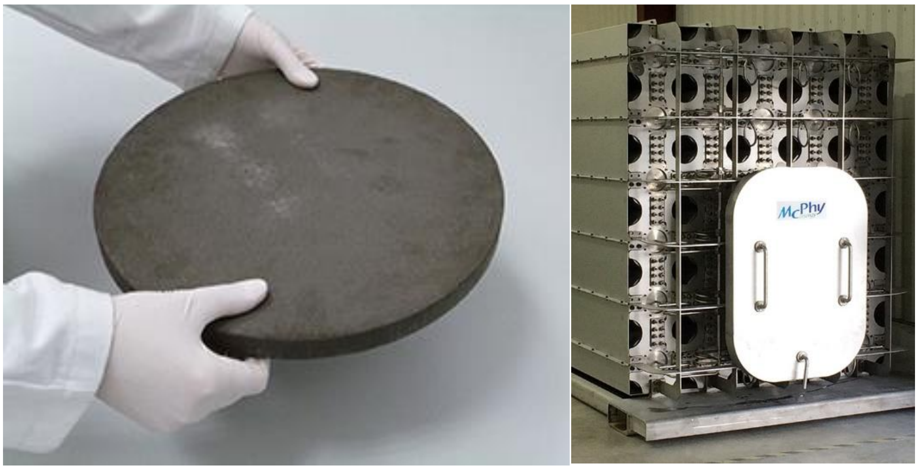


Figure 31 – The magnesium disk and the vessels installed inside an HSS system.

Each HSS system consists of magnesium disks inserted in the stainless cartridges, Figure 31: the cartridges are then assembled as a solid block and piped together through a welded inox piping. Each cartridge, composed by around 100 disks (containing 0,5 Nm^3 H2 per disk), thus stores 5 kg H2. Each block, composed by 30 cartridges, thus contains 150 kg H2.

A set of HSSs are installed inside the demonstration site, Figure 32: the complete equipment consists of three stations, two installed in the OL channel and one in the

CL one, and five hydrogen storage modules, to be installed inside a proper station depending on the operational configurations.

Figure 32 – The complete HSS systems installation inside the INGRID demonstration site.

In Table 4, some of the most significant parameters of the HSSs are shown.

Table 4 – Specifics and parameters of the HSS installed inside the INGRID demonstrator.

HSS system parameter	Notes
Heating power consumption:	150 kW (110 kVA) per filling station
Heating duration (from ambient to 350 °C):	10 hours
Operative power consumption (at 350°C):	1,5 - 10 kW (10 kVA) per filling station
Max absorption rate:	About 6 kg/h per storage (single charge)
Max desorption rate:	About 5,5 kg/h per storage (single discharge)
Max absorption duration:	10 hours for heating up + 21 hours (single charge) per storage
Max desorption duration:	27 hours (single discharge) + 4 hours for cooling down per storage
Maximum capacity (of 3 blocks under test):	105%, 100% and 110% (calculated on a theoretical basis of 150 kg)

- EV recharge station: this device is brought by e-distribuzione. It is part of the CL channel and, besides allowing an electromobility program, supports the implementation and provision of LV services. The feature of the power supply are:
    - 400 V (AC), 50 Hz, three-phase line;
    - connection terminal board for 25 mm^2 section cable, with booster to power charging stations in series;
    - a certified three-phase bidirectional electronic meters.

The station ensures full remote management and control functionalities, allowing to perform data acquisition as well as monitoring of station status and to integrate smart grid concepts by means of smart measurement features. The EV recharge station allows also to handle the automatic payment for the customer, properly identified by means of a wireless smart card.

In Figure 33, the charging station installed inside the INGRID plant for test purpose is shown.

Figure 33 – The EVRS installed inside the INGRID demonstration site.

4.2 Optimisation framework

In this section, the features of the optimisation framework are provided in order to describe the process allowing to handle the management task of the INGRID system. Firstly, the criteria that lead the optimisation process are addressed and the possibility of taking into account various of them is discussed and explained. After that, the overall architecture of the proposed optimisation framework is depicted, representing all the input and the output data of the optimisation mechanisms along with their features. Subsequently, the objective functions and the constraints set-up for the optimisation evaluation are shown are detailed.

4.2.1 Management criteria of the INGRID system

As already discussed in section 4.1.1.1, the INGRID project implies the accomplishment of several ambitious goals, mainly related to the integration of modern power system technologies, such as RESs, EVs, and storages, by adopting innovative techniques and intelligent control systems relying upon an advanced ICT solution. The cutting-edge magnesium hydride technology employed for the hydrogen storage systems covers a part of the innovation brought inside the project. A great portion of technological advancement is also represented by the EMS solution implemented for assessing the optimisation and control tasks of the system: this is based upon a multi-objective optimisation approach, allowing to deal simultaneously with several objective functions, thus to handle different control criteria. The solutions provided by this technique represent the best trade-off that can be obtained while pursuing more than a single objective.

The system envisioned by the INGRID project deals with two carriers, electricity and hydrogen, and can interact, either physically or economically, with several actors, such as DSO, RESs, energy retailers, hydrogen market, hydrogen customers, EV users, etc. It is clear how a plenty of management criteria can rise from the assessment of each single dynamic relationship and these can be of different nature: economic, technical, operational, environmental, safety-based, and so on.

Due to the great amount of criteria on which the energy management approach could rely on, it is thus pivotal to address several of them in a unique process: as such, the solutions provided by the process allow to pursue the objectives implied by several criteria. In the INGRID project, two main criteria have been chosen for designing and developing the EMS, economic criterion and technological one.

The economic criteria are usually driven by the evaluation of the net flows related to the purchasing of energy as well as auxiliaries for supplying the entire plant and the sale of energy, both in form of electricity and hydrogen. These can be rewarded as an amount of energy, thus monetised with a certain amount of money for each kWh, or as a service, thus monetised on the basis of power capability, kW, or on the basis of time availability of the service. In the case of the INGRID project, the economic criterion is leveraged by the purchase of electricity from MV grid and the sale of the hydrogen to an industrial customer as well as the provision of rewarded balancing services to the LV grid. This criterion in modelled by an objective function that evaluates the daily revenues of the system.

The technical criteria are often based on the provision of service to the actors responsible of the technical management of the grid infrastructure, such as DSOs and TSOs. These actors asks the energy system, or its manager, to provide services that can ease the management of the grid from the technical point of view by avoiding critical peak hours, reverse power flow phenomena, voltage sags, load unbalances, etc. Moreover, the services asked to a smart energy system can be related to the provision of ancillary services. Usually, grid operators ask for a certain behaviour in terms of power profile to be followed, inside defined tolerance range, for a certain time window, or the availability of energy and power reserves for the provision of ancillary services in some hours. In the implementation of the INGRID concept proposed in this thesis, the technical aspects are addressed by a strict collaboration with the DSO: it sends a request for power consumption profile related to the MV connection point (so basically the power absorbed by the WE) and a request for power generation profile related to the LV connection point (so basically the power injected by the FC). These criteria are addressed by two objective functions that parametrise the distance between the DSO requests and the actual energy behaviour of the system.

4.2.2 Architecture and approach

In this section, the structure of the optimisation process is described, in terms of steps of the process itself and actors interacting with them. Moreover, the input and the data of the optimisation are listed and the features of their structure are explained, along with the parameters characterising the optimisation algorithm.

The optimisation process is structured in several layers. Firstly, all the input data are collected and sent to the EMS through a communication layer, set-up through the OPC protocol and/or a REST service. The input data are:

- the DSO requests of services provision from the DSO itself as profiles complemented with an upper and lower tolerance limits;
- the generation forecast of RES plants connected downstream the connection point to the MV feeder supplying the plant and the consumption forecast of the EV recharge station, properly evaluated by a dedicated simulation tool;
- price signals related to the cost of the energy supplied from MV grid and to the incentives of LV services provision;
- monitoring data from the field device installed in each plant subsystems.

All these input data are sent once to the optimisation framework before the beginning of the optimisation itself, so that the availability of all the significant information to be taken into consideration during the process is ensured. Once these data are retrieved, they are properly manipulated in order to be compliant with the data structure of the algorithm, manipulating them according to the kind of action required by the optimiser. Moreover, all the constraints related to the operations carried out by the INRID system are implemented. These regard technical aspects of the devices, for instance their rated values, or operational phases, such as turning-on and switching-off delays, slope ratio, etc. The constraints about power balance are taken into account as well. The aspects regarding data and constraints will be addressed in the following sections more in depth.

Before the beginning of the optimisation process itself, an HMI is provided to the human operator of the INGRID plant in order to configure the most relevant parameter of the optimisation algorithm, such as the number of elements of the population and the number of generations to be performed (see section 3.3.3.3).

Once that all the required input information are provided to the optimisation algorithm, the process starts to evaluate and search the best solutions throughout all the solution space, whose boundaries are fixed by some of the technical constraints of the devices. Relying upon a randomised set of feasible solutions, the starting population set is created and processed. During the selected number of generations, all the operations described in the last chapter are implemented in order to improve, generation by generation, the fitness of the solutions with respect to the objective functions. At the end of the process, the algorithm provides a set of Pareto-optimal solutions, each of them representing a set of optimised variables. A single solution is linked to a corresponding value of each objective function, composing a Pareto-optimal solution front. Figure 34 presents an example of a population front of the last generation in a chart where two objective functions addressed by the optimisation problem are reported on the axis. It worth noting the shape of the front distribution, which graphically reports the trade-off performed between the two contrasting trends imposed by the two objective functions.

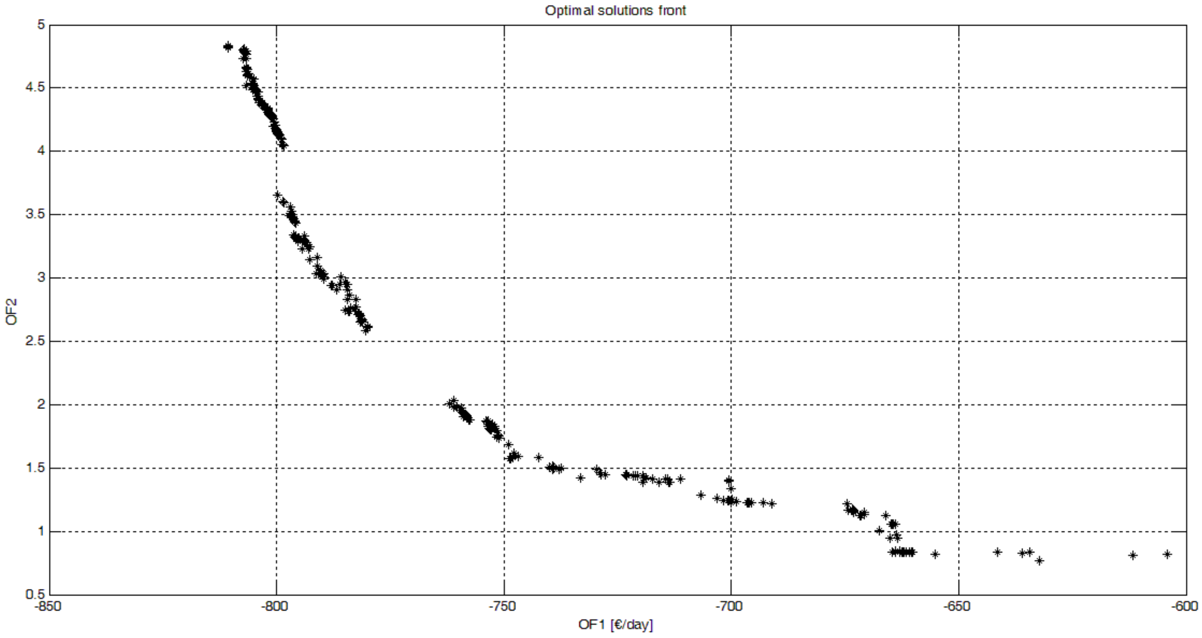


Figure 34 – The Pareto-optimal solution front of an optimisation problem with two objective functions.

It is clear how the different solutions provide very different fitness with respect to the different objective functions of the process. For instance, the solution that offers the best fitness with respect to one objective function is, at the same time, characterised by the less valuable fitness with respect to the other one. This heterogeneity in the fitness values of the Pareto-optimal solutions led to the selection of some solutions allowing the better performance following a certain criterion. This task is performed through the Decision Support System: using a criterion, that can vary according to the need of the plant operation, it selects a fixed number of solutions from the Pareto-optimal ones and provides an HMI to the human operator in order to make them the effective scheduled configuration of the plant.

After the selection of the operator, the chosen optimal solution is sent by the communication layer to both the visualisation dashboard and the OPC server, that is accessible also from the SCADA for setting the optimised data as actual setpoints of the working equipment. Also in this case, the most relevant communication means are OPC protocol and RES services.

The optimisation framework is able to cope with deviations of the real plant configuration from the setpoints suggested by the EMS or with errors in forecasted data. In this case, the optimiser performs a new optimisation in real-time, starting from the data of the current configuration and/or the new forecasted profiles; the time horizon can be set considering only the remaining hours of the day.

The output data of the optimisation process are essentially the scheduled operational configurations of the plant for the 24 hours subsequently the optimisation process. So they are composed by energy flow profiles, both electricity and hydrogen, and other relevant information about the revenues and production data. The output data are:

- the power absorption profile of the WE for the 24 h scheduling after the optimisation process;
- the power generation profile of the FC for the 24 h scheduling after the optimisation process;
- the hydrogen flow generated by the WE and the two hydrogen flows pertaining to the OL and CL channels;
- information about the generated amount of hydrogen in the OL channel and the related economic value;
- the single setpoint for each time stamp of the time horizon addressed by the optimisation process to be sent to the PLC of the devices.

In Figure 35, a graphic representation of the architecture of the optimisation process described above is provided.

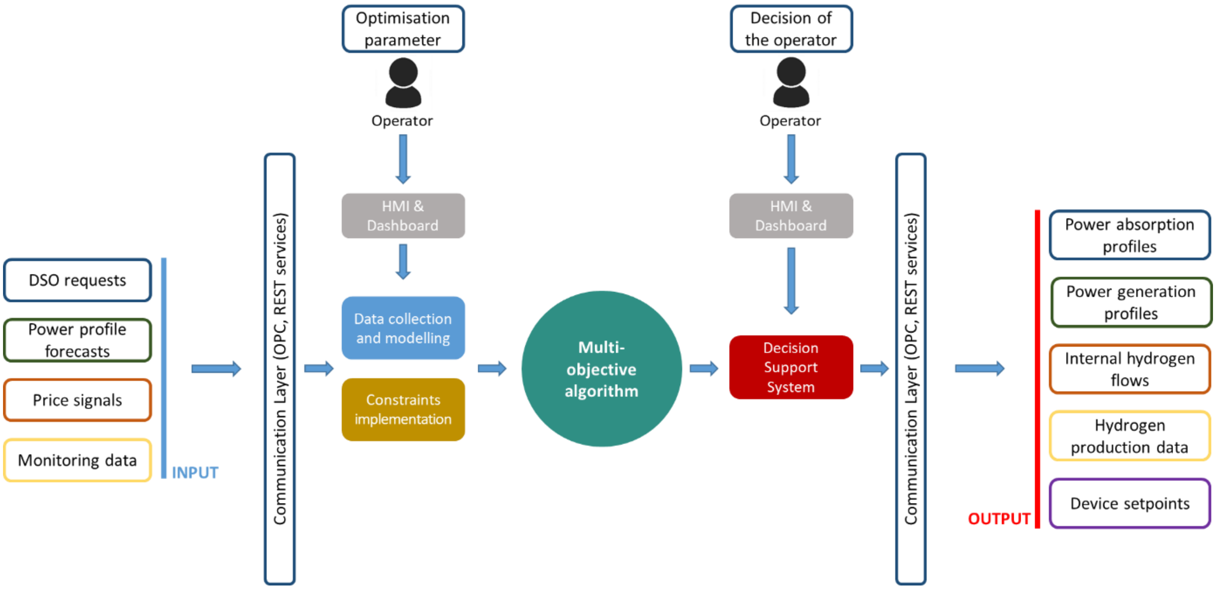


Figure 35 – The architecture of the optimisation process developed inside the INGRID system.

The optimisation process is performed once for the addressed time horizon. All the evaluations are indeed referred to the 24 hours optimisation of the plant, both in terms of economic and technical objectives, as clearly outlined by the objective functions discussed in the section 4.2.4.

The core of the optimisation framework is a component developed in MATLAB® environment implementing the algorithm, properly complied and exported as a JAR. This is imported and invoked by a Java program, which is in charge of receiving data from the OPC server, by means of tailored libraries, processing this information and structuring them for being evaluated by the optimiser, and then sending the setpoints, properly temporised, to the OPC server.

4.2.3 Data structure

The data provided to the optimisation algorithm and those evaluated by the algorithm itself and sent to the devices and/or to the visualisation tools are structured in a proper way in order to easy the access to the algorithm functions and schematically evaluate each time stamp over the time horizon.

As already mentioned, the optimisation process is tailored for performing its evaluation over a 24 hours time horizon, that is considered as reference time windows to which the considerations carried out by the INGRID project are addressed. Nevertheless, this parameter can be set by the operator and be reduced for allowing the process to address the desired time window inside a day.

Another relevant parameter is the time stamp of the process. It is actually the time distance between each evaluation point over the time horizon. The EMS implementation here discussed fixes this value to 15 minutes, implying that every optimisation process has to deal with 96 time stamps (1 time stamp every 15 minutes for 24 hours). Also the time stamp can be properly configured by the user, in accordance to the granularity of the input data provided to the EMS:

Taking into consideration both the time horizon length and the time stamp duration, the data retrieved by the algorithm and all the data coming out from it are structured in arrays (or lists) containing a number of element derived from the number of time stamps occurring inside the time horizon (96 in the evaluation reported for the INGRID project).

4.2.4 Objective functions

As already discussed in the previous sections, the optimisation process relies upon both economic and technical management criteria, addressing daily revenues of the INGRID system and the following of DSO requests at both MV and LV distribution network.

These criteria are implemented by three different objective functions, derived from the mathematical formulations provided in section 4.1.2. The variables chosen as optimisation parameters are three:

- the power absorption of the WE from the MV grid;

- the hydrogen flow through the OL channel;
- the hydrogen flow through the CL channel.

It worth noting that these three parameters allow to handle several aspects of the INGRID system operations: the power supply of the WE allows determining the cost of the purchased energy; the hydrogen flow towards the HSSs of the OL channels allows evaluating the amount of hydrogen stored for being sold and the related economic value; the hydrogen flow to be stored in the CL channel allows assessing the capacity of the CL itself to provided hydrogen to the FC for injecting power to the LV grid. In this way, all the main functionalities of an INGRID plant are taken into account.

The first objective function is based on economic criteria. It addresses the maximisation of the daily revenues deriving from the sale of hydrogen to the hydrogen market and balancing services to the LV grid. It can be defined by roughly considering the purchase cost of the input energy carriers, i.e. electricity from MV grid, and a sale price of the output energy carriers, i.e. electricity to LV grid and hydrogen to its proper market:

$$\mathrm{OF1}=\sum_{i=1}^{24}-\left\{\begin{matrix}\left[P_{e,WE}(t_i)c_{grid}(t_i)\right]+\\ -\left[L_{H2}(t_i)p_{H2}+L_{e,LV}(t_i)p_{ANC}(t_i)\right]\end{matrix}\right\}$$

where:

- $P_{e,WE}$ is the electric energy consumption of the WE during a time step, [kWh];
- L_{H2} is the amount of produced hydrogen to be sent to the H2 market during a time step, [kg];
- $L_{e,LV}$ is the electric energy produced by the FC injected into the LV grid during a time step, [kWh];
- c_{grid} is the energy purchase price from MV grid, [€/kWh];
- p_{H2} is the hydrogen sale price, [€/kg];
- p_{ANC} is the electrical energy sale price to the LV grid for balancing services, [€/kWh].

The second objective function is instead related to the smart grid philosophy adopted by the INGRID system: the DSO estimates a power consumption profile at the MV connection point that fits its technical contingencies and should be followed by the INGRID system. The EMS is therefore asked to accomplish this goal without constraining system operation to a fixed power value: actually, the WE is not forced to absorb the electric power suggested by the DSO, but its power consumption depends on the optimisation strategy. This approach is implemented by means of a technical objective function aiming at minimising the distance between the DSO power profile and the real power absorption of the INGRID system, designed as a numeric quadratic index in order to address suitably the distance between the two power profiles:

$$OF2=\sum_{i=1}^{24}\left[\frac{\left(P_{grid,MV}(t_i)-P_{DSO}(t_i)\right)}{100}\right]^2$$

where:

- $P_{grid,MV}$ is the total power absorbed from the MV grid, [kW];
- P_{DSO} is the power consumption suggested by the DSO, [kW].

It worth noting that the evaluation of daily economic revenues can also take into account the level of compliance of the INGRID plant with the DSO request at MV level: if the plant manages to satisfy DSO within the tolerance range around the suggested profile, a price discount for energy purchase can be considered.

The third objective function is employed in order to manage the power injection of the FC in the LV distribution grid. As seen above, the request of a power profile, either a generation or a production one, is not considered as a constraint but as a suggested behaviour to fulfil network operators' strategy. LV power profile is evaluated to exploit the availability of the INGRID CL storage system for, e.g., balancing services and for EV recharge programs. This third objective function is shaped as the second one, being a numerical index that stands for the distance between the power generation request and real power produced by the FC:

$$OF3=\sum_{i=1}^{24}\left[\frac{\left(P_{e,FC}(t_i)-P_{LV,dem}(t_i)\right)}{100}\right]^2$$

where:

- P_{FC} is the power produced by the FC available for LV balancing services, [kW];
- $P_{LV,dem}$ is the power demanded by DSO, [kW].

4.2.5 Constraints

The constraints of the optimisation process are mainly inequality constraints addressing the rated values of the INGRID plant equipment. Firstly, the rated values to be taken into account are the minimum and maximum power absorption and generation limits of both the WE and the FC. Moreover, the minimum and maximum hydrogen flow values of the OL and CL channels are taken into account as well. Finally, the capacity of the HSS systems is significant for constraining the State of Charge of the HSS devices. The equations related to these constraints are reported in the following:

$$P_{WE,min} \leq P_{WE}(t_i) \leq P_{WE,max} \qquad \forall t_i \epsilon T$$

$$P_{FC,min} \leq P_{FC}(t_i) \leq P_{FC,max} \qquad \forall t_i \epsilon T$$

$$H_{OL,min} \leq P_{WE\text{-}HSS\text{-}OL}(t_i) \cdot K_{WE} \leq H_{OL,max} \qquad \forall t_i \epsilon T$$

$$H_{CL,min} \leq P_{WE\text{-}HSS\text{-}CL}(t_i) \cdot K_{WE} \leq H_{CL,max} \qquad \forall t_i \epsilon T$$

$$SoC_{OL}(t_i) \leq HSS\_capacity_{OL} \qquad \forall t_i \epsilon T$$

$$SoC_{CL}(t_i) \leq HSS\_capacity_{CL} \qquad \forall t_i \epsilon T$$

where:

- $P_{WE,min}$ and $P_{WE,max}$ are, respectively, the minimum and the maximum electric supply rated values of the WE;
- $P_{FC,min}$ and $P_{FC,max}$ are, respectively, the minimum and the maximum electric generation rated values of the FC;
- $H_{OL,min}$ and $H_{OL,max}$ are, respectively, the minimum and the maximum hydrogen flow values allowed in the OL channel;
- $P_{WE\text{-}HSS\text{-}OL}(t_i) \cdot K_{WE}$ is the share of hydrogen generated by the WE conveyed to the OL channel;
- $H_{CL,min}$ and $H_{CL,max}$ are, respectively, the minimum and the maximum hydrogen flow values allowed in the CL channel;
- $P_{WE\text{-}HSS\text{-}CL}(t_i) \cdot K_{WE}$ is the share of hydrogen generated by the WE conveyed to the CL channel;
- SoC_{OL} and SoC_{CL} are, respectively, the state of charge of the HSS storages in the OL channel and in the CL one;
- $HSS\_capacity_{OL}$ and $HSS\_capacity_{CL}$ are, respectively, the capacity of the HSS storages in the OL channel and in the CL one.

Also the operational constraints are treated as inequality constraints: the power variation limits of both WE and FC, considered as the slope of their rated characteristic, are important parameters that narrow the solution space:

$$\frac{\Delta P_{WE}(t_i)}{\Delta t_i} \leq \text{ramp\_capacity}_{WE} \qquad \forall t_i \epsilon T$$

$$\frac{\Delta P_{FC}(t_i)}{\Delta t_i} \leq \text{ramp\_capacity}_{FC} \qquad \forall t_i \epsilon T$$

where:

- $\text{ramp\_capacity}_{WE}$ is the maximum ramp variation rate allowed by the WE;
- $\text{ramp\_capacity}_{FC}$ is the maximum ramp variation rate allowed by the FC.

Moreover, the dynamic performance of the HSS devices, especially regarding thermal processes, is crucial for assessing operational constraints since the heating and cooling phases of each storage system last a very long time and they affect the hydrogen absorption and desorption phases.

Besides the inherent power balance constraints, the requests of power profile at the MV and LV grid interfaces are not handled as equality constraints but by means of two different objective functions, so these profiles are followed according to the optimisation criteria inside a tolerance range. This is one of the most innovative concept proposed by the INGRID project.

4.3 Decision Support Systems

4.3.1 Purposes

As mentioned before, the DSS aims at providing a useful tool to the human operator supervising the INGRID plant for choosing the most suitable operational configuration. Depending from many external factors, the INGRID plant can adapt its energy behaviour to fit one of another goal; for instance, it there is an external request of a fixed amount of hydrogen, or the DSO requests for a significant contribution from the INGRID plant, the operator resolves to choose an optimised solution able to cover the one or another system goal.

4.3.2 Selection criteria

The DSS system designed for the INGRID plant selects three different solutions among those calculated by the optimisation algorithm. These solutions are chosen in order to cover the optimal solution front, so they are defined as follows:

- OF1 best: the individual of the last optimised population having a better fitness with the first economic objective function;
- OF2 best: the individual of the last optimised population having a better fitness with the second technical objective function;

- Trade-off: the individual of the last optimised population having the most similar distance values from OF1 best and OF2 best solutions.

In this context, the solution providing the best fitness to the third objective function is neglected. The goal of providing balancing services to the LV grid is considered as low priority achievement with respect to the economic revenues maximisation and the MV load profile following. In Figure 36, the solutions selected by the DSS within the optimal solution front are shown in comparison with solution front shown as example in Figure 34.

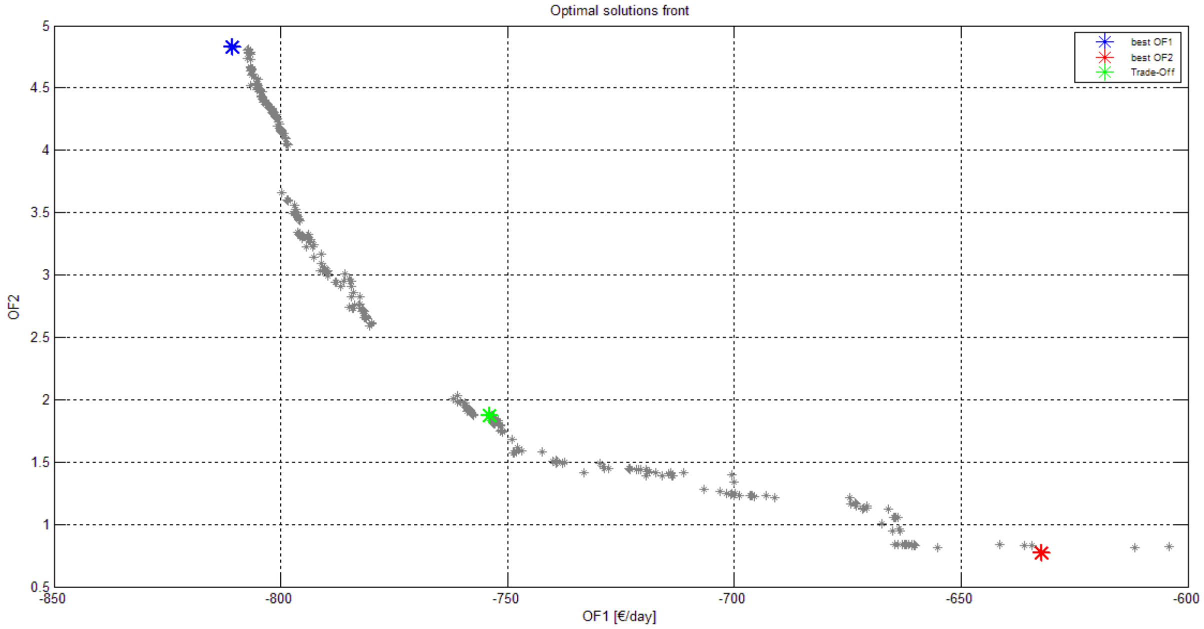
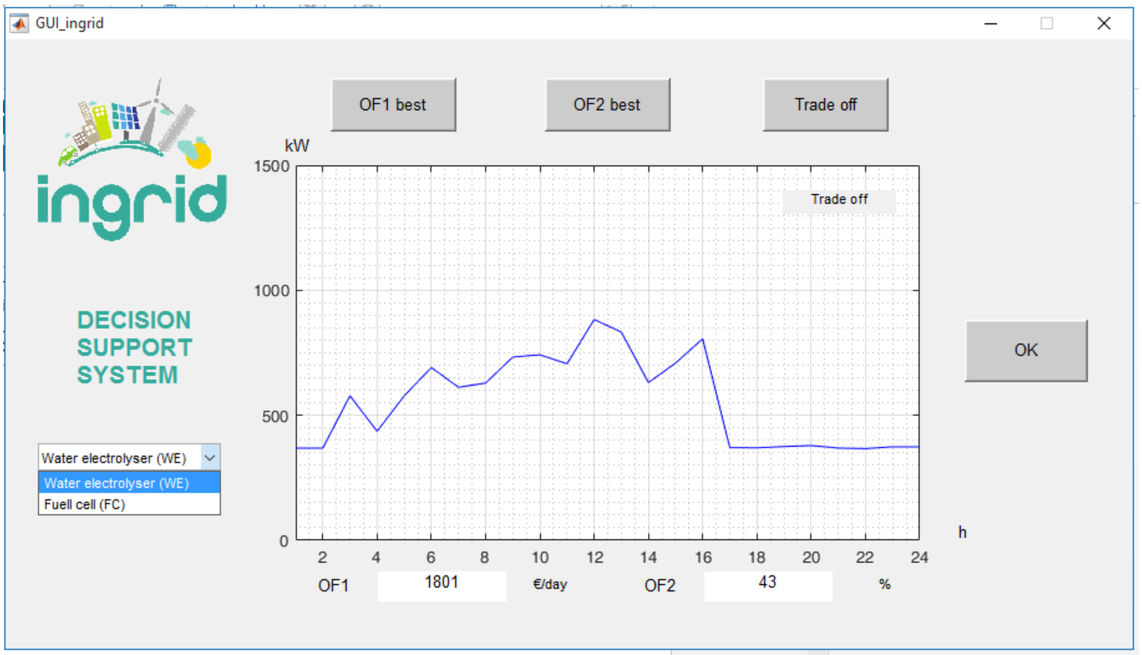


Figure 36 – The optimal solution front of the last population; blue marker stands for best OF1 solution, red marker stands for best OF2 solution and green marker stands for the trade-off solution.

4.3.3 HMI

As mentioned before, the DSS provides also a graphic interface to the human operator. By means of the HMI, the solution to be implemented into the plant is chosen: clicking on the “OK” button allows to send all the necessary data to the OPC server and then to the PLCs. In Figure 37, the HMI is shown. This interface allows to show the power profiles of both the WE and the FC for all the selected solutions.



Water electrolyser (WE)

OF1 1801 €/day

OF2 43 %

Figure 37 – The HMI provided by the DSS for the selected optimal solutions.

4.4 Communication framework, SCADA, and monitoring tools

In this section, a wide overview on the communication framework designed for the INGRID system is provided. The topic regarding the data exchange among the devices installed inside the INGRID system as well as between these devices and the external actors are addressed, along with the features and the components of the SCADA and monitoring tools made available for the proper plant management.

4.4.1 Communication framework

In this section, the communication framework among the EMS, the SCADA and monitoring tool, as well as the real plant devices are outlined. In Figure 38, all the modules of this framework and their interconnections are shown.

The OPC server has a central role in this structure since all the data are exchanged through the OPC protocol. The OPC protocol is a widely accepted industrial communication standard, which is used by the EMS components to communicate over TCP/IP technology with the different PLCs which, in their turn, control and monitor the different devices composing the INGRID system. The OPC is also adopted for the communication with the EMS optimiser.

In order to start the optimization process for the desired time horizon, the EMS reads the initialization data and the current plant configuration from the server. The data regarding the devices are synchronised to the PLC of each device inside the plant, and are also employed for the monitoring tasks handled by WinCC. In its turn, the EMS performs the optimisation and provides the system with the setpoints for the each time stamp over the entire time horizon. These setpoints are written in the OPC server and then are used by the monitoring tools, as well as by the PLCs of the real plant as an input for the real devices.

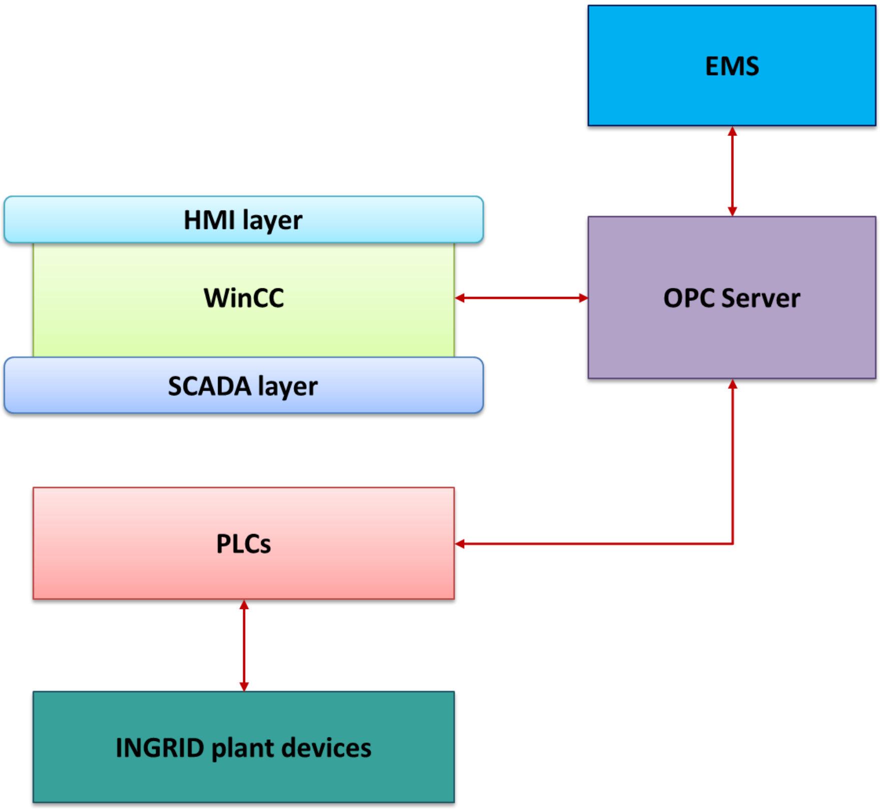


Figure 38 – The INGRID communication framework.

The monitoring tool is a component developed on purpose for the INGRID project, which collects and integrates all the setpoints, operational parameters and the alarms regarding the plant equipment. Its HMI is part of the SCADA of the plant, which can be used for the general control of the plant. The EMS, by means of the DSS, can access the SCADA to perform its optimisation. Human intervention is always prioritised, as it can be expected.

4.4.2 I/O data

The first static data required by the EMS optimisation algorithm are initialisation data related to the technical features of the devices planned to be installed in the demonstrator site. These data concern WE absorbed electric power and produced hydrogen flow, HSSs capacity, maximum flow values and temperature, both for OL and CL channels, FC minimum and maximum electric power limits. In Table 5, these data are shown along with their type, measure unit, I/O classification (seen from the EMS point of view), granularity (i.e., the frequency with which the algorithm calculations need a new updated value of that variable) and the expected provider.

Table 5 – Static initialization data for EMS optimization algorithm.

Description	Type	Unit	I/O	Granularity	Provider
WE minimum power consumption	Real	kW	I	Time slot	WE
WE maximum power consumption	Real	kW	I	Time slot	WE
FC minimum power consumption	Real	kW	I	Time slot	FC
FC maximum power consumption	Real	kW	I	Time slot	FC
Total capacity of HSS OL tanks	Real	kg (Nm^3)	I	Once	HSS OL
Capacity of HSS CL tank	Real	kg (Nm^3)	I	Once	HSS CL
WE maximum hydrogen flow	Real	kg/h (Nm^3/h)	I	Once	WE
WE minimum hydrogen flow	Real	kg/h (Nm^3/h)	I	Once	WE
HSS OL maximum hydrogen flow	Real	kg/h (Nm^3/h)	I	Once	HSS OL
HSS CL maximum hydrogen flow	Real	kg/h (Nm^3/h)	I	Once	HSS CL
HSS OL absorption temperature	Real	°C	I	Time slot	HSS OL
HSS CL absorption temperature	Real	°C	I	Time slot	HSS CL
HSS CL desorption temperature	Real	°C	I	Time slot	HSS CL

In order to initialise correctly the algorithm, some data related to the grid and the plant operating conditions are needed; furthermore, important data concerning energy conversion devices are expected. These are collected in Table 6.

Table 6 – Additional input data for EMS optimization algorithm.

Description	Type	Unit	I/O	Granularity	Provider and remarks
Energy purchase price from MV grid	Real	€/kWh	I	Time slot	Energy market
Energy sale price to the LV grid for balncing/ancillary services	Real	€/kWh	I	Time slot	DSO
Hydrogen sale price	Real	€/kWh	I	Time horizon	Hydrogen market
Forecasted power produced by RES system	Real	kW	I	Time slot	RES forecast system
Power profile requested by DSO	Real	kW	I	Time slot	DSO
Maximum contractual power value supplied by MV feeder	Real	kW	I	Once	DSO
WE conversion factor (electrical energy-hydrogen)	Real	Nm^3/kWh	I	Time slot/Once	Assumed: 5.2 kWh/Nm^3
FC conversion factor (electrical energy-hydrogen)	Real	Nm^3/kWh	I	Time slot/Once	Assumed: 1.8 kWh/Nm^3
Conversion factor Nm^3->kg	Real	kg/Nm^3	I	Once	Assumed: 11 kg/Nm^3
Discount value for the energy purchase price	Real	%	I	Once	Energy market
Difference between actual power consumption and DSO request to be respected in order to achieve price discount	Real	kW	I	Once	Energy market

In this case, energy and hydrogen prices are expected to be taken from the energy market and manually inserted by the operator. Currently these prices are modelled as a vector of 24 elements (1 value per hour each day), while the price of hydrogen is generally constant along all the 24 hours. Forecasted power production and demand are simulated by the INGRID simulator. The last four values, i.e., the maximum contractual power available from the grid and the conversion factors between the different energy carriers, are constant values used as parameters.

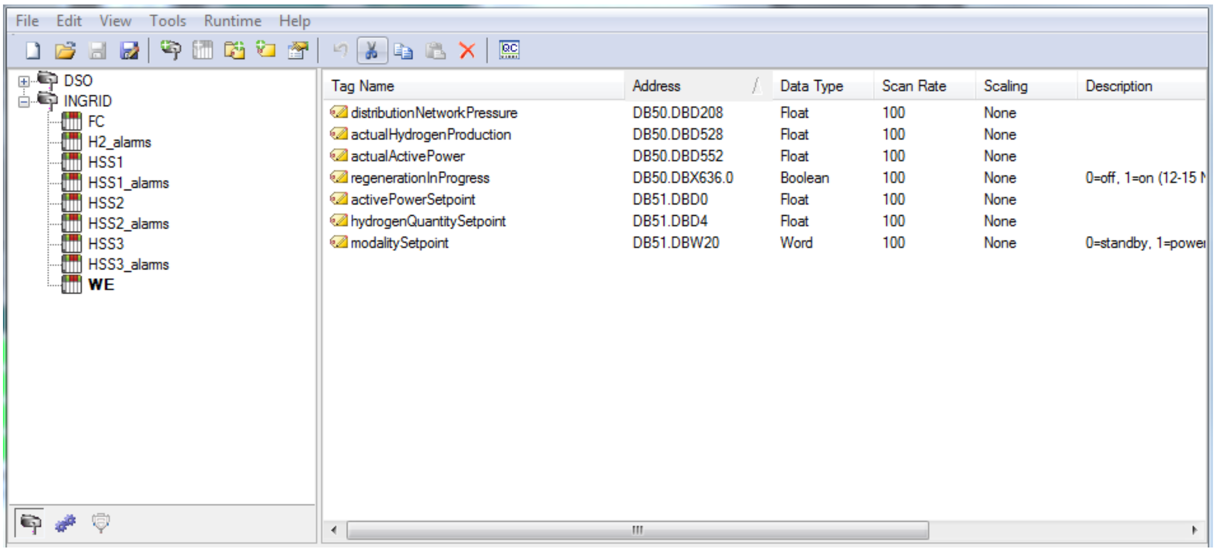
The last series of data is represented by the output data, seen as setpoints, shown in Table 7, which are calculated by the EMS optimiser. They are significant for the definition of a complete control strategy, allowing the EMS to communicate and optimise several needs coming from DSO, for both MV and LV grids; HSS devices are involved in this setpoint configuration, too.

Table 7 – Data evaluated by optimization algorithm necessary for control strategy definition.

Description	Type	Unit	I/O	Granularity	Addressee
Power absorbed from MV grid	Real	kW	O	Time slot	DSO (MV)
Hydrogen absorbed by HSS OL	Real	kg/h (Nm^3/h)	O	Time slot	HSS OL
Hydrogen absorbed by HSS CL	Real	kg/h (Nm^3/h)	O	Time slot	HSS CL
Ancillary services power produced by FC	Real	kW	O	Time slot	DSO (LV)

4.4.3 OPC server

The OPC server set-up for the INGRID system has a tailored structure in order to be compliant to the hardware equipment. It consists of a single channel, related to the OPC protocol communication, to which are associated different devices that, in their turns, provide different tags. As shown in Figure 39, the devices refer to the real equipment, such as the WE, FC, HSSs. Moreover, other devices are added for handling the alarms of the plant. Each of this device presents different tags related to the single data sent or received by the monitoring system; in the central tab of Figure 39, the tags related to the WE are shown. The proposed solution is seamlessly compliant with both Top Server 5 [234] or KEP Server [235].



Tag Name	Address	Data Type	Scan Rate	Scaling	Description
distributionNetworkPressure	DB50.DBD208	Float	100	None	
actualHydrogenProduction	DB50.DBD528	Float	100	None	
actualActivePower	DB50.DBD552	Float	100	None	
regenerationInProgress	DB50.DBX636.0	Boolean	100	None	0=off, 1=on (12-15
activePowerSetpoint	DB51.DBD0	Float	100	None	
hydrogenQuantitySetpoint	DB51.DBD4	Float	100	None	
modalitySetpoint	DB51.DBW20	Word	100	None	0=standby, 1=powe

Figure 39 – Structure of the OPC server to be employed for the control and monitoring task of an INGRID system.

4.4.4 SCADA implementation

The first instance of the SCADA proposed for the INGRID system has been developed within the TIA Portal environment [236], an integrated concept allowing to address automation engineering in several different context. This first implementation has been employed for design purposes and has exploited the SIMATIC S7-PLCSIM software for simulating the PLC that would have been installed in the real life plant. All the SCADA environment relies upon Siemens [237] automation and control products. These choice has driven the design and the selection of the PLCs installed on the demonstrator test site.

The second and final implementation of the SCADA for the INGRID system is developed within the WinCC Classic v7.3 environment. The first implementation has been simply adapted to the new environment since both TIA Portal and WinCC belong to the Siemens automation products ecosystem. This implementation is the one installed inside the control room racks in the INGRID demonstration site.

The SCADA system deployed for the INGID demonstrator consists of four PLCs installed by the plant devices:

- one PLC is responsible of the monitoring and data exchange of the WE and FC, both brought by Hydrogenics that provides also the PLC, belonging to the S7-3XX family;

- three PLCs responsible of the monitoring and data exchange of each of the HSS station, brought by McPhy that provides also the three PLCs, compliant with the S7 family.

The PLC consists of:

- a power supplier;
- a Central Processing Unit (CPU) including all network facilities;
- digital input/digital output units;
- analogic input/analogic output units.

The four PLCs are managed by the EMS Simatic PC station, a WinCC runtime installation, and an OPC server, which is used for the integration of the component and the intercommunication among them.

4.4.5 Cyber-security

The plant issues related to cyber-security and the general protection and access management of the plant towards the external actors is implemented by configuring properly the network infrastructure. Indeed, during the set-up operations of the Internet connection of the plant, a proper security layer has been provided to the entire system by shadowing the internal LAN by means of a Network Address Translation (NAT).

4.4.6 HMI

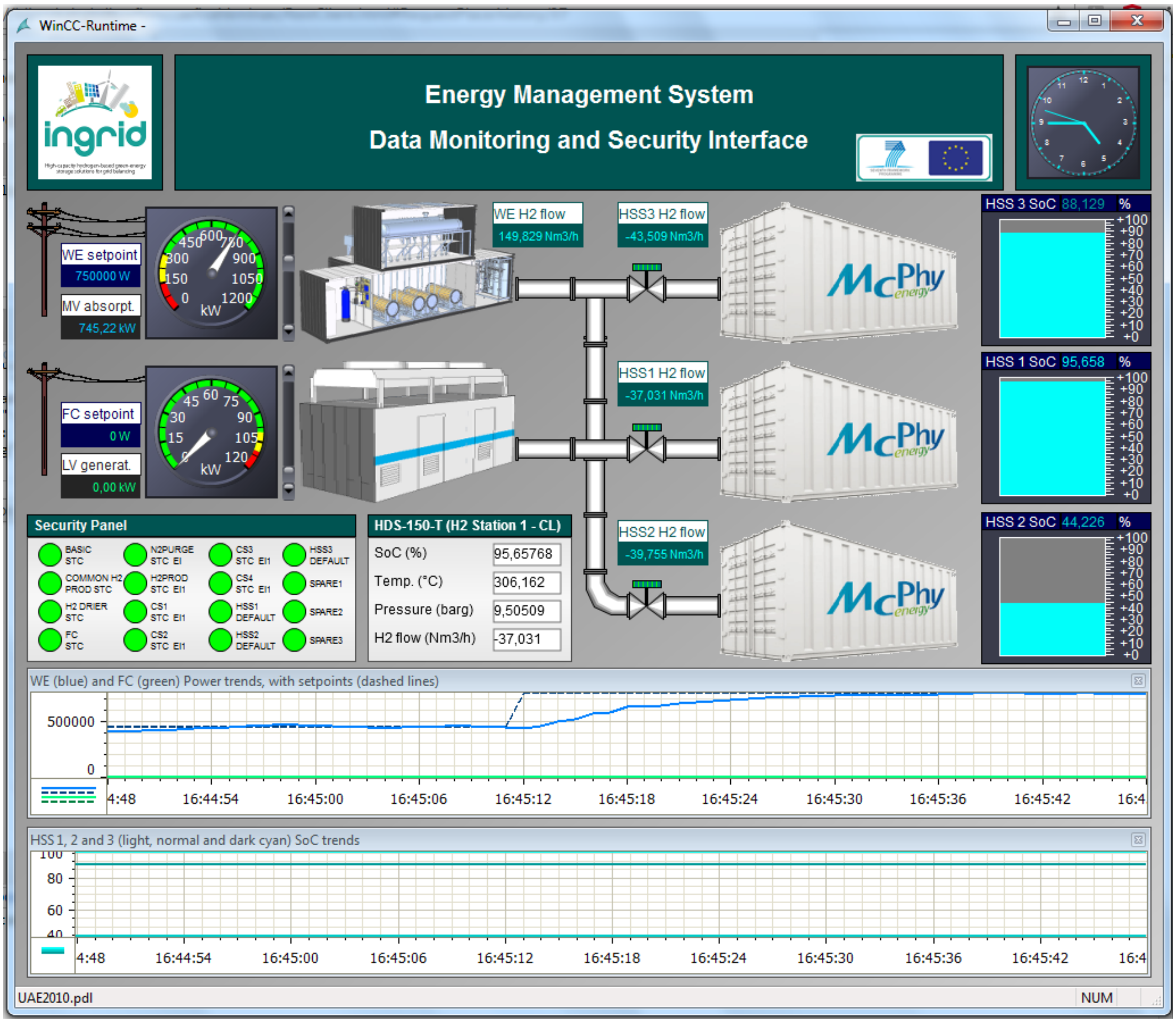
One of the most important tool provided by the SCADA is the HMI that natively collects and displays all the relevant data for the human operators appointed at the surveillance and maintenance of the equipment. The HMI, as part of the monitoring tool provided with the INGRID system, consists of:

- an integrated GUI to monitor the main variables and alarms at global level from a remote working station;
- a series of consoles at device level to monitor all the component values locally for maintenance and configuration.

In Figure 40, the HMI is shown; its various parts allows to monitor:

- the WE setpoint and its actual power consumption, along with the overall power absorbed by the grid (that includes also auxiliaries) and the hydrogen flow generated by the WE itself;

- the tree hydrogen flows pertaining to the three HSS stations installed inside the INGRID demonstrator;
- the state of charge of the three storage working inside the three HSS stations;
- the FC setpoint and the power injected into the LV grid;
- a security panel reporting all the alarms in a traffic light style graphic representation;
- a monitoring panel of the selected HSS storage system reporting data about its temperature, pressure, etc.
- the WE and FC power consumption/generation trends over a customisable time window;
- the state of charge trends of the three HSS storages over a customisable time window.



WE setpoint 750000 W
MV absorpt. 745,22 kW
FC setpoint 0 W
LV generat. 0,00 kW
WE H2 flow 149,829 Nm3/h
HSS3 H2 flow -43,509 Nm3/h
HSS1 H2 flow -37,031 Nm3/h
HSS2 H2 flow -39,755 Nm3/h
HSS 3 SoC 88,129 %
HSS 1 SoC 95,658 %
HSS 2 SoC 44,226 %

HDS-150-T (H2 Station 1 - CL)
SoC (%) 95,65768
Temp. (°C) 306,162
Pressure (barg) 9,50509
H2 flow (Nm3/h) -37,031

Figure 40 – The HMI providing a global view of the data monitored inside the INGRID demonstrator plant.

It worth noting that, besides saving the data inside the internal data storage of the WinCC environment, the relevant data regarding the EMS operations and the corresponding setpoints are sent and stored inside the OPC server discussed and shown in the previous section.

4.5 Integration environment and software deployment

The research activities performed within the INGRID project has led to the development of a framework of complex software tools that have been integrated and deployed inside the INGRID demonstration plant. These activities have been followed and coordinated, the system set-up has been lead from the initial stages, as both coordinator and system integrator of the ICT infrastructure.

All the hardware equipment to deploy the software framework developed in the course of the Project have been provided:

- WinCC V7.3 RT 2.048 PT licence;
- SIMATIC Scalance;
- SIMATIC IPC547G.

The IPC547G server equipped with WinCC represents the core of the hardware installation. The SCADA related parts has been customised and deployed. SIMATIC Scalance has been used to link all the PLCs with the central server. The local LAN and all the accessory services for the network interconnection has been installed. Tests have been performed on-site, even before the start of the demonstration phase. Tests have been performed both off line and on line, at single unit level and at network system level. In this way, the needed infrastructure to monitor and control any single component of the plant has been provided.

During the deployment of the demonstration phase, a proper framework for exchanging, storing and monitoring the setpoints and the data coming from the PLCs of the real equipment has been developed, tested and installed in the control room server. Three different levels of monitoring have been set up, to provide the plant with the necessary robustness and reliability. Figure 41 shows the final version of the ICT architecture deployed inside the INGRID demonstrator.

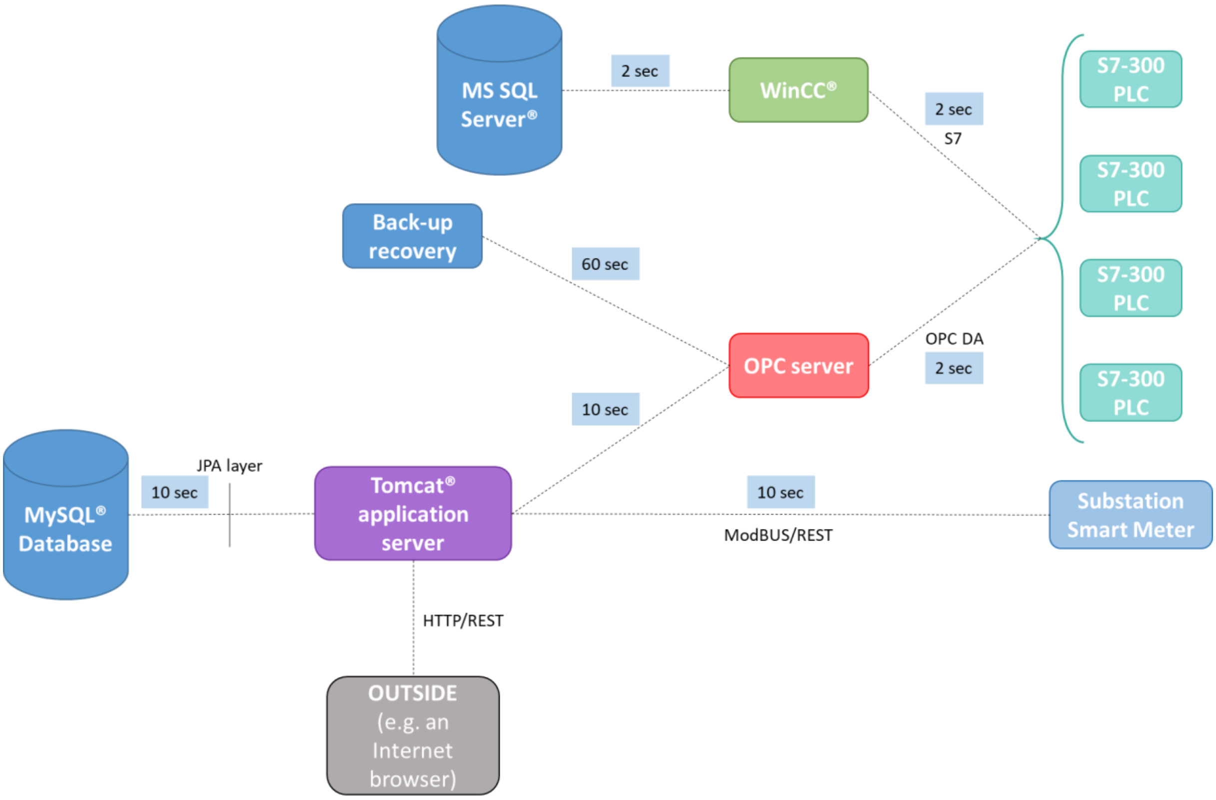


Figure 41 – Final monitoring and controlling architecture for the INGRID plant.

With reference to the architecture depicted in Figure 41, the main elements of this framework are:

- a KEPServer OPC server (DA type), accessible by OpenSCADA libraries;
- a Tomcat application server, through which two web applications are executed;
- a MySQL database, into which all the information regarding monitoring data and set-points are stored.

The OPC server is able to exchange data with the PLCs and with the application server, by means of libraries adapted from the OpenSCADA DA ones. In its turn, the application server runs: (i) a client-oriented web application providing the GUI that allows the human operator to interact with the charts displaying both monitoring data and operational plans and (ii) a server-oriented web application that manages all the web services needed for accessing the framework from outside the plant, e.g. from an Internet browser. Besides receiving data from the PLCs by means of the KEPServer OPC server, the application server is also connected to the measurement device installed inside the electrical substation, which sends the electrical power flow and voltage values recorded at the three connection points of the plant. All the information coming from the monitoring on the field and the setpoints sent to the devices are stored into the database by means a proper Java Persistence Architecture persistence layer. In particular, the web services consist of a set of REST services, developed for allowing the monitoring of the plant devices and the implementation of operational plans and, moreover, for performing the administration of the OPC server. Finally, a back-up server has been implemented in order to create a .csv file for the recovery of the information sent by the PLC in case of unavailability of the OPC server.

The data exchange rate between the PLCs and both the OPC server and WinCC platform is set to 2 seconds. Information from WinCC are saved into a MS SQL Server instance every 2 seconds. The communications between the OPC server and the substation meter towards the Tomcat application server occur every 10 seconds; data for the application server are saved into MySQL database every 10 seconds. Data for back-up recovery are stored every 60 seconds. All these rates are accessible and modifiable by means of parametrised variables; these values have been selected for optimising the overall framework performance.

As already mentioned, in order to integrate the measurements coming from the substation, an access point has been provided and set-up for point-to-point connection to the external antenna. As for the software part, the Modbus and the REST interface have been evaluated, opting for the second one.

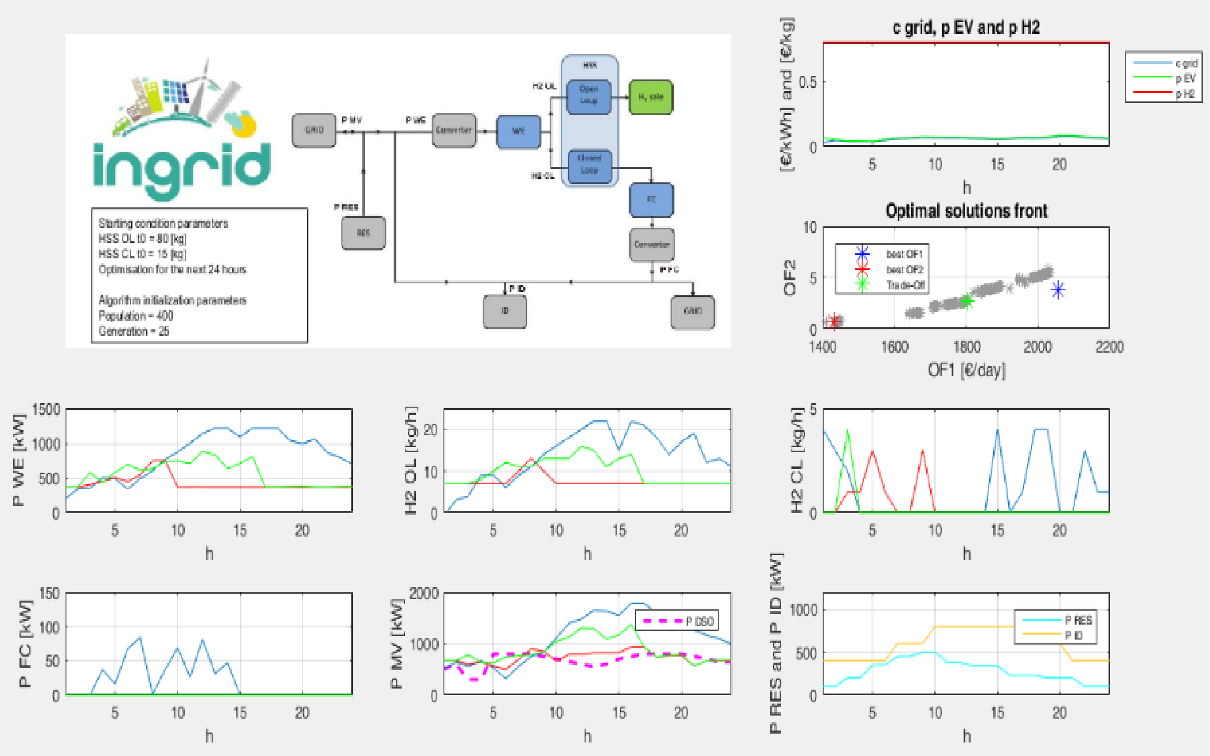
Finally, the integration and installation of the proper optimisation framework tool needs some third party components:

- Java JRE 1.7;
- MATLAB Runtime for version R2015b and/or MATLAB R2015b.

4.6 The GUI and console

The EMS of the INGRID system provides some different graphic tools in order to allow the actors interacting with it, such as plant operator, DSOs, etc., to visualise directly and simply the information needed for their tasks. Previously in this chapter, two of these tools have been shown and presented: the HMIs of both the DSS and the SCADA system, respectively in Figure 37 and Figure 40. In this section, other two graphic tools are presented, the GUI of the EMS optimiser and the EMS console.

The EMS optimiser of the INGRID systems provides a GUI to the plant manager which displays all the significant results and parameters of the optimisation itself. In Figure 42, this GUI in its complete shape is shown.



Starting condition parameters
HSS OL t0 = 80 [kg]
HSS CL t0 = 15 [kg]
Optimisation for the next 24 hours

Algorithm initialization parameters
Population = 400
Generation = 25

Figure 42 – The GUI of the INGRID optimiser application developed in MATLAB® environment.

On the top of the GUI, the general scheme of an INGRID plant is shown, along with some relevant parameter of the algorithm, such the population and the generation values, and the starting conditions of the plant devices, such as the initial state of charge of the HSS storages. Moreover, information about price trends related to the sale and purchase of electricity as well as hydrogen are shown. The last chart shown in the upper part of the GUI displays the Pareto-optimal front of the optimisation process; in this chart, the markers related to the solutions appointed by the DSS are highlighted with different colours: blue for the OF1 best solution, red for the OF2 best solution, and green for the trade-off solution.

The bottom part of the GUI shows several charts regarding the energy flows among the devices and the external actors of the systems:

- the power consumption of the WE (P WE);
- the hydrogen flow on OL channel (H2 OL);
- the hydrogen flow on CL channel (H2 CL)
- the power produced by the FC (P FC).
- the overall power requested at the MV connection point (P MV);
- the power forecast of both RESs system generation and the EV station consumption (P RES and P ID).

All these data are provided for the OF1 best solution (blue lines), OF2 best solution (red lines) and OF3 best solution (green lines).

It worth noting that, in the chart reporting the profile of the power absorption from the MV grid, the DSO profile request is reported as well (dashed purple line). It can be noticed the distance between the three optimised profiles and the DSO request and, in particular, how the OF2 best solution is the closest to the profile request, being the solution that provides the best fitness to the technical objective function parametrising the distance between the actual energy behaviour of the plant and the request from the operator. It is significant to underline also how the INGRID plant, not being committed to the request of the operator, tries to reply to the request of the DSO while keeping in its control criteria the other goals of the management.

The EMS console is an HMI aiming at showing graphically the information obtained by the EMS optimisation and it is accessible at low-level by means of REST services. The EMS console and the EMS optimiser internally exchange information via REST services, invoked by an URL accessing to the web application. Within this console, plant operational data are shown, both historical as well as real-time ones coming from PLCs. Moreover, data coming from the DSO and the electrical substation, exchanged by REST services or WISE devices, respectively, are collected and reported.

This console provides 6 tabs to the user: the first one (“Power monitoring”), shown in the figure below, presents the WE and FC monitoring data. Moreover, this tab shows the power absorption at the connection point, monitoring the power actually absorbed by the plant, as well as the power flowing downstream and upstream the connection point itself. The second tab (“Storage Monitoring”) shows both the states of charge and the hydrogen flows pertaining to each of the working hydrogen storages. The third tab (“Plans”) allows the user to select and start one of the available operational plans, besides interrupting and managing them. The fourth tab (“Storage Management”) allows inserting in the database information about the operational mode and the location of each storage. The fifth tab (“Settings”) is a GUI configuration panel, accessing to the setting of the OPC servers, such as the refresh rate and other parameters. The sixth and last tab (“DSO”) is employed for importing data from DSO, for both MV and LV requests.

As a front-end, the console is intended to be used by a human operator. No interfaces are exposed to external systems. In Figure 43, the graphic interface of the EMS console is shown, highlighting its tabs and in particular the charts of the “Power Monitoring” tab.

The console has been developed as an HTML page consisting of six tabs addressing various functionalities. The management of the tabs is performed by jQuery, whilst the management of the calendar and the time slots over a day is performed by customized widgets of jQuery UI. Each single tab is managed through JavaScript for handling dynamic section, as well as charts, and invoking the REST services for retrieving data. The graphic representations are implemented by Highchart and Highstock libraries.

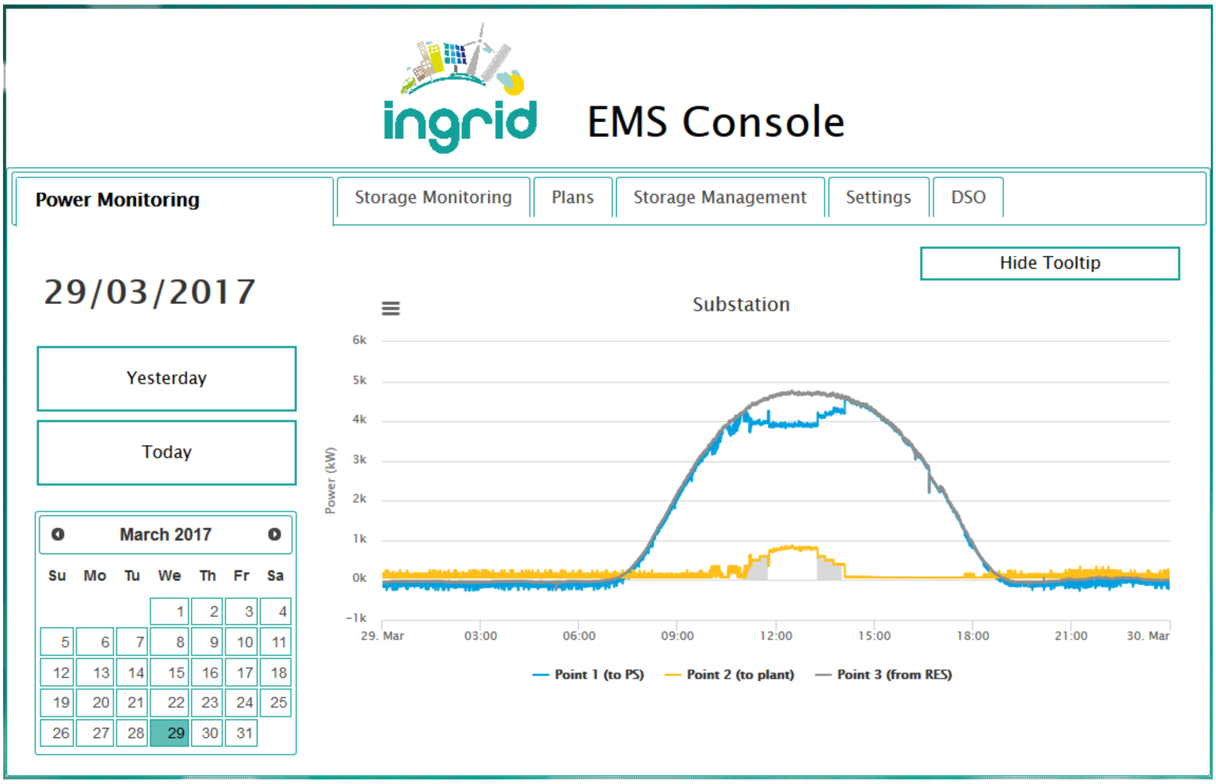


Figure 43 – The EMS Console of the INGRID system and the content of the first of its six tabs.

4.7 Results and test in real life demonstrator

At the end of the research activities, the INGRID demonstrator in all its hardware and software tools has been deployed and commissioned at the demonstration site in Troia, as shown in Figure 44. A rich test campaign has been performed in order to prove the effectiveness and the operation of all the devices and their integration in complex plant operations. Moreover, the effectiveness of the control actions performed by means of the setpoints evaluated by the EMS is tested and shown by means of the charts reporting the measured power consumption of the interested devices. These results show also the efficacy of the controlling and monitoring tools implemented for the INGRID plant, able to exchange successfully setpoints, read measured data and control plant behaviours.

Figure 44 – Final shape of the INGRID demonstrator in Troia.

The tests span from single unit tests, aimed at proving the integration of each component, to complex business tests, which execute and simulate operational scenarios of the whole plant. A second kind of tests have been designed in order to understand how the INGRID system works. Eight group of tests have been identified, which can be furtherly subdivided into two macro groups of test cases: integration tests and business scenarios. An intermediate group has been identified, as well, consisting of test cases used both as integration tests and as business scenarios, according to their actual implementation. The main test cases elaborated for the field demonstration phase are:

- Integration tests:
  - Test 1 – Fill up all the HSSs
  - Test 2 – Empty out all the HSSs
- Intermediate scenarios:
  - Test 3 – Fill up all the HSSs following a MV consumption profile
  - Test 4 – Fill and empty the HSSs following a MV consumption profile and a LV generation profile
- Business scenarios:
  - Test 5 – Respond to real time LV generation request
  - Test 6 – Provide full flexibility services at MV and LV to the DSO
  - Test 7 – Fulfil H2 requests within a period of time

- Test 8 – Fulfil H2 requests following a MV consumption profile

The first two groups aimed at defining how the plant reacts in stress conditions and defining its boundaries (max production time, ramp-up and ramp-down rates, etc.): they have been used as integration tests, as well, to demonstrate the ability of the EMS to command the plant equipment in automatic (via OPC) or semi-automatic (via SCADA) way. The third and the fifth group implemented the first basic business scenarios, and tested how the plant can manage the storages to provide flexibility services either at MV or LV level. Actually, they have been used also during the integration phase, providing simulated profiles, in order to test the dynamics of the system in depth. The fifth group tested the reactivity of the system basically in an EV recharging scenario. The sixth group tested how to provide flexibility services simultaneously at MV and LV level. The last two groups were only defined to test how to fulfil requests coming from the H2 market in possible future scenarios.

All these tests are designed to be run in series or in parallel, and results have been interpreted as scenarios for a fully operative plant running the INGRID concept. The results obtained matched, as expected, the mathematical model used by the EMS to perform its planning, and the output demonstrated its reliability.

Before introducing the detailed description of the tests, it worth explaining how the INGRID system is connected at the interface of MV and LV distribution grids, aiming at providing services to both the systems. In Figure 45, the details of the connection points are shown along with their number labels.

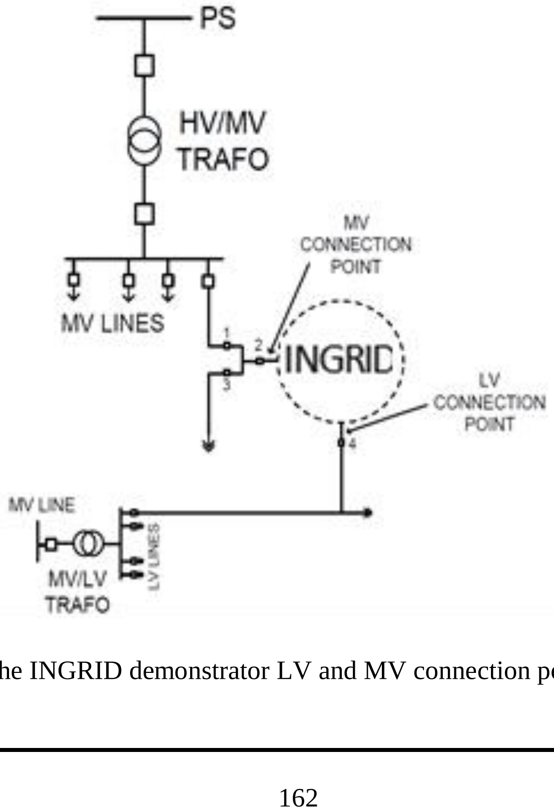


Figure 45 – The INGRID demonstrator LV and MV connection point details.

Basically, point 1 measures the power coming from the primary substation, or, if negative, the power reverse flow going upstream from the MV grid to the HV one; point 2 measures the overall consumption of the INGRID plant; point 3 measures the power going downstream. In the particular region in which the INGRID plant is located, this feeder is characterised by an enormous penetration of RESs: contrarily to most of other parts of the Apulia region, where the wind systems penetration is more relevant than the solar one, in this portion of the grid, the distribution is 90% PV systems and 10% wind turbines. During most of the year, the power incoming to point 3 is negative, well representing the huge power reverse flow occurring.

4.7.1 Integration tests

The first tests performed during the initial phases of the INGRID demonstration were the most technical ones. These have been conducted as unit integration tests. They served as validation test for the mathematical models adopted inside the EMS to perform optimisation and planning.

In Figure 46, the chart of the integration test of the FC is depicted.

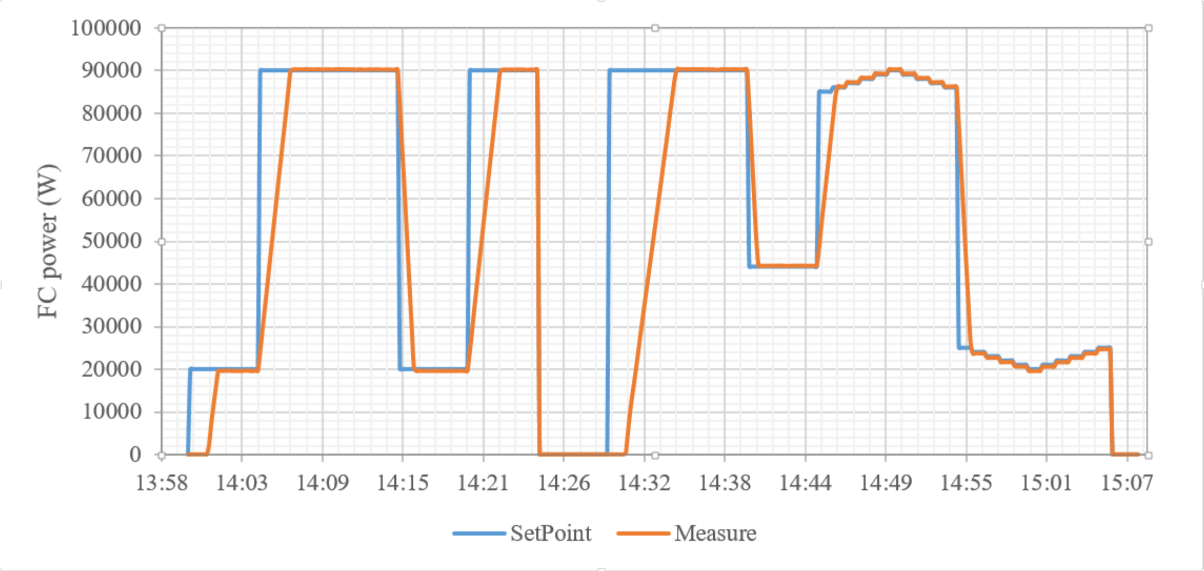


Figure 46 – The INGRID demonstrator FC integration test.

In stress conditions, the FC takes about one minute to start from the stand by and about three minutes to go from 0% to 100%. In a real business scenarios, these values are more than acceptable, especially considering the better reactivity in “normal” conditions, when the more changes occur but the required variation is lower, as shown in the rightmost part of the chart. The results shown in this figure were part of a Test 4 execution.

In Figure 47, the results of four hours of tests are reported, running Test 3. The setpoints sent by the EMS to the WE, and the actual process values of the WE power consumption are clearly depicted. The chart allows to appreciate the high reactiveness of the WE. Drops in hydrogen consumptions are justified by corresponding pressure drops, happening from time to time, but without jeopardising the overall behaviour of the system and compromising its results. The 900 kW setpoint (in the middle of the graph) has been given intentionally, to test the safety of the system, which automatically cuts the process values to the maximum allowed (870 kW).

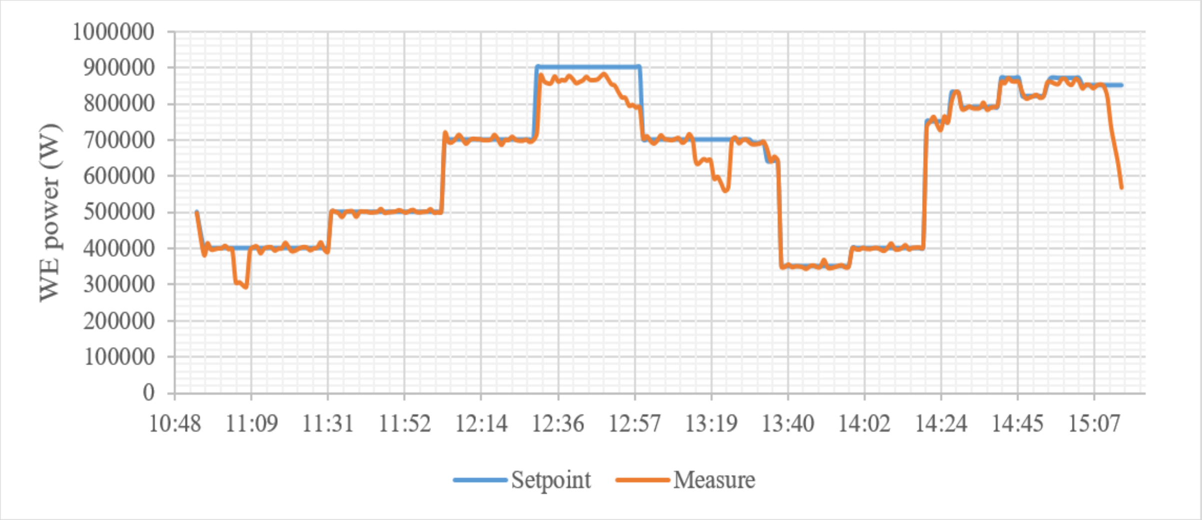


Figure 47 – The INGRID demonstrator WE integration test.

In accordance with the last test execution, the impact of the plant on the grid is represented in Figure 48. As already shown in Figure 45, point 3 indicates the power received by the substation coming from the RES, and point 2 indicates the power consumption of the INGRID plant. As a consequence, the power flow going to the primary substation is reduced to the one represented by point 1.

At the end of the integration test phase, the expected output of these tests was the definition of constants and relationships among variables in the plant operations, related to the different composing devices. During the tests, several setpoints have been used to establish the limits of the system.

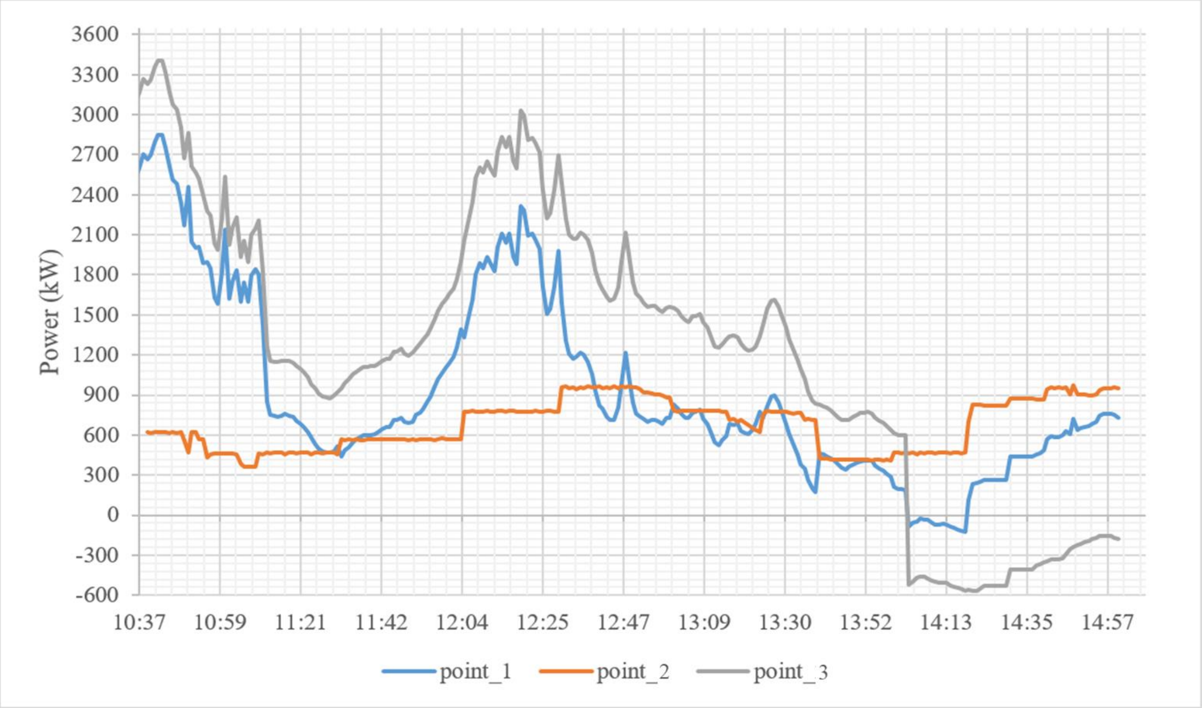


Figure 48 – The INGRID demonstrator substation power levels during Test 3.

4.7.2 General commissioning

The tests related to the general commissioning of the plant have been executed in order to test the behaviour of the overall system in different combination of boundary conditions. The scope is to test how the WE, the FC and the HSS react once all the devices have been set and connected all together. The tested combinations were nine, in chronological order:

- FC at minimum, WE off;
- FC at minimum, WE at minimum;
- FC at minimum, WE at maximum;
- FC at medium, WE at maximum;
- FC at medium, WE at minimum;
- FC at medium, WE off;
- FC at maximum, WE off;
- FC at maximum, WE at minimum;
- FC at maximum, WE at maximum.

In Figure 49, the results of the tests are depicted. The setpoints sent to the PLCs and process values measured by the sensors are reported together for the WE and the FC.

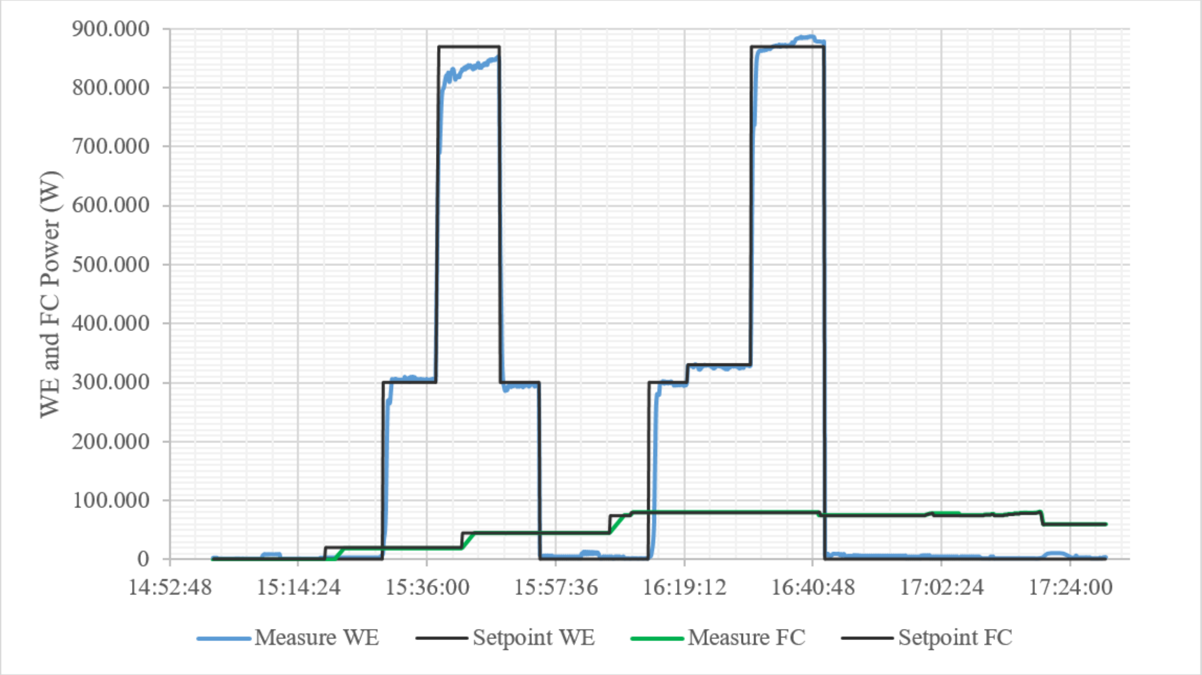


Figure 49 – The INGRID demonstrator general commissioning.

As it can be seen, the WE and the FC followed the setpoints with a good response. Basically, the results demonstrated that the behaviour of each component involved in H2 production and consumption is not affected by the dynamics of the other: the fidelity of each system has been confirmed, in terms of performance, with the respect to the single integration tests, which have been done singularly with each device. The WE managed to follow the maximum production asked by the setpoints in the second case. This is justified by the concurrent FC operations. At demonstration time, the storages were already partially full, which was another stress condition. During the first peak, the storages were very near to their saturation, and this partially affected the ability of the WE to reach its programmed maximum (870 kW). During the second peak, the consumption of H2 requested by the FC in the meantime has been enough to deplete the storage, so as the peak in consumption request has been followed perfectly in the second case.

4.7.3 Business scenarios

Beside the unit integration test phase and the general commissioning of the plant, a series of business scenarios have been executed in order to test the plant behaviour in possible real situations. The production of hydrogen in those days has been led taking into account the flexibility of the plant towards the collaboration with the DSO for the regulation of its consumption for the benefit of the grid, as managed by the optimisation criteria.

The plant consumption has been adapted considering the main flexible and controllable load of the plant, which is the WE. The optimised operational plans have been implemented so as the consumption of the WE is regulated with the aim of providing the overall level of consumption requested by the DSO, at plant level, including all the auxiliary consumptions. In the two charts of Figure 50, the DSO request is compared with the point 2 trend, since point 2 measures the actual consumption of the overall plant, which is the real value which the DSO is interested in, not just the WE consumption.

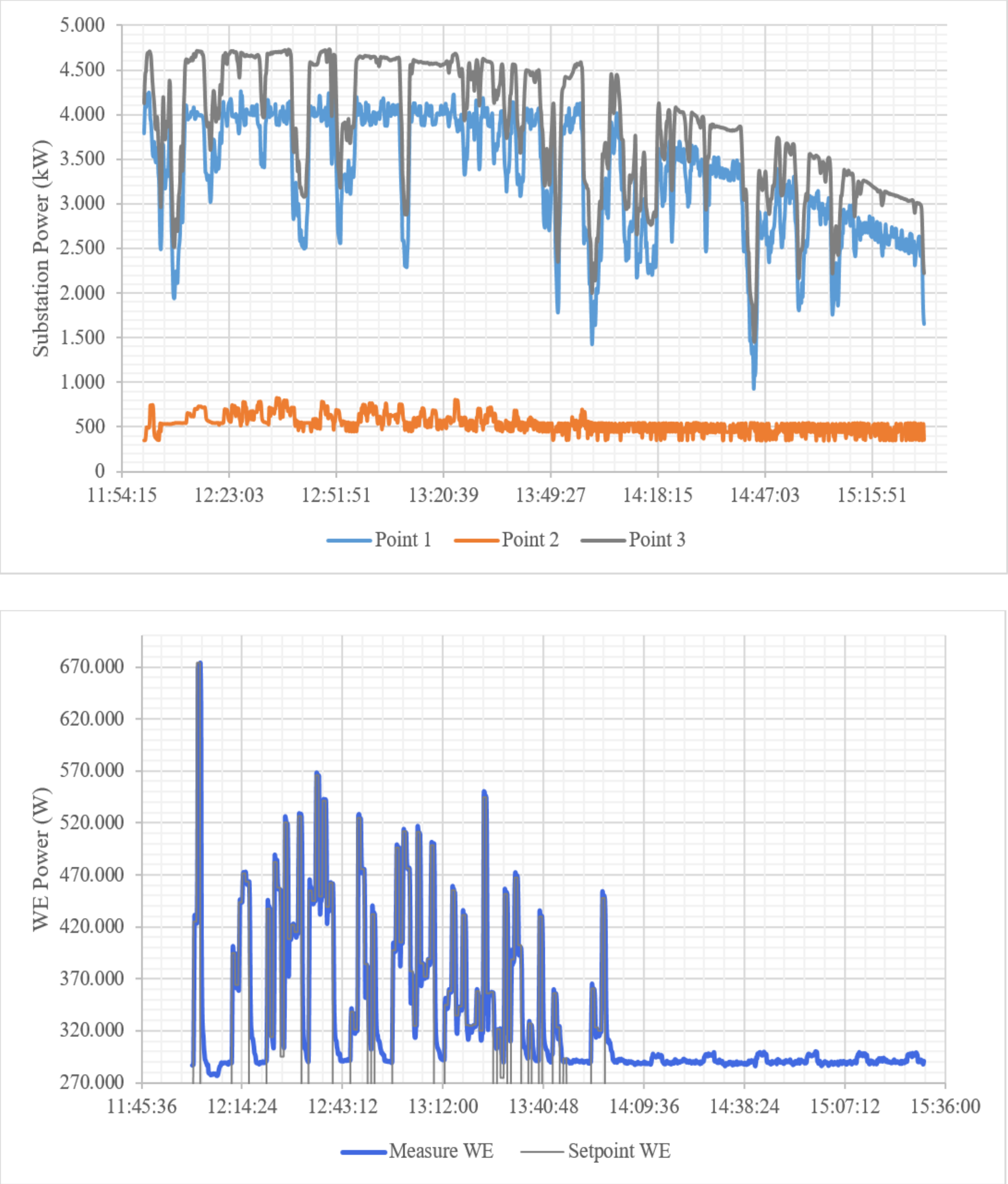


Figure 50 – The INGRID demonstrator business scenarios: peak shaving with fluctuant RES.

During sunny days, the power reverse peak can reach also 4,9 MW. Usually the power reverse flow follows a “bell-shaped” curve, starting at about 10-11 and finishing at 15-16 with 1-2 hours of difference according to the season. During cloudy days the power reverse flow tend to be more or less constant, while in days characterised by strong variability of the weather conditions, the RES production is strongly fluctuant.

In Figure 50, the result of a power reverse flow peak shaving is shown. In the first graph, the power levels registered in the substation are reported. Starting from 12:00 a target value of 4 MW has been set, in order to limit the power reverse flow towards the primary station, thus towards the HV system, to that predefined threshold. The RES production in that day, registered at point 3, was very fluctuant and the plant behaviour allowed to reduce this variability in terms of impact on the primary station, as well. As it can be seen, the plant has perfectly followed the RES trend, regulating the WE consumption so as to cut the reverse flow towards the HV only when the 4 MW threshold was matched. It is worth noting that most of the “noise” in the curves is unfortunately due to the resolution of the measurement instrumentation, which however did not affect the process and, in the end, the quality of the outcomes. The tests ended at 14:00, after two hours, when the WE was set at its minimum (300 kW).

The second graph shows the behaviour of the WE in correspondence to the setpoints calculated by the EMS to maintain the power reverse flow under its threshold. As it can be seen, the WE confirmed its capability in following the setpoints as they are given, if respecting the imposed limits to its maximum and minimum consumptions. Also the transitory phases have been executed with high precision.

This scenario demonstrated the ability of the plant to limit the power reverse flow to the primary station towards the HV, providing an important technical service to the grid.

4.7.4 Conclusions

As shown in Figure 48 and Figure 50, some of the main technical goals pursued by the INGRID system has been achieved, see section 4.1.1, thanks to ICT platform put at disposal of the management of the entire plant and to the technological features provided by the innovative equipment installed on-site.

As a matter of fact, the INGRID system is able to provide significant technical services to the grid operators, above all it can avoid the reverse power flow towards the HV grid. Figure 48 clearly depicts the difference between the power measured at the point 3, that would be the power coming upwards to the HV system without the intervention of the INGRID plant, and the power at point 1, which is the actual power that interests the station. It is clear how the effects of the INGRID plant allows to almost avoid reverse power flow phenomena: the blue line representing the power at point 1 is only slightly negative and only for few minutes, while the blue line representing the power measured at point 2 shows a negative power flow that lasts more than an hour.

Another key objective refers to the integration of RES into distribution grids. The load flexibility provided by the entire INGRID plant, mainly delivered by the WE operations, is able to cope with high RES fluctuation, as shown in Figure 50. Actually, once that the system sets its goal to maintain a constant power profile flowing towards the primary station, the INGRID plant is able to modify its energy behaviour and follow the fluctuations of RESs, especially PV plants, by modulating the power absorption of the WE and the hydrogen flows inside the HSS devices. The dynamic behaviour of the WE, of the gas panel and all the other involved equipment is the key technological feature that allows to deliver this service as well as to achieve this goal.

As clearly demonstrated, the ICT platform and the EMS developed for the INGRID system manages successfully to evaluate optimal configuration plans, as shown also in the previous sections, and to handle the data exchange, monitoring and control of all the plant equipment. All the data shown in the charts of this section have been retrieved by means of the monitoring system developed on purpose for the INGRID plant, as well as all the setpoints have been firstly evaluated and the properly handled and sent to the PLCs of every device inside the plant. Thanks to the attention paid on developing this framework in a modular-wise architecture, the proposed solution can be adapted and employed for the management of other system and other smart energy context.

Finally, the tests performed on the FC showed also the possibility of providing effective electro-mobility service to the LV grid. Even though the EV recharging station has been installed and tested, no real-life electro-mobility programs have been implemented due to the lack of available EV customers requesting for charging activity. So, a tool for simulating the behaviour of an EV fleet has been arranged in order to create a suitable power absorption profile related to the EV recharging station. The behaviour of the FC shown in Figure 46 demonstrates how the plant is able to face the requests from several EVs even with severe dynamic conditions. This result had been achieved thanks to the twofold contribution given by both the ICT framework and the hardware equipment of the FC.

Chapter 5

The EMS of a district context developed for the ELSA project

5. The EMS of a district context developed for the ELSA project

In this chapter, the results coming from the research activities conducted within the ELSA project are presented. The main achievement with respect to the topic of this thesis is undoubtedly the development of a flexibility platform aiming at constituting the EMS of the entire smart grid envisioned in the ELSA project. In particular, here are presented the results achieved in developing the ICT platform tailored to one of the Project demonstrator sites. The solution provided by the Project is indeed a complex framework that integrates different levels and structures of EMSs, from the system that manages a single energy unit to the framework in charge of coordinating the operation of all the energy resources and interfacing with the external actors. The key result of the work done in the ELSA project is actually the development of the ELSA District Energy Management System (EDEMS) that addresses almost all the relevant aspects related to the smart management of the energy resources installed within the energy district proposed in the ELSA project.

This chapter is structured as follows: firstly, an overview about the Project is provided, highlighting details about its goals, the project consortium, the ICT solution envisioned and the demonstrator sites where the ELSA concept is installed and tested. The subsequent sections depict the core of the proposed ICT infrastructure: the optimisation module, the modelling modules, the forecasting modules, and the negotiation module. Subsequently, the monitoring framework and the communication one are presented and described. All these components are presented along with their functionalities, their interfaces, and their interconnection in the overall ICT architecture. After that, the visualisation tools and their functionalities are explained; their human interfaces and the graphic tools are shown, as well. Finally, the results achieved by means of the ICT framework are presented and discussed, along with their impacts towards the technical and economic management criteria.

The major part of the research activities conducted for the ELSA project have been performed at RWTH Aachen University, as visiting PhD student. A strict collaboration with the RWTH team, which is partner of the Project, led to the main results discussed in this chapter. During this visiting period, the core of the optimisation platform has been designed and developed; moreover, also the modelling modules has been designed, developed, and integrated within the platform.

5.1 The ELSA project

5.1.1 Goals and overview

5.1.1.1 Concept and objectives

The ELSA project aims at smartly integrating storage technologies derived from 2nd life-batteries of the EVs into modern power grid concepts in order to provide a wide range of services, mainly technical and economic, to the grid operator and the customers (intended as final users and/or aggregators).

One of the most significant aspects of the ELSA project is the innovative integration of low-cost second-life Li-ion batteries from electric cars, allowing the re-employment of energy devices considered exhausted for their original purpose. This technological background is accompanied by a smart ICT framework for the optimisation of the usage of the energy resources and the flexibility provided by the resources themselves. The ELSA project delivers a hierarchical optimised EMS that optimises individual or previously aggregated storage resources in combination with DR programs and loads.

The ELSA project aims at revolutionising the market of local energy storage, thus creating a new solution characterised by a remarkable cost reduction and high level of flexibility. The ELSA small scale storage system is designed to achieve the following key objectives:

- Objective 1: low cost battery energy storage. The objective is to deploy an affordable battery energy storage system composed of technical equipment and battery management as well as optimisation software. This goal is one of the major objectives of the Project, in order to be able to bring the Project solution to the market.
- Objective 2: ICT-based EMS for grid support. The objective is to adapt and deploy an ICT framework able to deliver services to the grid by coordinating the battery storage with other on-site sources such as RES, building, or site loads.
- Objective 3: smart grid data models interoperability. The ELSA project includes communications and services in order to fully exploit the Project concept for local energy optimised management of hybrid virtual multi-source storage system and is integrating existing Web/IP based communication standards for automated DR into the EMS of the Project.
- Objective 4: service provisioning models and viable business models for storage. The ELSA project demonstrates the economic viability and effectiveness of

innovative storage services and related business models. Innovative service-oriented provisioning models are validated along the Project demonstration phase by combining storage based on second-life batteries with other direct (e.g. power to heat conversion in boilers) and indirect storage options.

- Objective 5: environmental and public social acceptance. The ELSA project carries out a comprehensive life-cycle assessment of the battery system. A first approach of the assessment is performed on the basis of the features of the proposed solution and is completed with elements coming from the different pilot sites during the Project life-time.
- Objective 6: impact on regulatory framework. An analysis of the current standardization and regulatory framework is performed in relation to the different services provided by the ELSA concept. Identification of the needs for adaptation of existing standards and regulations is performed, as well.

The objectives of the Projects strongly focus on relevant challenges of modern power systems and of local storages concept. Firstly, the reduction of the barriers associated with new storage concepts integrated into the distribution grid and at building/house level is addressed. The costs is reduced thanks to the mass volume as well as the industrialization brought by the automotive industry. The storage concept is deployed at the widest range of usages and regulation contexts: factory, office building, district, and distribution grid. Moreover, anticipation of potential market and regulatory issues, taking into account the social and socioeconomic aspects, is performed. Recommendations will be made to the national and EU relevant bodies about the regulatory changes needed to fully exploit the potential of distributed local storage. The safety issues and the acceptance of distributed storage in the buildings and district will be addressed, as well. Secondly, local storage applications interaction between the electricity grid and other energy uses such as the district heating/cooling network, CHP, micro-generation, local renewable is addressed, as well as the inclusion of the most advanced ICT for optimising the whole system. The ICT systems are designed to optimise the energy usages on sites which include interaction between different sources, storage systems, and energy resources (both direct and indirect). The demo sites explore electricity storage and its integrations with different energy resources. Thirdly, the demonstration proposals include market uptake measures for integrating energy storage in the electricity network and power system management as well as cost-benefit analyses of the possible uses of the technology seen from a system perspective. A significant part of the value creation associated to the distributed storage comes with the services that could be proposed to local retailers, DSOs, and TSOs. Moreover, the Project performs a cost-benefit analysis and operational optimisation of storage. All the costs associated to the installation, operation, and maintenance of the storage system in the demonstration sites are consolidated. This data will be the basis of a mass market industrial scenario representative of real business conditions.

The architecture of the ICT framework proposed for the ELSA project consists in a structured platform designed for covering all the energy processes of a smart grid equipped with the ELSA solution and the data exchange among all the actors involved. The DSO accesses to the system sending service requests directly to the ELSA District Energy Management System (EDEMS) or invokes the availability of a technical aggregator or a commercial one, in case one of these figures complies with the services to be provided. The information sent by the DSO is processed by the EDEMS which coordinates the all the operations and the communication means of the energy context addressed by the ELSA concept. In particular, the EDEMS manages the flexibility of all the resources inside the district, optimising the exploitation of the services that can be provided. In its turn, the energy management of the low level resources, also labelled as energy units, is performed by tailored EMSs that take into consideration the features of each typology of energy unit, its operation, constraints, technological limits, etc. These EMSs address the control and monitoring tasks of generation units, such as RESs or DGs systems, and innovative units, such EV recharging stations. Moreover, dedicated EMSs are developed for controlling and monitoring buildings, ELSA Building Management System (EBMS), and storages, ELSA Storage Management System (ESMS). The former are tailored for the management criteria and the ICT framework to be adopted in a building, employed for residential purpose, offices, SMEs, etc. The latter manage the usage and the exploitation of the flexibility provided by the ELSA storage system installed inside the grid, taking into consideration all the innovative technological features of the 2nd life-battery system.

The last layer described above is strictly connected with the grid equipment and the hardware devices installed inside the district. As briefly described above and detailed in the section dedicated to the Project pilots, many kind of units are envisioned to be employed and controlled inside an instantiation of the ELSA project. As far as the load units are concerned, many kind of consumers are foreseen: households, offices, factories, etc., and each of them can provide different flexibility services, in terms of magnitude and duration. For instance, the residential building can modify their power absorption for thermal comfort, or factories can schedule their internal operations over a day. Another kind of load is the power consumption of an EV station providing the supply of an electro-mobility program; in this case, the load consumption can be properly allocated over a recharge time for providing grid services. As far as the generation systems are concerned, the RES plants are taken into account as uncontrollable and partially unpredictable sources, in order to allow their integration. Moreover, the presence of DG systems, such as CHP generators, is handled by the ELSA system and their flexibility is managed. Finally, the storage units are the key technological devices, aiming at providing flexibility services by both injecting and absorbing power according to the service requests or economic considerations.

In Figure 51, a complete picture of the architecture proposed by the ELSA concept is provided, detailing a high-level modular description of the layers.

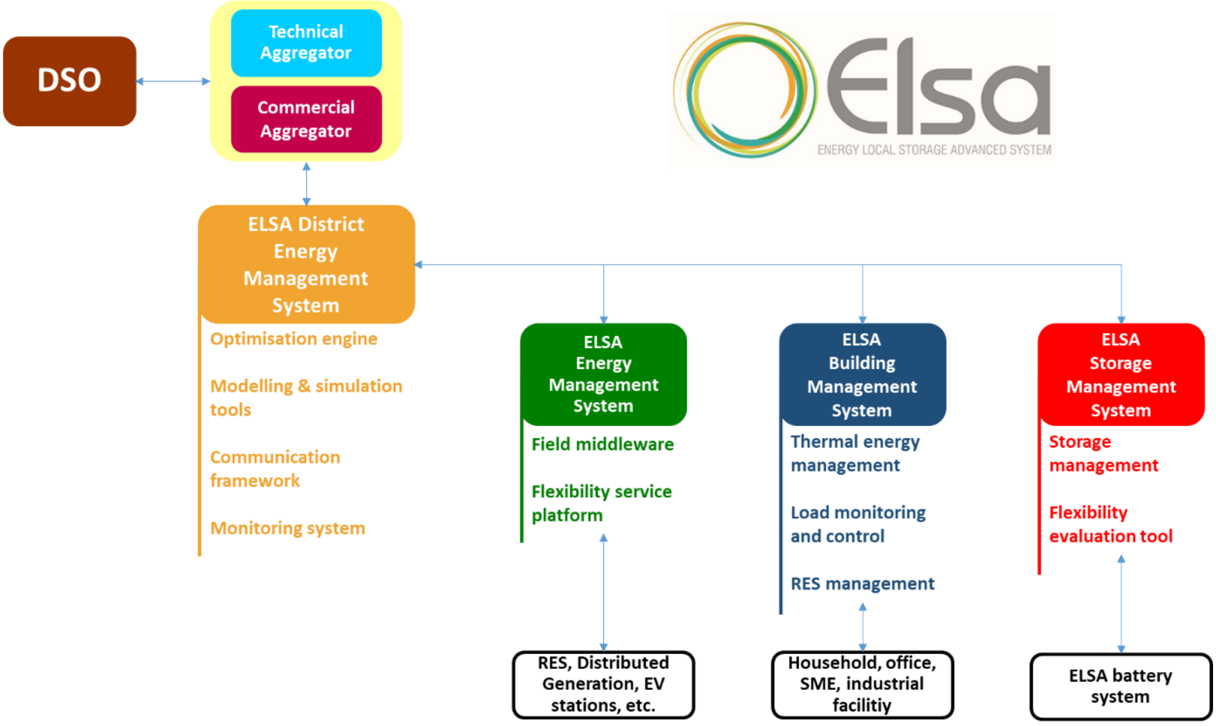


Figure 51 – Scheme of the general framework of a perspective ELSA instantiation.

As highlighted many times, the 2nd life-battery technology is at the basis of the innovation carried out by the ELSA project. The batteries are brought by the two key industrial partners of the Project, Nissan and Renault. Here, a brief description of the battery pack used as a stationary electricity storage system is provided.

The batteries from Nissan and batteries from Renault have the same components. Battery cell type is manganese cathode material pouch structure lithium-ion battery. The battery pack contains the following main component parts, as shown in Figure 52:

- Battery Management System or Li-ion Battery Controller;

- cells;
- plug-service;
- connection box;
- fuse and relays.

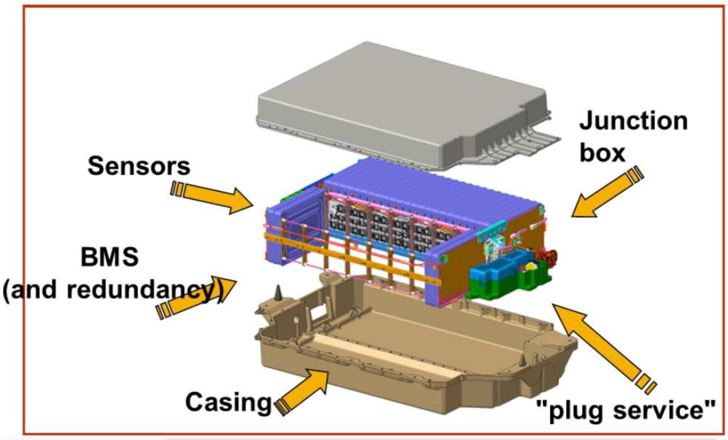


Figure 52 – Exploded view of the battery pack installed in the ELSA system.

Each battery pack is connected to a power module which adapts the electrical characteristics of the pack to the electrical environment in which it is used, for instance to comply with grid requirements. The ESMS, contained in a separate command module, manages the charge and discharge of each battery pack and ensures the safety of the whole system. This ESMS is integrated with an industrial computer able to manage and control different types of batteries in a coordinated way. This ESMS is also able to communicate with different EMSs of the ELSA ICT architecture.

Figure 53 – Picture of the installed storage system proposed in the ELSA project.

In Figure 53, the ELSA storage system is shown. Its features are:

- an electrical enclosure per battery composed of an inverter, a charger, and safety devices, called power module;
- a main electrical cabinet composed of a central controller, a safety controller, and security devices, called command module;
- a system composed of 2 to 6 power modules;
- each battery pack is stationed on a frame with wheels, and connected to its respective power module by a DC cable;
- a modular layout of the equipment;
- a storage capacity of up to 16 kWh for the Renault battery;
- a storage capacity of up to 24 kWh for the Nissan battery;
- a maximum active charging performance of 16 kW per module;
- a maximum active discharging performance of 16 kW per module;
- a communication link to an ESMS that can retrieve information from the storage system (actual status as well as forecast of 48 hours). The ESMS can send power requests to the storage system (either an instantaneous re-quest or a profile);
- if there is no ESMS, the storage system can actually follow power profiles that have been declared by end-user.

5.1.1.2 Details of the Project

The ELSA project is funded within the EC programme Horizon 2020, participating in the call "Local/small-scale storage". The project lasts 36 months and started on the 1st April 2015. The participants of this Project are ten, providing different know-hows and technologies to the ELSA system:

- Bouygues Energies & Services S.A.S. (France): sustainable development is one of the most important strategic directions of the Bouygues group. Bouygues Energies & Services delivers global and integrated solutions, oriented at designing, building, and operating tasks as well as maintenance ones. Furthermore, the group is active in many research and development programmes, alongside the rest of the Bouygues group, particularly in the fields of energy, digital technologies and sustainable buildings. Bouygues Energies & Services coordinates the Project and leads the installation and the maintenance activities of electrical facilities.

- Renault S.A.S. (France): Renault is among the leaders of the Zero Emission automotive market and is offering the widest range of EVs, also going much further in the sustainability in investing for the development of solutions re-using EV batteries. Renault brings into the Project its expertise in the design and the development of storage solutions made of EV batteries and its knowledge in EV batteries usage.
- Nissan West Europe S.A.S. (France): Nissan is pioneer in zero-emission mobility and, as part of its Zero Emission activities, it has commercialised battery storage solutions for households, buildings and grids. It provides EV Li-ion batteries to be integrated as storage solution in this Project. Nissan takes part in the development, management and demonstration of the storages and also leads the economic and environmental impact assessment.
- RWTH Aachen University (Germany): the E.ON Energy Research Center is a research department of RWTH Aachen University aiming to develop a comprehensive understanding of how sustainable energy can be realized. The vision of the Energy Research Centre can be realised by focusing on the reduction of energy consumption and the use of environmentally friendly energy sources. Within the Project, RWTH contributes to requirement definition and development of the ICT solution, as well as to the design of the battery storage solution. In addition, validation and evaluation are be performed by hardware-in-the-loop techniques as well as by scaling up field test scenarios to system level for proof-of-concept analysis.
- United Technologies Research Center, UTRCI (Ireland): UTRCI provides its experience in developing EMS and middleware for optimising the thermal and electrical generation, storage and consumption in commercial and industrial buildings. Specifically, UTRCI leads the adaptation and implementation of an ICT platform for integrating 2nd life batteries with other energy vectors in several energy domains. Furthermore, UTRCI participates in analysing storage services in every demo site.
- Engineering Ingegneria Informatica S.p.A. (Italy): the company profile is the same depicted for the previous chapter for the INGRID project. Engineering leads the elicitation of requirements and the specification of the ELSA system. Moreover,

Engineering develops and deploys the ICT framework for the optimised management of the district envisioned for one of the Project pilot.

- B.A.U.M. Consult GmbH (Germany): B.A.U.M. supports enterprises, municipalities, regions and governmental institutions throughout Germany and abroad with consultancy and training on sustainable development. As a knowledge management company, BAUM has a key role as link between research, development, production, and marketing of sustainable products and services. B.A.U.M. contributes on the requirement analysis and economical and environmental impact assessment. B.A.U.M. further leads the dissemination of the Project results, elaborates and maintains the dissemination plan, and is in charge of the implementation of various dissemination measures.
- ASM Terni S.p.A. (Italy): ASM Terni is a company fully owned by the local municipality (City of Terni). The activity of the company is related to public services in the City of Terni area as: production and distribution of electricity, management of public street lighting, environmental issues, drinkable water distribution as well as water treatment plant, and gas distribution. ASM directly possesses the power distribution grid from the MV/LV and HV/MV stations to the end consumers’ smart meters. Moreover, it owns some power generation units, with an increasing share of RES. ASM Terni is a major contributor to test the software engineering framework in a real trial, providing access to its energy network management, to all the essential services for citizens (water, gas, waste management, etc.) and customer management expertise. As owner of a test site, Terni is involved in all the tasks of the Project in order to evaluate the proposed solutions in its own environment.
- Gateshead College (United Kingdom): Gateshead College is an education college established in 1955. The college is fully committed in studying smart homes and energy management options. Gateshead College contributes to the Project by integrating and evaluating the new solution in the own test site. The integration of battery storage into a live test site at Gateshead College provides a holistic experimentation facility encompassing both thermal and electrical aspects. Optimised energy management is performed, monitored and validated at the site.
- Allgäuer Überlandwerk GmbH, AÜW (Germany): The utility company Allgäuer Überlandwerk GmbH supplies 90.000 customers in the Allgäu region (Alpine region in Southern Bavaria, Germany) with electricity. AÜW will further expand its role as

a cutting-edge company within the energy industry constantly oriented towards innovation, above all, the involvement of the public and networking with regional, national and international actors. Main tasks of AÜW are the contribution to installation and maintenance in the test sites; further, AÜW provides larger contributions to the definition of the scalable ICT platform for storage and grid services management. Finally, it contributes on the studies about the economic and environmental impact assessment.

In Figure 54, the partners of the Project are listed and graphic reported over the Europe map.

Figure 54 – Partners beneficiaries of the ELSA project.

5.1.2 ICT-based EMS solution

In this section, a complete overview of the architecture of the ICT solution is provided, highlighting the different layers of resources management. In particular, the interaction among all the energy management tools developed for controlling each energy unit is depicted. The architecture of this ICT platform is structured in layers addressing energy management aspects of the different levels of the proposed ELSA system:

- Storage level: the ESMS algorithms are implemented within the storage system installed in the pilot sites for storage services provision, oriented at both optimisation services and fast services, such as ancillary and power quality services.
- Building level: the EBEMS implements an energy management software system which optimises building energy resources usage and takes into account all the

operational aspects of building inhabitants, such as comfort. It implements also communication with EDEMS allowing district energy resources coordination.

- District level: the EDEMS algorithms is implemented in a high level energy management software system which allows communication with the storage system and the different energy resources within the district. The proposed algorithm allows the adaptability to the needs of the district and the coordination of the needs reported by every energy unit in a comprehensive optimisation approach.

Moreover, an ELSA Energy Management System (EEMS) is provided in order to address all the aspects of a general purpose EMS tailored for controlling and monitoring the operations of units that can be installed inside a typical ELSA system instantiation. These units consists of RES systems, DG devices, EV recharge stations. By means of the EEMS, the tasks regarding these systems, such as the energy forecasting, modelling, monitoring, etc., are addressed and the related data are exchanged with the other tools.

The ICT tools, ESMS and EBEM, seen as specialization of the EEMS, as well as EDEMS, are part of the overall ICT architecture including the communication level for the cooperation among resources. Additionally, the architecture includes the communication towards grid external stakeholders, such as DSO, Technical Aggregators (TA) and Commercial Aggregators (CA). The latest communication layer is intended to provide interoperability features between external stakeholders’ platforms and the ELSA system.

The data processing mechanisms for the optimisation of energy management exploiting storage services is here described.

The ELSA system pursues a systematic exploitation of the flexibility resources provided by the energy units, thereby implementing a comprehensive set of services to the facility owners and grid operators or aggregators. As shown above, the overall ELSA general architecture covers all these aspects through the different EMSs that conceptually model the coordination and control process all of the energy units. These EMSs enable different management and control modalities, depending on the selected control objective and specific configuration.

In Figure 55, the hierarchical structure of the ELSA architecture is shown, where all the different management systems are outlined. The EDEMS exchanges signals with the DSO or with TA/CA. The requested service is received by the EDEMS directly from the DSO, or through a TA/CA. The EDEMS communicates with all the other management components (EEMS, ESMS, or EBMS depending on the resources installed in the system) acting as a first resource aggregation, where at least one energy unit consists in a storage system. The EDEMS here proposed is designed and modelled for a centralized approach aiming at coordinating directly all the district energy units. Each EEMS communicates with the EDEMS its electrical load/generation behaviours that each energy unit can provide. In its turns, the EDEMS collects them and optimises the exploitation of their availability for providing services. After having evaluated the energy behaviour with respect to the request of the DSO, the EDEMS forwards flexibility requests to the EEMSs of the energy units. Such a request will include start/stop time, requested power profile and related economic incentive compensation. The EEMSs can decide to accept the flexibility request from the EDEMS and respond with a signal indicating whether the request is accepted or not. Moreover, each EEMS communicates with the controlled energy unit for implementing the optimised setpoint, in case the request is accepted, or the forecasted one, in case the request is not accepted. At the end of this process, the EDEMS presents to the grid operators its proposals for grid services in comparison with the solution evaluated and optimised on the basis of the flexibility availability provided by the energy units controlled.

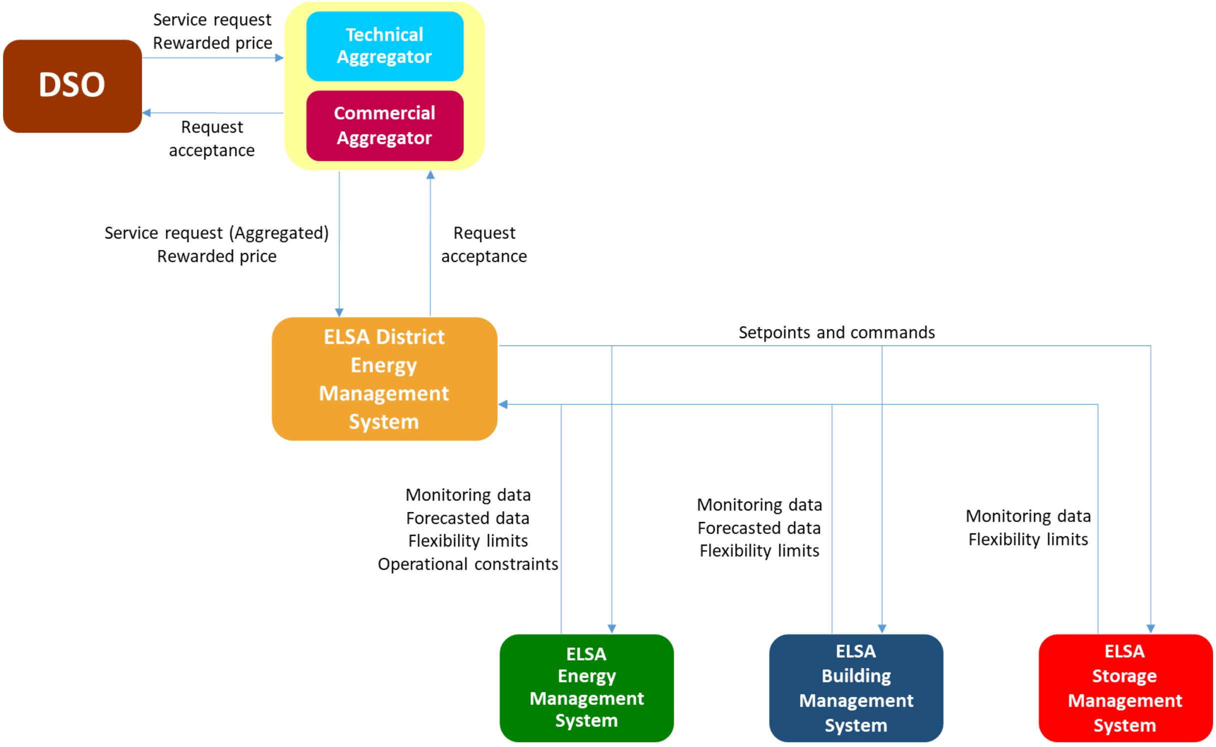


Figure 55 – Detailed architecture of the ICT framework proposed inside the ELSA project.

5.1.3 Test sites

The ELSA project has the main goal of implementing storage systems in six test sites across the Europe, in order to test their integration within different operating conditions and in particular different scenarios involving different smart grid technologies. In this view, the pilots present different energy contexts in which the services provided by the exploitation of energy flexibility, in particular by the storage system, can be tested and assessed: factories, office buildings, districts, and distribution grids. In the following, the six pilots description is provided.

1) Gateshead SASMI Building: United Kingdom, Gateshead College at its Skills Academy for Manufacturing and Innovation (SASMI) facility. The Skills Academy for Sustainable Manufacturing and Innovation is a world class centre to train workers for green industry. The centre provides a training infrastructure for low carbon vehicle manufacturing industry and a world class learning facility for employers, apprentices, and students, providing new skills for new jobs. The consortium installs at the SASMI building a storage capacity of 72 kWh, an electric water heater, and adds 30 kWp of PV. The ICT system is the EMS developed by UTRCI. This system is not only used to optimise the electricity grid locally but also to develop a training package to support the wider deployment of distributed storage.
2) Ampere building: France, Ampere Building at La Defense, Paris. This office building owned by the company Sogeprom is situated in the most important business area of Paris. The ELSA project provides a storage solution able to satisfy the most stringent safety and security specifications in critical office environment. The configuration includes a 32 kWh battery, heat pump for heat and cold generation of 130 kW, a connection to the heat distribution network of La Defense, and solar panels.
3) Barcelona plant: Spain, Nissan Barcelona Factory. Introducing storage in a large manufacturing plant is difficult because of the poor business model and the requirements of safety and security. Two pilots are installed at the factory (with a consumption of 100.000 MWh). The storage capacity of 430 kWh (Li-ion batteries equipping the new Nissan EV, eNV200A) are integrated with 25 kWp of wind generation and with the BEMS in order to optimise the energy consumption for lighting. As part of a larger Nissan investment in replacing the lead-acid batteries of its fleet of autonomous guided vehicles by lithium batteries with an induction charging system, the ELSA project contributes with the installation of 575 kWh storage capacity and 75 kWp of wind generation that will be connected the inductive recharging system.
4) E.ON Energy Research Centre: Germany, E.ON Energy Research Centre. The E.ON Energy Research Centre is a multi-disciplinary research institution of RWTH Aachen

University. The main building of the Centre has been designed and built to be an experiment in itself including advanced building management system integrating different solutions for heating and cooling including geothermal storage, CHP and cold via an open sorption process. The building is also equipped with a set of solar panels on the roof. Two more buildings (one experimental hall and one office building) complete the scenario together with a small wind turbine (Enercon, 500 kW). In the framework of the ELSA project, the electrical storage is added to increase the flexibility of the local services to be exploited in a district vision among the three buildings. The building management system is expanded and enriched to incorporate the new functionalities of the ELSA project solution and integrated at the upper level for the micro-grid coordination.

5) Terni district: Italy, City of Terni. Italy is a very important market for electricity storage, with a very large capacity for photovoltaic energy. ASM Terni deploys and operates a battery energy storage along the LV branch of its owned smart grid, in order to mitigate and smooth the fluctuating power output generated by the nearby PV farm. The resulting configuration for the ASM Terni pilot consists of two PV plants, connected to the LV branch of the network, which is complemented by a battery energy storage situated close to the secondary substation (and immediately downward the secondary substation). Secondary substation is already equipped with power automation. This demonstration site is fully described in the following sections.
6) City of Kempten: Germany, City of Kempten-Halde. About 33% of the electric energy consumed in Kempten and the region Oberallgäu (the distribution area of AÜW, Bavaria) is already produced from regional RESs. As one of the most important service partners of the City of Kempten, AÜW is involved in the planning development of a new residential area. The aim is to set up a light-house project with 50 single and 2-family houses in the highly energy efficient passive house standard. This is planned to be combined with the use of the maximum of solar electricity that can be generated by PV roof-top plants (200 kWp). A CHP plant with a small district heat grid or several small CHPs within the individual houses, both with thermal stores, are optionally foreseen to be added and provide the balance of the energy demand of the new residential area. The ELSA project contributes to demonstrate the optimisation of the district storage size in a local area network to minimise the inserted fixed capital for network infrastructure in an urban development area.

5.2 Optimisation framework

In this chapter, the overview of the proposed optimisation process is provided, depicting all aspects of the framework, its goals and how the optimal solutions are found and elaborated. Firstly, the criteria of the process itself are proposed, highlighting the services and the goals of the optimisation algorithm as well as how they are handled. Subsequently, the architecture of the process is shown and explained, detailing its steps. Finally, after having addressed the data structure employed for exchanging information, the mathematical formulations of both objective functions and constraints are provided.

Before to address the topics listed above, some specifics and definitions about the energy context taken into account have to be provided.

5.2.1 Addressed energy context

The proposed flexibility platform discussed in this chapter is tailored to one of the test site of the ELSA project, into which it is going to be installed and deployed. This choice has been done in order to highlight the effectiveness of the optimisation approach into an energy district conceptually close to an urban micro grid context in which smart energy services to the distribution grid are provided. The selected test site is located in Terni, Italy, on the premises of ASM Terni (see section 5.1.3). This test site has been appointed because of the great amount of RES generation units connected to the MV and LV grids that causes severe technical issues on the power system devices. As reported by data provided by ASM Terni itself, the number of PV plants connected to the LV network surrounding their premises increased fivefold in the last five years, reaching up to the 50% of the electric power consumption of Terni. DR, energy storage and prosumers’ flexibility are pointed out as the most effective actions for coping with these phenomena in order to improve the reliability of the network and the overall efficiency of the energy supply and generation processes. The Terni test site is able to provide these kind of services, mainly by means of the employment of the battery system proposed by the ELSA project, discussed below in this section. In Figure 56, the geographic reference of the Terni site and a satellite imagine of the site itself are shown.

Figure 56 – Geographic location of the ELSA demonstrator and a satellite view of the site.

The system is considered as an energy district that can be defined as an energy infrastructure consisting of different kind of energy resources, intended as loads, generation devices, storages, and any other electrical component, whose consumption of electricity, thermal energy, gas, etc., relies upon the same distribution systems. In this view, the management of their energy behaviour affects the operation of the overall system. Usually, the sizes of an energy district is limited both in terms of distances (for instance, an urban neighbourhood) and in terms of interested energy amount.

In the context of the ELSA project, the energy resources inside an energy district are addressed as energy unit, considered as internal actors of the district that interact with the energy flows of the system. An energy unit can be represented by a passive consumer, an active consumer (prosumer), a generation system, a storage system, etc. It can be controllable or uncontrollable, depending on the availability on providing flexibility.

As mentioned in the previous section, the platform here proposed addresses the optimisation of the district by managing and exploiting the flexibility of each energy unit in a coordinated operational configuration.

The Terni district consists of four energy units, thus a passive generation unit, a passive load, a flexible load, and a flexible storage system:

- 2 PV plants: they are installed upon the parking shelters of the Terni demonstrator premises and they are aggregated in order to form a unique energy unit. The total peak power of these plants is 240 kW, derived from the sum of the two peak powers of the different installations, 180 kW and 60 kW.

- 3 passive buildings: these three users are aggregated for creating a single consumer energy unit. The building are: (i) the headquarter offices located in a three-story building (2.790 m^2), (ii) technical offices, a computer centre and an operation control centre located in a single-story building (4.050 m^2), and (iii) the warehouse (1.350 m^2). The maximum rated consumption power is 195 kW.
- 1 EV recharge system: the station is able to charge all EVs compliant with CHAdeMO system and Combined Charging System standards. Two charging stations are installed: (i) EFAPOWER EV-QC45 with rated power amounting to 49 kW and (ii) SPOTLINK – EVO filling station, with 22 kW of maximum charging rate. The total power of the energy unit is considered 71 kW, managing to recharge up to three EVs.
- 1 storage system: it consists of 6 different batteries derived from EVs. They are installed and equipped in a unique storage unit providing flexibility to all the test demonstrator. The capability of the entire storage is 96 kWh. Both the maximum absorption and the maximum injection power is 96 kW. Further information about the batteries are detailed in the following sections.

In Figure 57, the complete layout deployed inside the Terni demonstrator is shown, mapped with the EMS components of the ICT architecture briefly presented in the previous section.

One of the most significant aspects of this energy district is the innovative integration of low-cost second-life Li-ion batteries from electric cars, allowing the re-employment of energy devices considered exhausted for their original purpose. The batteries installed in the Terni test site have been previously employed in Renault Kangoo EVs. The storage capacity of each of these batteries is 16 kWh; the maximum active charging performance of 16 kW and the maximum active discharging performance of 16 kW. As already mentioned, the battery pack of the Terni demonstrator consists of six storage devices; it can be noticed how the rated features of the entire storage system is derived from the values just provided.

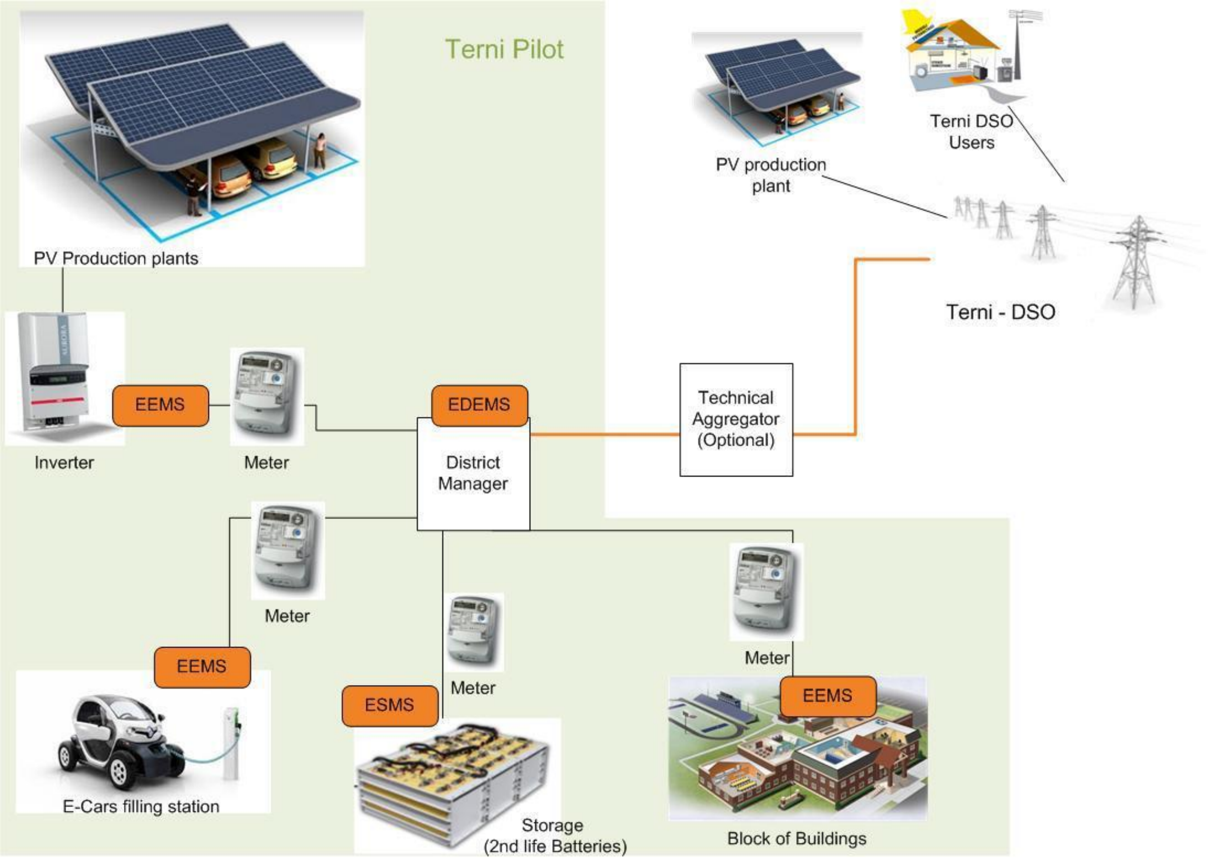


Figure 57 – General layout of the Terni demonstrator of the ELSA project.

In Table 8, a detailed overview of the battery system parameters is provided. It worth noting that this system is able to provide both generation and absorption flexibility up to 96 kW. It represents the most relevant flexibility source of the ELSA district since the provision of flexibility is not related to other energy activities but the operation of the battery is only committed on facing the district need regarding the shaping of power profiles.

Table 8 – Parameters of the battery system installed in the ELSA demonstrator.

ELSA Battery System (Renault Kangoo)				
	Type	**Description**	**Unit**	**Value**
Specifications	No. of batteries		-	6
	Capacity	Nominal manufacturing capacity	kWh	96
	Max charge rate	AC side of SPC (Smart Power Converter)	kW	96
	Max discharge rate	AC side of SPC	kW	96
	Min charge rate	AC side of SPC	kW	0
	Min discharge rate	AC side of SPC	kW	0
Efficiency & Losses	Inverter efficiency		%	Up to 96

	6 battery system energy efficiency	Approximately: higher than 80%	%	TBC
	Fixed power consumption	Approximately: less than 0.5	kW	TBC
Flexibility	Max	1.0	kW	96
	Min		kW	0
	4 hour hin		kW	24

The other energy unit able to provide flexibility is the EV recharging system, representing a controllable load. As a matter of fact, the charging stations can provide flexibility as a load from 0 kW (lower limit) to an upper limit that depends on the number of EVs inside the parking lot and their availability to be charged in that specific time window. In general, the flexibility spans from 0 kW to 66 kW, being able to absorb steps of 22 kW, thus corresponding to zero, one, two, or three EVs in charge. In particular, the fleet of EVs employed for this ELSA demonstrator is composed by Renault Zoe cars, whose maximum recharge rate amounts to 22 kW.

The energy unit consisting of the PV plants cannot provide any flexibility. It is considered as a non-programmable generator whose only forecasted generation profile could be known.

The passive load related to the 3 passive buildings is considered as an energy unit that cannot provide flexibility. Nevertheless, the possibility of employing HVAC systems, in particular the heat pumps and the air handling units, for providing flexibility to the loads is under investigation for further studies.

The energy district taken into account receives requests from DSO for the provision technical grid services, such as peak shaving and PV power smoothing services. As far as the peak shaving is addressed, this service aims at reducing peak loads in the district during the peak hours. Indeed, the DSO realises that there is a peak power demand in the grid and requests this service to the district manager responsible of energy flows inside the district. If the PV power smoothing is taken into account, this service aims at reducing the amount of exceeding power generated by the RESs. The DSO, having forecasted the generation profile of the PV plants of this specific test site, asks the district manager to cope with the over-generation phenomena by exploiting the flexibility from the energy units.

The flexibility platform presented in this work is developed in the shape of the EDEMS inside the Terni demonstrator of the ELSA project discussed in the present section. The EDEMS adopts a multi-objective optimisation framework in order to implement all the functionalities required by the smart management of the district itself.

5.2.2 Management criteria of the ELSA system

The objectives of the ELSA project entail several aspects of the management of smart powers system. In particular, the most relevant within the smart grid context addressed by the present study is the integration of local energy storage devices into different energy systems by exploiting the flexibility of the energy resources in order to provide services to the grid operators and gain economic benefits. All these topics are handled through an ICT-based flexibility platform able to address all the management aspects, from the technical to the economical ones.

The management criteria of the optimisation process discussed in this section are taken into account at district level. The EDEMS has to coordinate the district and provide the peak shaving and PV power smoothing services since it knows both the DSO request (in terms of reference power, tolerance and addressed time horizon) and the flexibility offered by each energy unit belonging to the district. For the specific time horizon, the EDEMS computes the flexibility requested to every energy units taking into account the difference between total power consumption in the district and the reference power requested by DSO. The EDEMS distributes the service request to all the energy units addressing its own criteria; each energy unit that accepts the request applies the flexibility actions in different way according to the typology it belongs to. If at least one energy unit does not accept the request, the EDEMS establishes a proper negotiation process in order to find a suitable overall solution.

In this view, the optimisation process relies upon three different criteria: an economic criterion, a technical one, and an operational one. The economic criterion is driven by the minimisation of the money rewarded to each energy units for the provision of flexibility services. The district manager is the actor responsible of the management of the energy resources inside the district and exploits the functionalities of the EDEMS for pursuing its goals. The district manager gains economic revenues for the services provided to the DSO and rewards with incentives each energy unit for the flexibility, in terms of power, put at disposal of the EDEMS management process. Since the difference between these two amounts of money represents a net profit for the district manager, the first criterion aims at minimising the rewards of the energy units in providing flexibility. This first criterion is strictly coupled with the second technical one. It is driven by the DSO requests, aiming at minimising an objective function that parametrises the distance of the requested profile from the effective power exchanged at the connection point of the district. In this way, the power profiles of each energy units tend to vary in order to be compliant with an overall district power profile that fulfils the profile request of the DSO. These two criteria therefore allow to take into account two important trends: the provision of flexibility actions by the energy units of the system for providing grid services and the economic benefit of the district manager in doing this. As mentioned above, the district manager gains incentives from the DSO if the power profile of the district stays within the tolerance range of the DSO request, in terms of money rewarded for the provision of the service in that time stamp. In this view, the third operational criterion allows the process to choose the solutions that minimise DSO request violations, in order to provide operational configurations that comply all the aspects of the district management also in case of strongly constrained contexts. Actually, the DSO request could not be followed in case of particular operational configurations that limit the flexibility capabilities of the district. This operational criterion gives relevance to the solutions that avoid violations of the requests sent by the DSO and, consequently, the loss of the incentives.

5.2.3 Architecture and approach

The optimisation framework proposed for the ELSA project consists of several modules designed and developed in order to perform all the different tasks envisioned for the management of the district. The different modules are structured through three main phases:

- the first one addresses the conditioning and manipulation of the input data coming from the external systems, that are subsequently collected and shaped following the EDEMS data structure;
- in the second phase, these data are sent to the optimisation module that performs the optimisation process taking into account all the objectives of the system and the related constraints, providing the optimal solutions for the district operational configuration;
- thirdly, the optimised information coming from the previous step are elaborated by a DSS that performs a selection relying upon user choice or pre-configured criteria;
- finally, a negotiation process is performed in order to allow the energy units to accept or not the optimised solution provided by the previous step. The negotiated solution is going to be adopted as optimal configuration for the considered energy unit.

The first phase is performed through two main modules that address the forecasting and modelling tasks of the system. The forecasting tool receives the historical data of the interested energy units in order to perform forecasting algorithms evaluating their forecasted energy behaviour. This evaluation can be performed for both controllable units, such as the EV recharge station, and uncontrollable ones, such as passive buildings and PV plants; in this context the latter energy units are those addressed by the forecasting tools. The modelling modules aim at modelling and simulating the behaviour of the energy units in order to provide both power profiles as well as constraints and flexibility boundaries of the energy units considered. The key information needed by this module are the current statuses of the energy units and their rated values as well as operational constraints. The energy units addressed by this module are both controllable units and uncontrollable ones. In particular, as far the controllable units are concerned, the flexibility capability of the resources, thus the storage system and EV system, is evaluated as well, as key parameter of the optimisation process. Both the forecasting and modelling modules are fully detailed in the next sections.

All the information provided by these modules and the other input data of the optimiser are collected and adapted to the EDEMS data structure, presented in next section, and then forwarded to the optimisation module.

The process starts when the DSO sends its service request, that consists of a reference power profile accompanied by an upper limit and a lower one defining a tolerance range within which the DSO request is fulfilled, and the corresponding economic value of the service. Subsequently, the optimisation module asks for the data related to each energy unit in order to gather information about their energy behaviour and flexibility. In particular, it needs information about the forecasted power profiles of the buildings energy unit and the PV energy unit evaluated by the forecasting modules that receive historical data about the power profiles of these energy units. Moreover, information about the forecasted power profiles and the flexibility availability of both EV system and battery energy units are retrieved from the modelling modules of these two energy units. The data input conveyed to the optimisation are:

- the DSO request, accompanied by tolerance limits;
- forecasted power generation profile of the PV energy unit;
- forecasted power absorption profile of the buildings energy unit;
- forecasted power absorption profile and related flexibility limits of the EV system energy unit;
- flexibility limits of the battery energy unit;
- money rewarded to the district manager in case of DSO request fulfilment;
- prices rewarded by the district manager to each energy unit for flexibility provision.

Moreover, the district manager is provided with a console through which it is able to set both the time horizon of the optimisation process, over a day, and the timestamp of the process itself. These information are employed as data input, as well.

The optimisation module relies upon the same algorithm developed and deployed for the INGRID project, the Non-dominated Sorting Genetic Algorithm II. So, the optimisation process provides a set of Pareto-optimal solutions and each of them represents a set of power profiles related to the energy behaviour of each energy unit, the related incentives for providing flexibility as well as the remuneration rewarded to the district manager for the provision of services to the DSO.

After this phase, a tailored DSS is provided in order to select the solutions allowing the best fitness toward three appointed criteria of the optimisation. This choice could be performed either automatically or manually, by means of a dedicate GUI.

Finally, once the optimised profiles are known, an early negotiation mechanism has been developed with the EV system unit: a dedicated module implements a negotiation taking into account the solutions chosen by means of the DSS and the technical and operational feasibility of them with respect to the criteria of the EEMS controlling the EV recharging stations. The selected optimal solution is then sent to the visualisation tools as well as to each EEMSs for being translated in setpoints and forwarded to the device control equipment (smart meters, actuators, etc.).

At the end of the optimisation process, the following data are provided to the external tools of the overall ELSA architecture:

- the optimised power profile of the EV system energy unit;
- the optimised power profile of the battery energy unit;
- the optimised power profile of the overall district;
- the service rewards to the microgrid owner;
- the incentives rewarded to the EV system;
- the incentives rewarded to the battery;
- the system setpoints, arranged in an unique file containing all the optimised profiles properly temporised.

In Figure 58, the overall architecture of the optimisation framework described above is depicted along with all the modules exchange data with the framework.

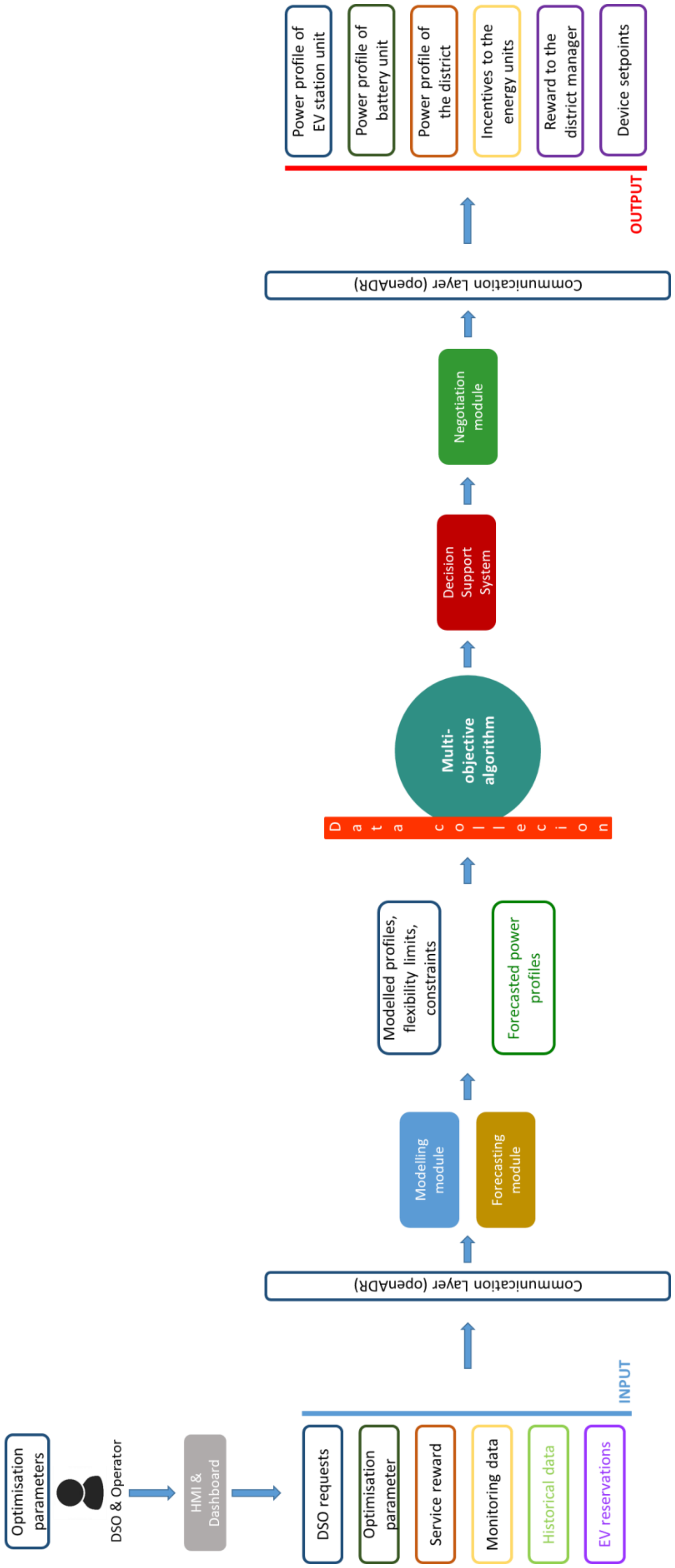


Figure 58 – The architecture of the optimisation process developed inside the ELSA system.

The optimisation process is performed every time stamp over the addressed time horizon: since the optimal overall solution of the optimisation process is composed by the series of the optimal solutions evaluated for each time stamp, the above mentioned steps are performed for every time stamp. This design choice allow to take into account also the evaluations performed by all the modelling and forecasting modules, whose information changes time stamp by times stamp, as explained in sections 5.4 and 5.5.

5.2.4 Data structure

As seen for the data structure proposed for the INGRID project, the information conveyed to the optimisation framework have to be structured in a proper way in order to be compliant with the interfaces of the all the modules of the proposed solution. These data are arranged in profiles, represented by arrays or lists, whose every elements reports the information of a single time stamp. In the platform developed for the ELSA system, the user have the chance to set both the time horizon addressed by the optimisation and the time stamp of the process.

The profile of an energy unit is defined as a set of values concerning the power to be provided/consumed: it identifies the space of all the possible concrete behaviours that a system can accept and implement (as load or as generator, controllable or not). From the conceptual point of view, the profiles coming from the different district units consists of a set of condition above the power profile of these units: a reference power profile, which is the power effectively generated or consumed; one or two profiles representing the maximum or minimum deviation allowed with respect to the reference one, considered as the flexibility limits of the energy unit.

The most common format used for manipulating the information conveyed by a power profile consists in a set of data structured in an array, or a list, whose each elements consists of:

- a reference to the time stamp;
- one or more power values;
- a price value (optional).

Through this format, the information regarding power absorption/generation profiles and the related flexibility (either forecasted, modelled, or optimised), the requested profiles (in term of service request), the costs of the energy and the rewarded incentives are represented.

In order to allow the data exchange between the modules of the architecture, this profiles are written and properly formatted inside Json files.

5.2.5 Objective functions

The objective functions are the mathematical means through which the optimisation process addresses the management criteria of the EDEMS proposed for the ELSA system. The optimisation algorithm refers to the flexibility provided by the flexible units as optimisation variables. The exact evaluation of these values allow to assess both the flexibility provided by each every unit involved in the management process and the corresponding rewarded incentives. Moreover, these variables allow to evaluate the overall power behaviour of the district with respect to the request of the DSO.

The first objective function addresses the economic criterion described in the previous section. It evaluates the incentives that should be payed to each energy unit in order to reward the provision of energy flexibility by multiplying the delivered flexibility, in terms of power, for the corresponding incentive:

$$\mathrm{OF1}(t_i)=\sum_{i=1}^{n_{EU}} \mathrm{flexibility}_{EU,i}(t_i)\times I_{EU,i}(t_i) \qquad \forall t_i \in T$$

where

- n_{EU} is the number of energy units providing flexibility;
- $\mathrm{flexibility}_{EU,i}$ is the flexibility provided by the i-th energy units in every time stamp t_i, [kW];
- $I_{EU,i}$ is the incentive that should be rewarded to the i-th energy units in every time stamp t_i, [€/kW];
- T is time horizon of the optimization process. [h].

The technical criterion is implemented through the second objective function, which parametrises the distance between the actual power demanded/injected by the district and the request sent from the DSO by means the evaluation of a percent index with respect to the DSO request:

$$\mathrm{OF2}(t_i)=\frac{\left|P_{DSO,request}(t_i)-P_{district}(t_i)\right|}{P_{DSO,request}(t_i)}\times 100 \qquad \forall t_i \in T$$

where:

- $P_{DSO,request}$ is the reference (or central) value of the power profile requested by the DSO in every time stamp t_i, [kW];
- $P_{district}$ is the power demanded/injected by the district to the grid in every time stamp t_i, [kW].

Finally, the third objective function focuses on the operational criterion. Actually, the third objective function evaluates for each timestamp if a violation of the DSO request occurs (thus the solution is outside the requested tolerance range) for every proposed solutions and allows the process to choose the solutions in which these limits are violated as less as possible:

$$OF3(t_i)=\begin{Bmatrix}0\\1\end{Bmatrix} \qquad \forall t_i \in T.$$

5.2.6 Constraints

The constraints taken into account for the optimisation process address mainly the flexibility boundaries of the energy units providing this service. As a matter of fact, each flexible unit informs the EDEMS about their availability in modifying their power profile, providing a reference power profile, an upper flexibility profile, defining the maximum power injected/absorbed, and a lower flexibility profile, defining the minimum power injected/absorbed. Since these profiles take into account the rated values of the energy units, the technical feasibility of the solutions constrained by the flexibility boundaries is considered satisfied:

$$\text{flexibility}_{\text{battery,min}}(t_i) \leq \text{flexibility}_{\text{battery}}(t_i) \leq \text{flexibility}_{\text{battery,max}}(t_i) \qquad \forall t_i \epsilon T$$

$$\text{flexibility}_{\text{EV,min}}(t_i) \leq \text{flexibility}_{\text{EV}}(t_i) \leq \text{flexibility}_{\text{EV,max}}(t_i) \quad \forall t_i \epsilon T$$

where:

- $\text{flexibility}_{\text{battery,min}}$ is the lower flexibility limit of the battery energy unit;
- $\text{flexibility}_{\text{battery}}$ is the flexibility evaluated by the optimisation algorithm for the battery energy unit;
- $\text{flexibility}_{\text{battery,max}}$ is the upper flexibility limit of the battery energy unit;
- $\text{flexibility}_{\text{EV,min}}$ is the lower flexibility limit of the EV station energy unit;
- $\text{flexibility}_{\text{EV}}(t_i)$ is the flexibility evaluated by the optimisation algorithm for the EV station energy unit;
- $\text{flexibility}_{\text{EV,min}}$ is the upper flexibility limit of the EV station energy unit.

Besides these technical constraints, the operations of the system are taken into account for outlining some relevant operational constraints that suitably limit the solution space of the optimisation problem. These constraints are related to the operational feasibility of the optimised solution, thus allow to consider the state of each energy unit and its operations in defining a proper energy behaviours. As far as the storage system is concerned, the limits related to the state of charge of the batteries is taken into account. Actually, the power injection/generation that the batteries can provide depends from the state of charge: if they are partially empty they are no able to provide the rated power injection; if they are partially full they are not able to provide the rated power absorption. As such, the following constraints have to be respected:

$$P_{battery,min}(t_i) \geq -\frac{SoC(t_i)}{\Delta t_i} \qquad \forall t_i \epsilon T$$

$$P_{battery,max}(t_i) \leq \frac{capacity - SoC(t_i)}{\Delta t_i} \qquad \forall t_i \epsilon T$$

where:

- $P_{battery,max}$ is the maximum power that can be absorbed by the battery energy unit;
- $P_{battery,min}$ is the maximum power that can be injected by the battery energy unit;
- SoC is the actual state of charge of the battery system;
- Δt_i is the length of the time stamp;
- capacity is the overall energy capacity of the battery system.

It worth noting that the power convention employed for the EDEMS refers to positive power values for the power consumption and negative power values for power injection.

As far as the EV system is concerned, a first aspect to be taken into account is the fact that the power absorption of this energy unit is characterized by a step-wise behaviour: depending from the EVs recharging during that time stamp, the overall power absorbed by the EV energy unit is the sum of the powers requested by the connected EVs. This means that, considering three recharging stations and the maximum power requested by a single EV:

$$P_{EV}(t_i) = \begin{Bmatrix} 0 \\ 22 \\ 44 \\ 66 \end{Bmatrix} \qquad \forall t_i \in T.$$

where P_{EV} is the maximum power absorbed by the EV system energy unit.

Moreover, the maximum and the minimum power absorption of the EV energy unit is constrained by the number of EVs present inside the parking lot requesting for recharge. In particular, the minimum power requested by the EV system is linked to the requests of the EVs in order to handle them before they leave the parking lot. The maximum power requested by the EV energy unit amount to the number of EVs requesting for recharge that is obviously limited by the number of recharging stations.

Detailed information about the constraints presented in this section are provided in the section describing the modelling modules.

5.3 Modelling framework

In this section, all the modules composing the modelling framework are depicted and their logics are explained. The modelling modules designed and developed for the ELSA system presented in this study are two: the battery system modelling module and the EV system modelling module. They have been developed in Java environment and integrated with the optimisation framework since many data are exchanged each time stamp between the optimisation algorithm and the modelling modules. In particular, the main goal of these modules is to provide detailed information about the energy behaviour of the appointed energy resource, such as the flexibility assessment and the status evaluation also over a fixed time horizon.

5.3.1 Battery energy unit

The module responsible of modelling and simulating the behaviour of the battery system provides two different functionalities, one invoked before the optimisation process for evaluating the availability on providing flexibility, the other invoked after the optimisation itself for updating the state of charge of the battery by simulating the charging/discharging process.

The flexibility evaluation is performed by calculating both the upper and the lower power limit of the battery system operation. It worth noting that the convention adopted for the proposed ELSA system considers the positive power flows as power consumption and the negative ones as power generation. As such, the lower flexibility limit of the battery system, since the battery is able to both absorb and inject electricity, is considered as the availability on injecting power. The calculation is performed every time stamp in order to provide the optimisation framework with the updated value of the flexibility on the basis of the choices made in the previous time interval.

The input data are the monitored state of charge of the battery system and rated parameter of the battery system itself, that are communicated every iteration to take into account any changes due, for instance, to degraded operational conditions, equipment ageing, etc. but also operational choice of the battery system owner. This communications occurs by means of tailored APIs put at disposal of the EDEMS by the EBMS. As mentioned in the previous section, the state of charge limits the energy behaviour of the battery: depending if the battery system is almost empty or almost full, the power that can be injected or absorbed, respectively, changes significantly. The flexibility limits are calculated as follows. If the state of charge is so low that the minimum rated power of the battery cannot be reached during that time stamp, the flexibility limit is fixed to the maximum power that the battery can inject during that time stamp; if not, the flexibility limit is fixed to the minimum rated power value:

$$\begin{cases} \text{if } -\frac{SoC(t_i)}{\Delta t_i} > P_{battery,rated\_min}(t_i) & flexibility_{battery,\ min}(t_i) = -\frac{SoC(t_i)}{\Delta t_i} \\ \text{if } -\frac{SoC(t_i)}{\Delta t_i} \leq P_{battery,rated\_min}(t_i) & flexibility_{battery,\ min}(t_i) = P_{battery,rated\_min}(t_i) \end{cases}$$

As for the lower limit, a similar approach is adopted. If the state of charge is so high that the maximum rated power of the battery cannot be reached during that time stamp, the flexibility limit is fixed to the maximum power that the battery can absorb during that time stamp; if not, the flexibility limit is fixed to the maximum rated power value:

$$\begin{cases} \text{if } \frac{capacity - SoC(t_i)}{\Delta t_i} > P_{battery,rated\_max}(t_i) & flexibility_{battery,\ max}(t_i) = \frac{capacity - SoC(t_i)}{\Delta t_i} \\ \text{if } \frac{capacity - SoC(t_i)}{\Delta t_i} \leq P_{battery,rated\_max}(t_i) & flexibility_{battery,\ max}(t_i) = P_{battery,rated\_max}(t_i) \end{cases}$$

where $P_{battery,rated\_max}$ and $P_{battery,rated\_min}$ are the maximum and minimum rated power values of the battery system, respectively, and $flexibility_{battery,\ max}$ and $flexibility_{battery,\ min}$ are the upper and lower flexibility limits, respectively. It worth noting that $P_{battery,reference}$ is considered always equal to 0 kW, depicting a scenario in which the battery system is totally dedicated to the management of the EDEMS. Anyway, if a desired or suggested reference profile is requested from the EBMS, it can be seamlessly taken in into account for the provision of flexibility.

The update of the state of charge of the battery system is instead performed at the end of the optimisation process, where a negotiated solution is provided by the EDEMS for being implemented by the real equipment. This task is performed in order to simulate the behaviour of the battery in response to the setpoints calculated by the optimisation. Actually, the state of charge is updated in order to provide the optimisation framework with the actual status of the battery system during its calculation. The updated value of the state of charge is therefore calculated by a simulation and put at disposal of the optimisation algorithm at run-time in order to provide information that, otherwise, could be known only at operational time.

The updated value of the state of charge is simply calculated by adding or removing the energy related to the power absorption or injection during the current time stamp:

$$SoC(t_{i+1}) = SoC(t_i) \pm P_{battery,negotiated} \times \Delta t_i$$

where $P_{battery,negotiated}$ is the power setpoint coming from the optimisation framework after the negotiation process. The model of the battery charge/discharge phase could be further detailed and more complex behaviours, for instance related to the temperature, the depth of discharge, etc., can be modelled. The simplicity of this approach is given to the lack of information about the battery system.

In the last section of this chapter, the modelled behaviour of the battery energy system is shown; in particular, the flexibility limits of this energy unit are provided along with the optimised power profile which these limits are referred to.

5.3.2 EV system energy unit

The modelling module addressing the energy behaviour of the EV system energy unit performs very relevant calculation related to the optimisation of flexibility resources of the EVs fleet. The main functionalities of this module are essentially two: a load profile scheduling module, addressing the calculation of the power consumption profile of the EV system for the optimisation time horizon; a flexibility evaluation module, addressing the evaluation of the flexibility boundaries of the EV system on the basis of the monitoring data and the available EVs to be recharged. Moreover, an EV booking tool is provided as an external components to the EV drivers. This tool allows the users to book their recharge reservations within the 24 hours of the day after to the reservation itself.

The EV system consists in a parking lot hosting a fleet of EVs that can be booked and rented for a time period within a day. This system is equipped with three recharging stations, as explained and detailed in section 5.2.1. After some investigation on the power requested by the EV station, the fleet simulated for assessing the effectiveness of the services provided to the DSO has been set to ten EVs.

The main input data of this modelling module are derived by the booking system. This component allows each user requesting for renting an EV to book its car on the basis of the availability of the EVs parked inside the EV system. The booking tool collects the information regarding: the time departure of the EV, the time arrival of the EV, the desired EV state of charge at the withdrawal. This data are properly arranged for being manipulated by the EV system modelling module.

The load profile scheduling module is responsible of evaluating the load consumption profile of the EV system for all the day taking into consideration the EVs reservation and the state of charge of the EVs. After having assessed which EVs are present inside the parking lot during each time stamp of the considered time horizon, it performs a scheduling of the recharging phases by considering the cars needing for being charged over the day and the residual charge with respect to the residual time elapsed before the next withdrawal or before midnight. Indeed, by these two times, the target about the state of charge has to be achieved. During this first simple power consumption assessment, the EVs are scheduled to be charged on the basis of the chronological order of their reservation and taking care of the available recharging station. For instance, if four EVs request for charging during the same time window, only three cars are charged, in particular those which have been reserved earlier. After that one of the EV leaves the station since it has been reached its target, the fourth in chronological order of reservation is put on charge. This approach allows to evaluate a first power profile addressed as reference forecasted profile, which is taken into consideration for model the behaviour of the district before the optimisation process. As a matter of fact, it reflects the usual business approach of an unconstrained EV recharging system:

$$\begin{cases} \text{if number\_EV\_charging}(t_i)\geq 3 & P_{battery,reference}(t_i)=66\text{ kW} \\ \text{if number\_EV\_charging}(t_i)<3 & P_{battery,reference}(t_i)=\text{number\_EV\_charging}(t_i)\times P_{EV\_station} \end{cases}$$

where number_EV_charging is the number of EVs requesting for recharge in that time stamp and $P_{EV\_station}$ is the power of a single EV charging station, equal to 22 kW.

The load profile scheduling module is invoked every time stamp in order the provide a detailed reference power profile taking into account the updated recharging operations performed until the last time stamp. It worth noting that the reference power profile is updated only if in the previous time stamp the negotiated optimised setpoint is different from the power value calculated by the scheduling module.

The flexibility evaluation module aims at calculating the flexibility limits provided by the EV system to the EDEMS in order to assess the service that can be provided by this energy unit. The flexibility limits are evaluated in order to let the optimisation algorithm to span over the widest capability that can be delivered by the EV system in that time stamp. This choice has been adopted in order to let the optimiser reschedule in an optimised way the allocation of charging time slot over the considered time horizon. In this views, the flexibility evaluation is performed every time stamp before the optimisation process and provides both upper and lower flexibility limits, thus the maximum and the minimum power values that can be absorbed by the EV system.

As for the upper flexibility limits, the criterion taken into account addresses roughly the maximum capability of the system in terms of availability of EVs inside the parking lot: if the number of EVs inside the parking lot is higher than three, the maximum flexibility limit is set at the maximum power of the EV system; if not, the maximum power flexibility limit is set according to the effective EVs available for recharging:

$$\begin{cases} \text{if number\_EV\_parked}(t_i)\geq 3 & \text{flexibility}_{EV,\,max}(t_i)=66\text{ kW} \\ \text{if number\_EV\_parked}(t_i)=2 & \text{flexibility}_{EV,\,max}(t_i)=44\text{ kW} \\ \text{if number\_EV\_parked}(t_i)=1 & \text{flexibility}_{EV,\,max}(t_i)=22\text{ kW} \\ \text{if number\_EV\_parked}(t_i)=0 & \text{flexibility}_{EV,\,max}(t_i)=0\text{ kW} \end{cases}$$

where the number_EV_parked is the number of EVs present inside the parking lot requesting for being recharged. It worth noting the difference between the number of EVs parked inside the parking lot and the number of EVs requesting for recharge: even though an EV is present inside the parking lot, it could not be asking for recharge. As said before, in the case of the maximum flexibility evaluation, the former values in considered in order to refer to the widest flexibility availability is considered, figuring out that an EV can ask for recharge over all the time stamp during which is parked.

The lower flexibility limits is calculated taking into account the minimum amount of time stamps needed for achieving the target state of charge of the EVs. In particular, if there are enough time stamps available for recharging each the EV towards the target state of charge, the minimum flexibility limit is set to 0 kW; if not, the EVs that requires to be recharged in that time stamp have to be connected to an available station and the minimum flexibility limit is evaluated by summing all the EVs requiring for being recharged:

$$\begin{cases} \text{if } \nexists j \,|\, \Delta\text{t\_to\_target}(j)>\Delta\text{t\_to\_departure}(j)\rightarrow\text{flexibility}_{EV,\,min}(t_i)=0\text{ kW} \\ \text{if } \exists j \,|\, \Delta\text{t\_to\_target}(j)>\Delta\text{t\_to\_departure}(j)\rightarrow\text{flexibility}_{EV,\,min}(t_i)=\sum_{i=1}^{m} P_{EV\_station} \end{cases}$$

where:

- Δt_to_target is the number of charging time stamps before the achievement of the state of charge target;
- Δt_to_departure is the number of charging time stamps before the departure of the EV;
- m is the number of EVs which are forced to recharge for achieving their target state of charge;
- j is the index spanning over the number of EVs available inside the parking lot.

In any case, as explained in section 5.6, the technical feasibility of the solutions provided by the optimisation framework is assessed and properly handled by a tailored module for the negotiation tasks.

In the last section of this chapter, the modelled behaviour of the EV system is shown; in particular, the flexibility limits of this energy unit, along with the optimised power profile which these limits are referred to, and the reference forecasted profile of EV recharging operations are provided.

5.4 Forecasting framework

The forecasting framework allows to calculate forecasted power profiles by performing a forecasting algorithm based on autoregressive techniques on the basis of historical data about the power profile of each energy unit. These approach is adopted for those energy unit whose energy behaviour is not simulated by their own modelling module, because there is no need of implementing such a complex process for retrieving information about energy unit that have a static energy behaviour, thus they do not provide flexibility. In this view, the energy units that are handled by a forecasting module are those composed by the PV plants, for its power generation profile, and by the buildings, for its power consumption profile.

5.4.1 PV system energy unit

As already mentioned, the forecasting module of the PV system energy unit relies upon an autoregressive model. An autoregressive model can be defined as follows:

$$x_t = \sum_{i=1}^{N} a_i x_{t-1} + \varepsilon_t$$

where a_i are the so called autoregression coefficients, x_t is the series under investigation, N is the order (or length) of the filter which is generally lower than the length of the series, ε_t is the white noise. The historical data of the PV power generation values are measured and stored by tailored devices installed within the energy unit equipment.

One of the most challenging issue in defining autoregressive models is to derive the most suitable values for regression coefficient for a given series. These coefficients can be calculated following different techniques. In this implementation, the Least Square and the Max Entropy methods have been employed. Both methods have a degree parameter that allows to define the desired autoregression degree. In particular, the algorithm uses an optimised method that incrementally searches for the best settings, which lead to the lowest mean squared error.

In the specific case of the PV system, whose energy production is extremely dependant from weather conditions, a method that adjusts input data in accordance to the monitored current cloud cover percentage value has been implemented. If the historical data was generated in favourable weather conditions respect to the current ones (the historical cloud cover is lower than current cloud cover), then the forecasted value is decreased:

$$\text{PV\_forecasted\_generation}_{\text{new}} = \text{PV\_forecasted\_generation}_{\text{old}} -$$

$$-\left[\text{PV\_forecasted\_generation}_{\text{old}} \times \left(\text{cloud\_cover\_\%}_{\text{current}} - \text{cloud\_cover\_\%}_{\text{historical}}\right)\right];$$

otherwise, the value is increased:

$$\text{PV\_forecasted\_generation}_{\text{new}} = \text{PV\_forecasted\_generation}_{\text{old}} +$$

$$+\left[\text{PV\_forecasted\_generation}_{\text{old}} \times \left(\text{cloud\_cover\_\%}_{\text{current}} - \text{cloud\_cover\_\%}_{\text{historical}}\right)\right];$$

Weather conditions data are given as input to the module. These information are taken by darksky.net service [238]; APIs are available for hourly and daily forecasts for the next week, together with historical data.

5.4.2 Buildings energy unit

As the building energy unit is concerned, the same autoregressive technique described above is employed for evaluating the forecasted power consumption profile for the appointed time horizon. The historical data of the buildings power absorption are managed by the smart meters installed at demonstration premises and stored into dedicated systems in order to be easily retrieved by the forecasting module.

It worth mentioning that several improvements for the buildings are under investigation. In particular, some studies are taking into account the possibility of directly managing the most relevant and impacting appliances inside the buildings in order to modify their load consumption and provide a flexibility range to the entire buildings energy unit. In this case, a detailed model of the energy unit could be developed and the consideration about forecasted and/or modelled energy behaviours of the system would be assessed by means of this module.

5.5 Decision Support System

5.5.1 Purposes

The EDEMS of the ELSA system is provided with a DSS in charge of supporting the choice of one optimal solution among those made available by the Pareto-optimal solution front evaluated by the optimisation algorithm. Whilst for the INGRID system the DSS has been developed as tool dedicated to the intervention of the human operator that had to choose the operational configuration of the INGRID plant, in the ELSA system the DSS represents an internal process of EDEMS. The architecture of the ELSA solution foresees that the selection performed by the DSS is not directly proposed to the district energy manager, but is forwarded to the negotiation framework, see section 5.6, for assessing its feasibility based upon many considerations performed by the addressed energy unit.

5.5.2 Selection criteria

The DSS system designed for the ELSA project selects three different solutions among those calculated by the optimisation algorithm. These solutions are chosen in order to cover the optimal solution front, so they are defined as follows:

- F1 best: the individual of the last optimised population having a better fitness with the first economic objective function;
- F2 best: the individual of the last optimised population having a better fitness with the second technical objective function;
- Trade-off (A): the individual of the last optimised population having the most similar distance values from F1 best and F2 best solutions.

In this context, the solution providing the best fitness to the third objective function is neglected. Actually, in this stage the information about the occurred violations of the DSO request are not relevant for the selection of a suitable operational configuration.

5.6 Negotiation framework

Since the energy unit represented by the battery system is considered to be totally devoted to the flexibility management of the district, the only energy unit interested in negotiating the flexibility provision with the EDEMS is the EV system. As a matter of fact, whilst the battery energy unit is intended as the system able to afford all the flexibility actions allowed inside the flexibility limits provided by the modelling modules, the EV system energy unit is instead committed to a negotiation process aimed at assessing if the solutions proposed by the optimiser, that rely upon the flexibility range provided by the energy unit itself, are accepted by the EV recharge station. The goal of this process is twofold: to take into account unpredicted changes in flexibility boundaries provided by the energy unit; to assess the technical and economic feasibility of the proposed solutions.

The negotiation module is invoked after the selection performed by the DSS: this module provides three solutions evaluated on the basis of their fitness values with respect to crucial operational strategies. The negotiation module takes into consideration these solutions for comparing them with the reference one provided by the module modelling the behaviour of the EV system unit. The need for negotiating the provision of flexibility by the EV system is given to the approach taken for evaluating the flexibility of this energy unit. As said in section 5.3, the flexibility limits are evaluated by taking into account the minimum recharge slot that as to be allocated for recharging the EVs, as for the lower limit, and the total number of EVs requesting for recharge, as for the upper limit, in each timestamp. In this way, the algorithm is able to reshape over the entire time horizon the forecasted power profile, evaluated taking into consideration only the chronological order of the booking reservations and available charging stations, exploiting all the flexibility of the EV system. Nevertheless, each time stamp, a deviation from the reference forecasted profile as to be negotiated in order to assess the technical feasibility of the proposed optimal solutions. In particular, the negotiation module assess if the new solution allow to recharge all the EVs inside the departure times, thus ensuring a complete recharge when the EV is booked to be withdrawn from the parking lot.

The process starts comparing the optimised solutions with the reference forecasted power profile that is updated every time stamp after having chosen the setpoint for the EV system. The first solution to be compared is the one that provides the best solution for the first economic objective function, then the solution providing the best fitness for the second technical objective function is taken into account, and, finally, the trade-off solution is compared.

If the reference forecasted power consumption is equal to the optimised one, no negotiation occurs. If these two values are not the same, the negotiation starts by simulating the behaviour of the recharging process taking into account the new setpoint coming from the optimiser. If the solution of the optimisation allow to handle all the EVs requiring for recharging, thus all the EVs are recharged before their departure time, the solution is accepted. If not, a feasibility exception is raised and the first solution is rejected. Subsequently, this check is performed again taking into consideration the second solution, so it is compared with the reference consumption and its technical feasibility is performed. This iteration occurs for the three proposed solutions discussed above.

Finally, the results of this negotiation are taken into account for deciding the setpoint to be implemented in the district: if one or more of the provided solutions allow to respect the feasibility constraints, the first one that satisfies this conditions is considered as the accepted operational configuration; if not, the reference forecasted power consumption is adopted as setpoint. It worth noting that this choice affects the adoption of the appointed solution also for all the other energy units. For instance, is the solution providing the best fitness for the second objective function is chosen by the EV system negotiation, all the other power setpoints for the energy units are chosen accordingly.

5.7 Monitoring framework

In order to support the implementation of the ELSA flexibility platform in the demonstrator site, a set of monitoring device are installed within the district infrastructure. These devices aim at providing a precise monitoring of the power consumption and production of the different energy units. Data from the meters are collected by the corresponding EEMS.

Within each energy units, a class A power quality analyser is installed: the WALLY A-RTU, manufactured by TeamWare [239]. This device is a three phase high-precision power quality analyser compliant to Class A, according to IEC61000-4-30, and Class 0.2S, for energy metering. It is capable of measures the following parameters: voltages and currents; active, reactive and apparent power; active and reactive energy; power factor; frequency, flicker; voltages and currents harmonics; voltage unbalance; voltage dips and swells; voltage interruptions; rapid voltage changes and waveforms. Figure 59 shows the sensor deployment.

Two different channels are employed for the collection of data from the meters: one is exclusively used at the connection points for the energy units with rated power up to 30 kW; the other for the energy units whose power consumption is greater than 30 kW. Data related to first channel are exchanged via PLCs; these data are temporarily stored in an electric energy meter concentrator, then extracted and transmitted via GPRS network towards central servers of the ICT platform; these data is stored for 5 years for legal reasons. Data related to the second channel is extracted and transmitted via GSM/GPRS; specific ENZ 2000 software is used for this purpose. After a consistency check, the data is stored in central servers for 5 years, as well. Data from both channels will be extracted and parsed in order to constitute the historical knowledge of the energy consumption and production to be exploited for forecasting calculation.

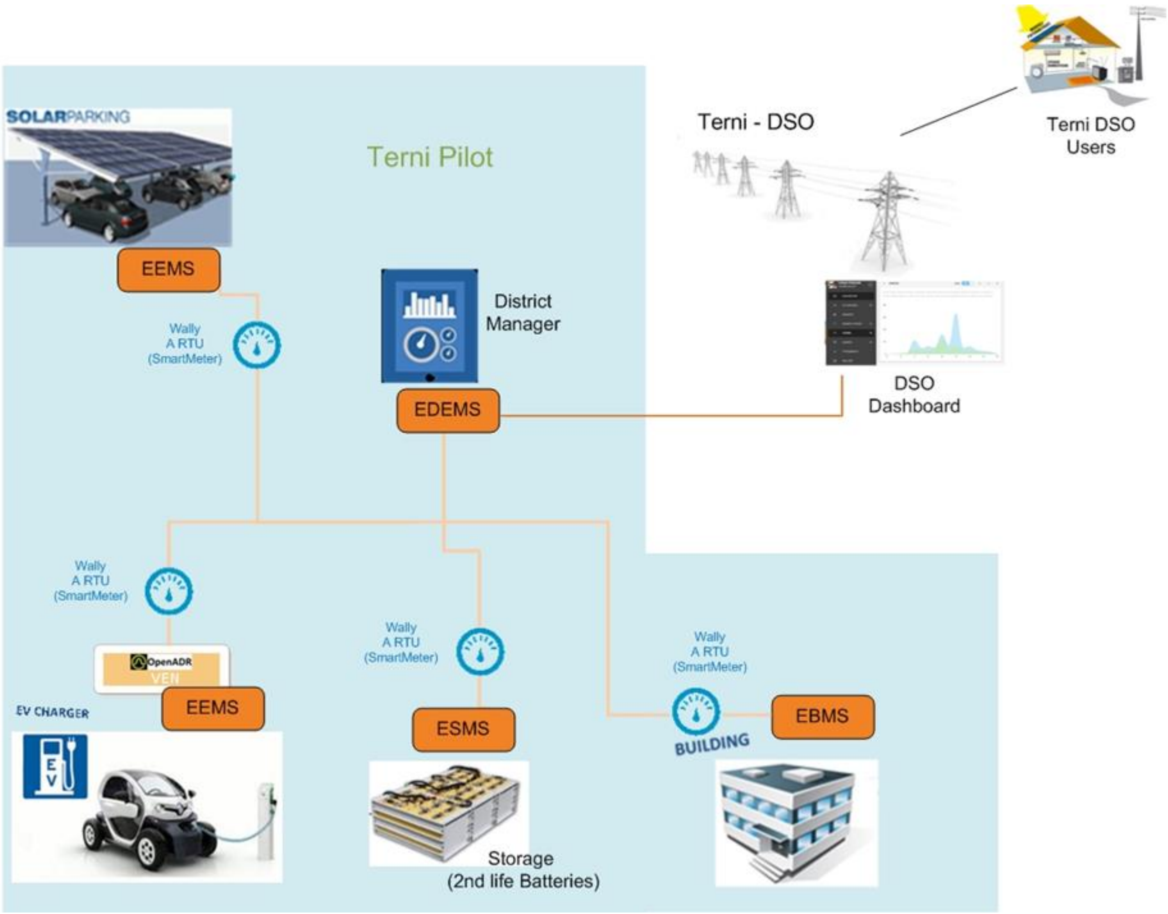


Figure 59 – Physical implementation of the WALLY meter inside the ELSA demonstrator.

5.8 OpenADR and communication framework

Communication among architecture components is performed using the OpenADR standard, profile 2.0b. The OpenADR is an open standard for automated demand response which relies on the concepts of VEN and VTN nodes. Every component of the ICT platform includes a VEN or a VTN (or both) applications in order to communicate with other components.

In this section, the implementation of such a standard is depicted and explained and the communication framework is shown. Moreover, information about the exchanged data, the data storage and the cyber-security are provided.

5.8.1 OpenADR standard

Open Automated Demand Response (OpenADR) is an open and standardized way for electricity providers and system operators to communicate DR signals with each other and with their customers using a common language over any existing Internet Protocol (IP) based communications network, such as the Internet [109]. There are two actors in OpenADR communication exchanges: a Virtual Top Node (VTN) and a Virtual End Node (VEN). Generally, the VTN acts as the server, providing information to VEN, which responds to the information. The data exchange relies upon standard-based IP communications such as Hyper Text Transfer Protocol (HTTP) and eXtensible Markup Language (XML), Messaging and Presence Protocol (XMPP). These nodes may communicate using a variety of protocols. OpenADR currently defines two feature sets, each of which represents a subset of OpenADR functionalities: the feature 2.0a (or simply profile A) aims at proposing a range of functionalities that can be supported by devices as simple as a thermostat; the feature 2.0b (or simply profile B) provides functionalities compliant with more complex ICT based systems such as aggregators.

VENs and VTNs can exchange different types of messages. These messages can be translated mainly in events or reports. An event is a notification from the utility to demand side resources requesting an action at a specific time, over a specified duration, and may include targeting information designating specific resources that should participate in the event. Reports are used by VENs and VTNs to exchange historical, telemetry, and forecast data. Resources can report their status, availability, and forecasts, but also real time energy readings. In order to access to these messages, the functionalities of VENs and VTNs have been extended to export appropriate services. In specific, the extended services of the VTNs are: send report requests to VENs, send events to VENs, queue to collect report responses from VENs, queue to collect event responses from VENs. In the case of the VENs, the services are: queue to collect report requests from VTN, queue to collect event requests from VTN, send report responses to VTN, send event responses to VTN.

5.8.2 Communication framework

The communication framework designed for the ELSA system is a complex architecture both in terms of technologies adopted and interconnections between the modules. Within this framework, some adapters have been designed for easily integrate the OpenADR standard. In particular, the module that allows the external communication with the DSO represents a VTN. The modules installed in the EEMS of each energy unit represent different VENs. The district manager module, that contains the EDESM and constitutes the central part of the ICT framework, represents at the same time a VEN towards the DSO and a VTN towards the EEMSs.

In Figure 60, a complete overview of the communication framework is shown, highlighting all the communication modules and the OpenADR nodes.

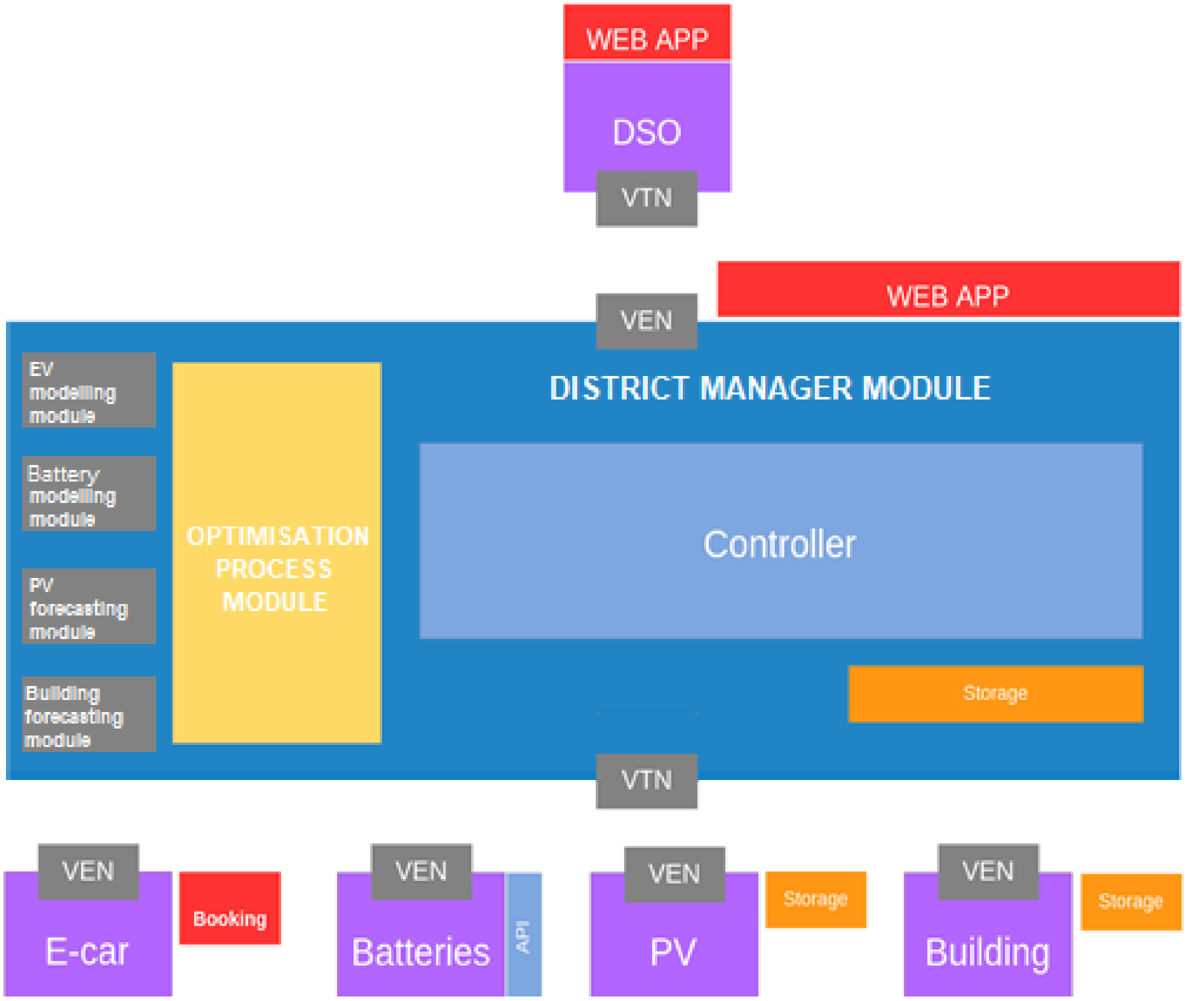


Figure 60 – The ELSA system communication framework.

Each module conceptually includes two macro-components:

1. the one related to the communication, handling directly the OpenADR protocol implementation, such as resources registration, monitoring and forecast communication. This part includes both the VTN and the VEN nodes of the OpenADR protocol according to the hierarchical structure;
2. the elaboration core related to the implementation of the algorithms, such as energy production and consumption forecast, historical data storage and elaboration, energy resources optimisation. Moreover, the implementation of some dashboards is performed also within the core of these modules.

VEN and VTN implementations are based on Certified EPRI Open Source OpenADR 2.0b VEN and VTN [240] and refer to OpenADR 2.0b Profile Specification data model. In particular, the VTN application is developed using the Ruby on Rails framework and uses Postgres as persistence layer. The VEN is developed in Java and runs on Tomcat application server.

The components of these framework do not communicate directly with their VENs and VTNs, but with OpenADR adapters. The main purpose of the adapter is to interface with VEN and VTN components in order to make requests and receive messages in an appropriate format. OpenADR adapter is a separated Node.js module which includes a VENClient and a VTNClient. The application which includes the module can choose to use one client or both.

Some web applications have been developed in order to allow the communication between the external actors of the EDEMS and the optimisation platform. These applications, addressing the task of the district manager, the DSO, and the EV stations booking system, are developed using the MEAN stack. The MEAN Stack is a set of JavaScript components that represents modern approach to web development: one in which a single language (JavaScript) runs on every tier of the application, from the client and server implementation to persistence layers. The MEAN Stack is made up of four frameworks: MongoDB, Express, AngularJS, and Node.js.

The district manager module component stands between the DSO system and the energy unit systems. It is divided into two main sub-components: the controller and the optimisation process module. The controller covers the core communication logic of the framework, whilst the optimisation process module includes the algorithm for the district optimisation, thus the EDEMS. Moreover, the district manager module includes a web administration app for the district monitoring and settings activities.

It worth noting the central role of the controller. Since the district manager module coordinates district blocks with the purpose of satisfying DSO request, the controller is responsible of all the following coordination activities. Firstly, the controller receives report requests from the DSO concerning consumption/production power profile and related tolerance range. Once received a report request, the controller sends a message to every energy unit modules in order aggregate the necessary information. More in details, it receives forecasted power profile from PV and buildings energy units, modelled and forecasted power profiles of the EV system and battery energy units, along with their energy flexibility. At this stage, a first report is provided to the DSO concerning the energy capability of the district: the forecast profile is given from the sum of the forecasted or modelled consumption/generation profiles of the energy units; the flexibility boundaries are calculated as well, taking into consideration the power absorption that can be provided by the EV charging stations and power absorption/desorption that can be provided by the batteries.

Another activity of the controller is the management of power profile request from the DSO. In order to accomplish the request, the district manager module determines the optimal profiles to be submitted. Since the OpenADR 2.0b Profile specification does not provide any negotiation feature, the negotiation phase is performed internally to the optimisation module. The EDEMS uses its optimisation process module to get the final optimised profiles. Once the power profiles are generated, the district manager module sends them to the energy units. The OpenADR standard handles this kind of request by translating them to event objects and every energy unit acknowledges only once to the district manager module the response. Finally, the optimised results are notified back to the DSO.

The optimisation process module is a standalone component developed in Java where the algorithms are implemented on MATLAB environment. The controller interacts with the optimiser employing REST APIs. Each energy unit module consists of a Node.js applications, using a NoSQL database instance (MongoDB) as persistence layer.

As already discussed, the energy units are managed at low level by their dedicated EMSs. In particular, the architecture consists of an EBMS for the buildings, an EEMS for the PV plants, an ESMS for the battery system and an EEMS for the EV system. Tailored modules have been integrated for allowing data exchange between the EDEMS and these systems.

The EV recharging system component is composed of two separated applications: the EV booking system and the core block application. The latter is responsible for the communication with the district manager module. In particular, in order to address the forecast requests, the block calls the booking system for gathering all the information about the scheduled reservations to be sent to the EV forecasting module.

The battery system is managed from an external application which exposes different APIs. The communication with the ESMS is done through the REST services deployed by the middleware platform installed in the Terni premises. One API is used to retrieve the information of the batteries in order to know their data at a specific time. These information are the maximum capacity the batteries can store, the charging and discharging power they can provide, and their state of charge. Another API is employed to manage the ESMS: it offers a fine-grained way to set multiple values to charge or discharge the batteries.

The PV plants module is responsible for collecting energy production information and for aggregating historical information for the forecast calculation. This block interacts with the district manager module only for forecast report requests. Once the block receives a forecast request, it aggregates historical information, uses the API of an external service (in particular, the one provided by The Dark Sky company [238]) in order to get historical and current weather conditions, and invokes the PV forecasting module for profile evaluation

The buildings module represents passive units, thus only a load that do not have controllable appliances. The main activities of the EBMS are: saving consumption information, aggregating historical data and forward them to the building forecasting module, providing forecast consumption values to the district manager module.

5.8.3 I/O data

In this section, the input and output data of the EDEMS are highlighted along with some of their main features. Moreover, some relevant data exchanged within the modules of the optimisation processes are listed.

Firstly, the input data of the optimisation process are provided. The static initialisation are the first set of information about the energy units received by the EDEMS. They are mainly related to the maximum and minimum rated power values of the energy units, the capacity of the battery and other operational parameters of the energy units. In Table 9, these data are shown with their main relevant features: the type of data exchanged, the units of measure, if they are input or output data, the granularity of the data (in terms of amount of information over the time horizon), and the actor providing for them.

Table 9 – Static initialisation data for the optimisation process.

Description	Type	Unit	I/O	Granularity	Provider
EV system maximum power consumption	Real	kW	I	Single	EV system

EV stations number	Integer	-	I	Single	EV system
EV station power consumption	Real	kW	I	Single	EV system
Battery maximum power flow	Real	kW	I	Single	Battery system
Battery minimum power flow	Real	kW	I	Single	Battery system
Battery capacity	Real	kWh	I	Single	Battery system
PV maximum power generation	Real	kW	I	Single	PV plant
Buildings maximum power consumption	Real	kW	I	Single	Buildings unit

Subsequently, the proper input data that are sent to the optimisation process are addressed. They are related to: the requested services to be provided to the DSO and the corresponding incentive rewarded for its provision; the information of every energy units, in terms of monitoring data of the energy unit current status and historical data recorded; the incentives rewarded to the energy units for flexibility provision; other information about the EVs reservations. These data, shown in Table 10, are sent to the dedicated modules for being furtherly processed.

Table 10 – Input data for the optimisation process.

Description	Type	Unit	I/O	Granularity	Provider
Optimisation time horizon	Real	h	I	Single	DSO
Optimisation time stamp	Real	min	I	Single	DSO
Request for grid	Real	kW	I	Each timestamp over the optimisation time horizon	DSO
Tolerance range for service provision	Real	kW or %	I	Each timestamp over the optimisation time horizon	DSO
Incentives for service provision	Real	€	I	Each timestamp over the optimisation time horizon	DSO
Monitored battery SoC	Real	kWh	I	Single	Battery system
Monitored battery power flow	Real	kW	I	Single	Battery system
Monitored PV power flow	Real	kW	I	Single	PV plant

Monitored buildings power flow	Real	kW	I	Single	Buildings unit
Monitored EV system power flow	Real	kW	I	Single	EV system
Historical PV data	Real	kW	I	Each timestamp over the historical time reference	PV plant
Historical buildings data	Real	kW	I	Each timestamp over the historical time reference	Buildings unit
EV system reservation (ID)	Integer	-	I	One reservation ID for each reservation item	EV system
EV system reservation (time)	Real	hour	I	Two time signals (arrival and departure) for each reservation item	EV system
Battery flexibility incentives	Real	€	I	Each timestamp over the optimisation time horizon	Battery system
EV system flexibility incentives	Real	€	I	Each timestamp over the optimisation time horizon	EV system

As outcomes of the process, the output data of the optimisation process are outlined. These data concern: the optimised power profiles sent to the energy units providing flexibility and the corresponding incentives rewarded; the optimised power profile of the overall district and the corresponding reward for service provision; all the setpoints of the system saved in a unique file sent to the database. In Table 11, the output data of the process are shown.

Table 11 – Data evaluated by the optimisation process necessary for control strategy definition.

Description	**Type**	**Unit**	**I/O**	**Granularity**	**Addressee**
EV system optimised power profile	Real	kW	O	Each timestamp over the optimisation time horizon	EV system
Battery optimised power profile	Real	kW	O	Each timestamp over the optimisation time horizon	Battery system
Microgrid optimised power profile	Real	kW	O	Each timestamp over the optimisation time horizon	DSO
Service rewards to the microgrid owner	Real	€	O	Each timestamp over the optimisation time horizon and once for overall amount	District manager
Incentives rewarded to the EV system	Real	€	O	Each timestamp over the optimisation time horizon and once for overall amount	EV system
Incentives rewarded to the battery	Real	€	O	Each timestamp over the optimisation time horizon and once for overall amount	Battery system
System setpoints (unique file containing all the optimised profiles properly temporised)	Real	kW	O	Each timestamp over the optimisation time horizon	DB

Finally, it worth highlighting the proper input data that are conveyed directly to the optimisation algorithm. They are related to the power profiles of every energy units, in terms of reference power profile, forecasted or modelled, and the corresponding flexibility limits. Moreover, also other information about the constraints of the energy units are reported.

Table 12 – Data internally exchanged within the optimisation framework modules.

Description	**Type**	**Unit**	**I/O**	**Granularity**	**Module**	**Addressee**
EV system reference power profile	Real	kW	O	Each timestamp over the optimisation time horizon	EV modelling module	Optimisation process
EV system maximum flexibility limit	Real	kW	O	Each timestamp over the optimisation time horizon	EV modelling module	Optimisation process
EV system minimum flexibility limit	Real	kW	O	Each timestamp over the optimisation time horizon	EV modelling module	Optimisation process
EV system constraints	Real	kW	O	Each timestamp over the optimisation time horizon	EV modelling module	Optimisation process
Battery maximum flexibility limit	Real	kW	O	Each timestamp over the optimisation time horizon	Battery modelling module	Optimisation process
Battery minimum flexibility limit	Real	kW	O	Each timestamp over the optimisation time horizon	Battery modelling module	Optimisation process
Battery constraints	Real	kW	O	Each timestamp over the optimisation time horizon	EV modelling module	Optimisation process

PV forecasted power profile	Real	kW	O	Each timestamp over the optimisation time horizon	PV forecasting module	Optimisation process
Building forecasted power profile	Real	kW	O	Each timestamp over the optimisation time horizon	Building forecasting module	Optimisation process

5.8.4 Database

The communication framework implements a persistence layer for data storage and analysis. Different kinds of data will be managed including time series data. The persistence layer is developed relying on MongoDB database [241], which is a non-relational Json based database. This database is a *de facto* standard solution with a proper level of robustness; moreover, time series data fits perfectly with MongoDB, since it implements consolidated schemas to store and analyse time series data. The MongoDB management service is used in order to put in place monitoring, visualization and alerting mechanisms. In detail, the data processes involve:

1) data from the pilot site extracted by DSO platform infrastructure;
2) unstructured data exported and parsed from CSV or Excel formats;
3) procedures for data harmonization to and from the ESMS via OpenADR protocol.

5.8.5 Cyber-security

As discussed in the previous chapters, cyber-security is a relevant aspect of smart ICT platforms. The platform in Terni site essentially involves the interaction between the DSO and the EDEMS as well as the interaction among the EDEMS and the different EEMS installed within each energy unit. For the former interaction, the communication framework relies upon a typical HTTP implementation for the authentication of DSO dashboard web application and the encryption of the data transferred among the actors. For the district side, the ICT platform is relying on EPRI open source implementation of the OpenADR standard; OpenADR Alliance maintains its own Public Key Infrastructure that uses server and client side digital certificates that act as digital keys to ensure that only clients and servers communicate between each other and their communication is secure. The EPRI implementation is compliant with OpenADR 2.0 and supports Elliptic Curve Cryptography and Rivest–Shamir–Adleman server and client certificates with Transport Layer Security and XML wrapping functionalities.

5.9 GUI and dashboards

The flexibility platform developed for the ELSA system consists also of a rich GUI provided to the actors interacting with the energy district under the control of the EDEMS. In particular, two dashboards are provided to the district manager and to the DSO. The former is a complete solution where all the information related to the energy units managed inside the district are made available and displayed. The latter is an add-on component provided to the DSO in order to ease the interaction with the flexibility platform.

5.9.1 District manager dashboard

The district manager dashboard is the tool provided to the manager of the energy resources of the district. It allows to access to all the significant data of the energy behaviour of the energy sources within the controlled district, from the forecasted data to the economic values associated to the provided services. Moreover, a set of relevant parameters related to the operation of the energy units and their communication tasks can be provided by means of this dashboard.

The dashboard is implemented as a web application developed on MEAN stack. MEAN is a JavaScript full stack that includes a NoSQL database instance (MongoDB), a Node.js server side environment, a backend web application framework (ExpressJS) and a client side Model View Controller framework (AngularJS).

The district manager is supposed to use the dashboard for controlling and managing all the energy behaviour inside the plant directly and clearly by visualising the charts related to the power flows of each unit (historical data, optimised data, and forecasted data) and the economic exchanges between the district manager itself and both the energy units as well as the DSO. A list of functionalities provided by this dashboard is listed in the following:

- sign in/login to the dashboard;
- show details of each energy unit within the district;
- set parameters of energy unit;
- show the history of forecasts of each energy unit (list and detail);
- show the history of dealings of each energy unit (list) and the status of these dealings;
- show the history of dealings of the entire district, the list of involved energy units and the detail of these dealings;
- access a billing section where the analytics of the activities of the district are displayed.

After the login tasks, the district manager is provided with a console consisting of three main tabs besides the “Home” one: the “Blocks” tab, the “Billing” tab, and the “Dealings” tab.

In Figure 61, a screenshot of the first interfaces displayed to the district manager is shown.

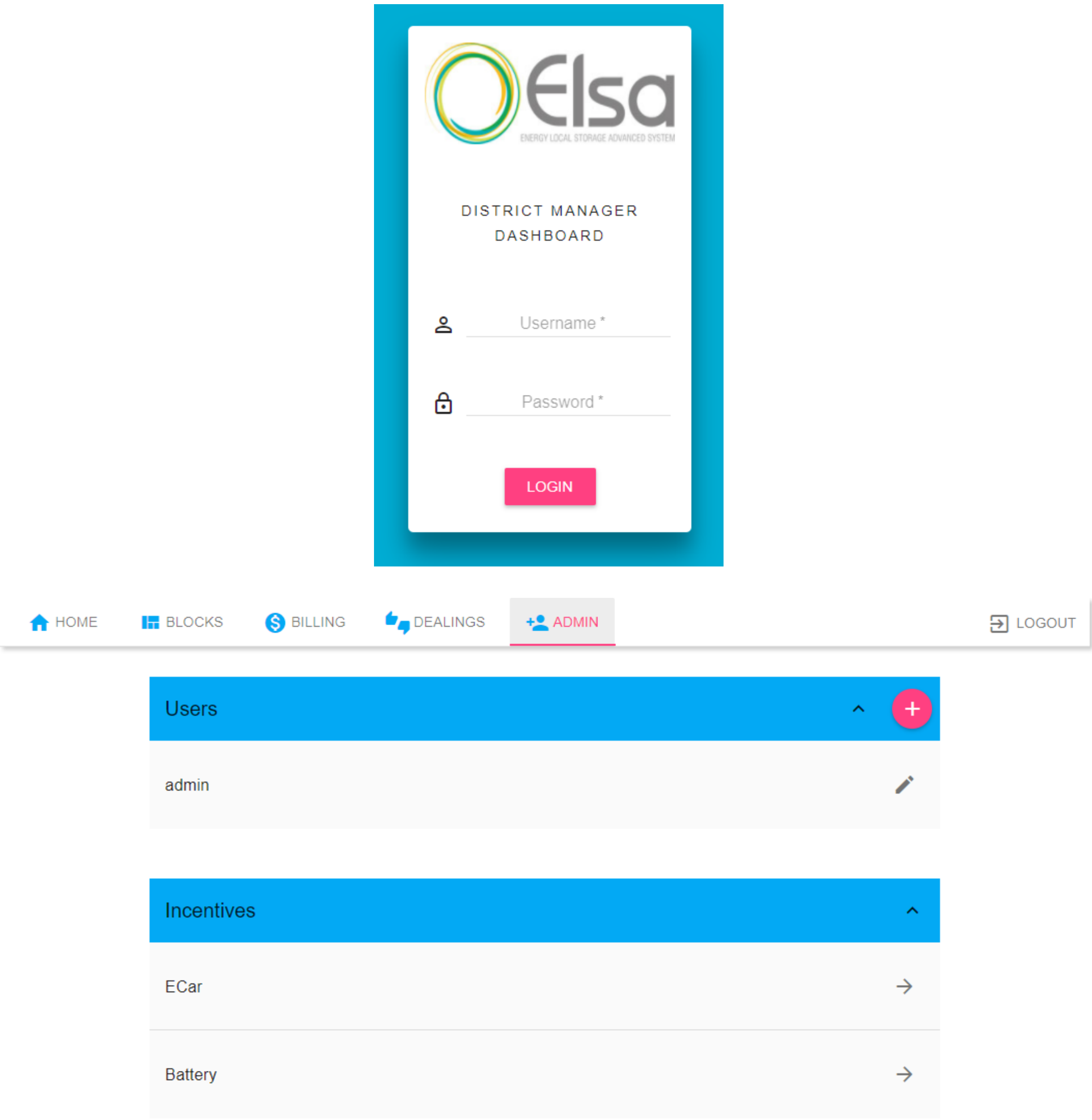
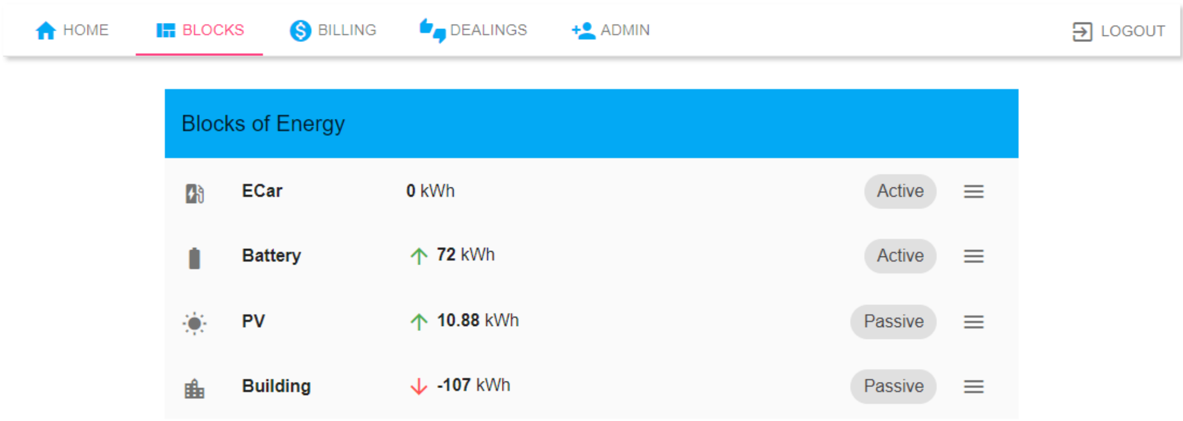


Figure 61 – The login in interface and the “Admin” tab of the district manager dashboard of the ELSA system.

The “Block” tab contains a table with the list of all the energy units. For each energy unit the following information are shown: an icon that represents the typology of energy unit, its name, its current power consumption, an active or passive tag (depending on the energy unit) and a dropdown button with some actions depending on the type of the unit, such as detailed information about the unit, historical data, some settings, etc. In Figure 62, a screenshot of the “Block” tab is shown.



Blocks of Energy

ECar	**0** kWh	Active	≡
Battery	↑ **72** kWh	Active	≡
PV	↑ **10.88** kWh	Passive	≡
Building	↓ **-107** kWh	Passive	≡

Figure 62 – The “Blocks” tab of the district manager dashboard of the ELSA system.

The “Billing” tab displays to the district administrator some statistics about the energy billing. In particular, there are two charts: incentives and profits. The incentives chart shows the daily rewards that the DSO pays to the district, and the incentives that the district rewards to each energy unit that offers flexibility during dealings. As already mentioned, the difference between these amounts generates the daily profit for the district manager, which can be positive or negative. The profits chart shows the aggregation of total of profits for the energy units and the daily profits for the district. In Figure 63, the chart displaying the daily incentives of both district manager and energy units is reported.

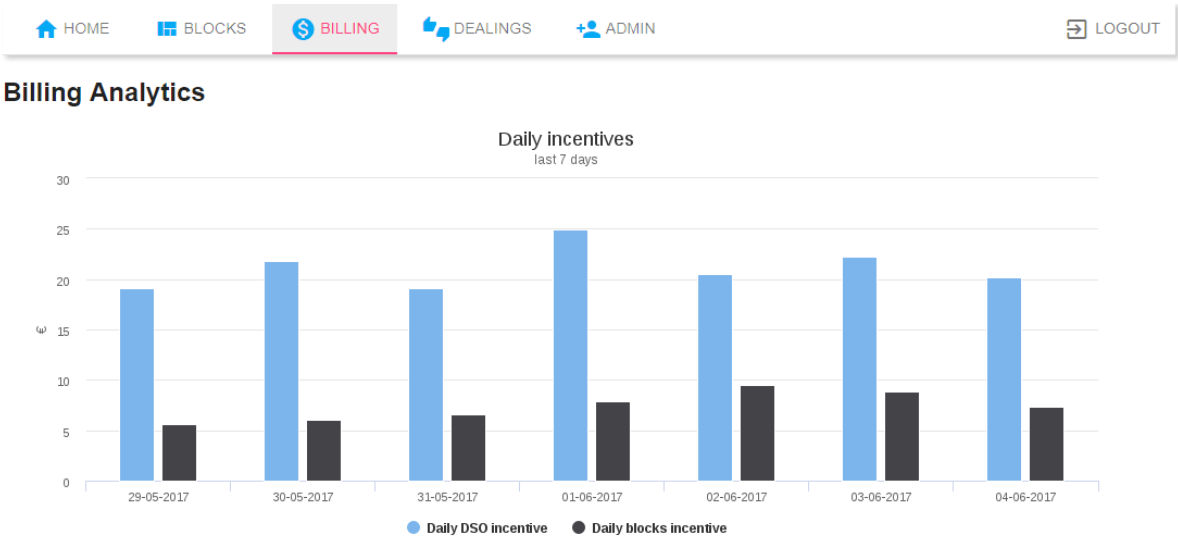
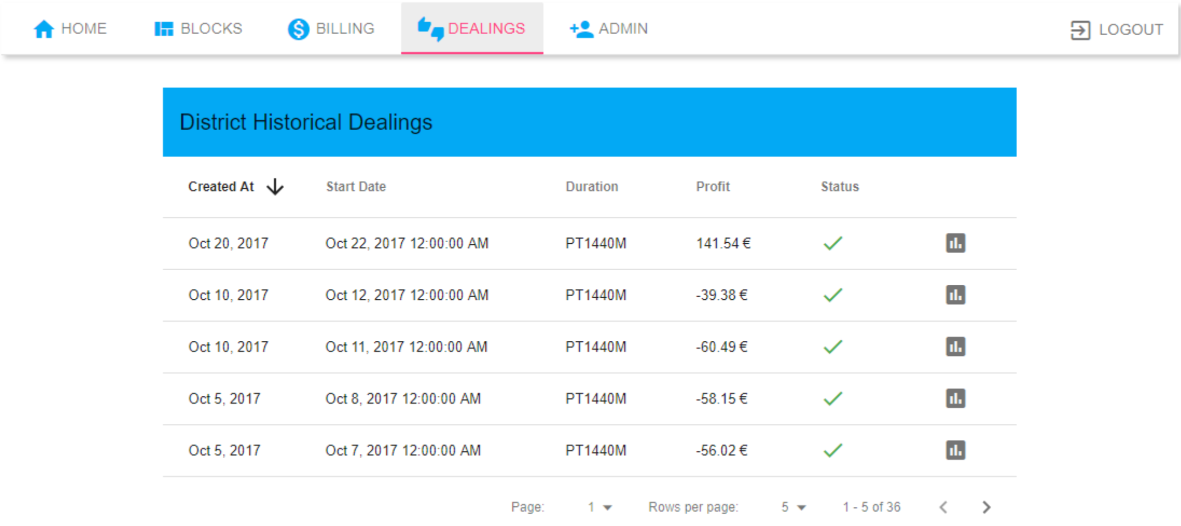


Figure 63 – The daily incentives paid by the DSO to the district manager and by the district manager to the energy units in the “Billing” tab of the district manager dashboard of the ELSA system.

Finally, the “Dealings” tab provides detailed information about the dealings between the DSO and the EDEMS, in terms of service requests and responses of the district. The tab mainly consists of a table of all the dealings, with sorting, filtering and pagination features. The columns in this table represent, for each of the dealings, the following data:

- time information about the DSO request (start time, end time, etc.);
- the incentives paid by the DSO and the district manager;
- status of dealing (accepted, rejected, or waiting);
- further information button.

In particular, detailed information about the optimised power profiles can be displayed: a chart that highlights the difference between the requested profile and the optimised one evaluated by the EDEMS.



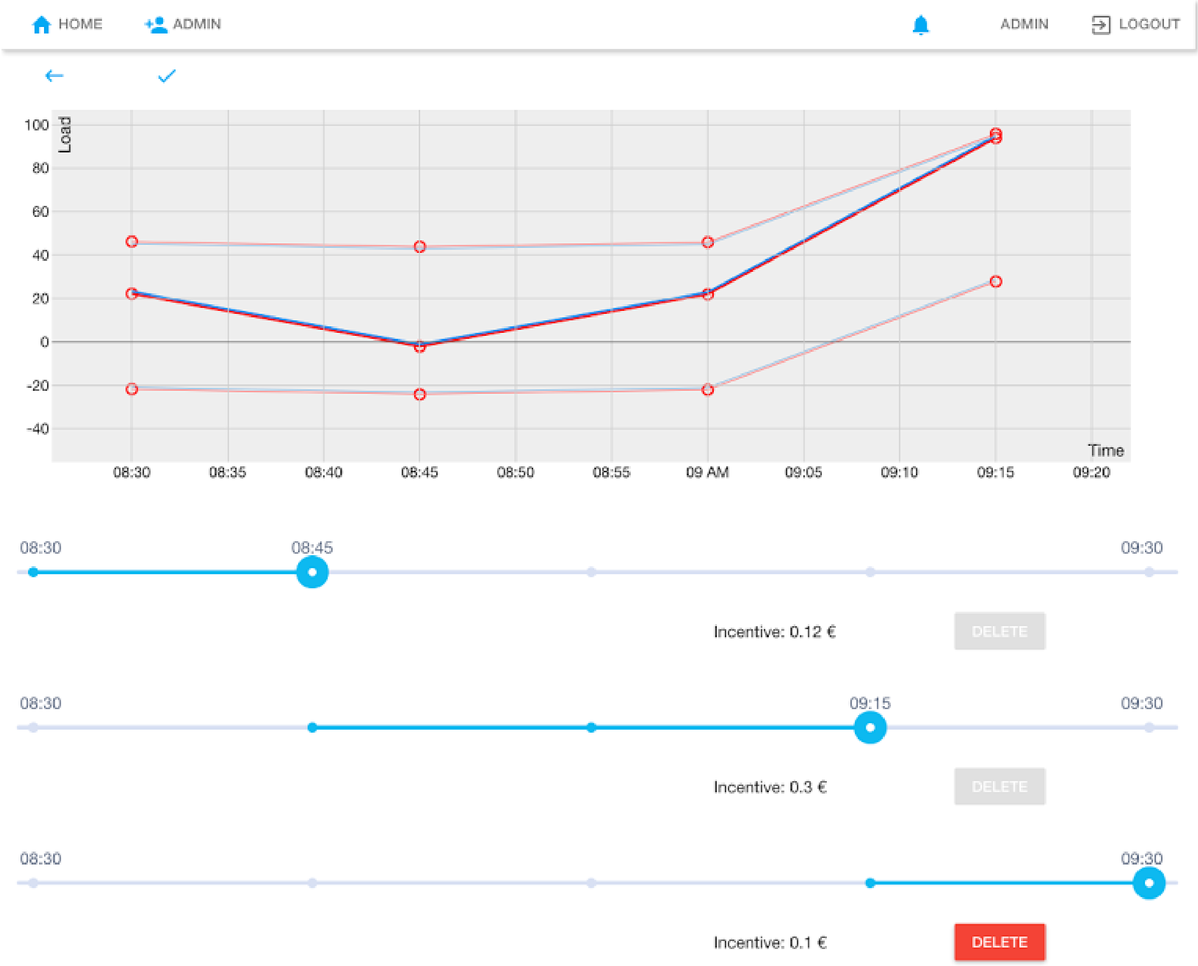
District Historical Dealings

Created At ↓	Start Date	Duration	Profit	Status	
Oct 20, 2017	Oct 22, 2017 12:00:00 AM	PT1440M	141.54 €	✓	
Oct 10, 2017	Oct 12, 2017 12:00:00 AM	PT1440M	-39.38 €	✓	
Oct 10, 2017	Oct 11, 2017 12:00:00 AM	PT1440M	-60.49 €	✓	
Oct 5, 2017	Oct 8, 2017 12:00:00 AM	PT1440M	-58.15 €	✓	
Oct 5, 2017	Oct 7, 2017 12:00:00 AM	PT1440M	-56.02 €	✓	

Figure 64 – History table of the dealings within the “Dealing” tab of the district manager dashboard of the ELSA system.

5.9.2 DSO dashboard

In this section, a brief overview of the dashboard provided to the DSO is given. This GUI allows the DSO to create a power request profile by comparing its technical requests with a first estimation of the flexibility that could be provided by the district. In particular, the DSO can effectively draw a power profile between an upper and a lower flexibility limit profile estimated by taking into account only the rated flexibility capability of the energy units inside the district. Moreover, the DSO can also insert the economic value rewarded to the district manager for the provision of grid services in an editable time window. In Figure 65, a screenshot of the DSO dashboard is shown.



Incentive: 0.12 €

Incentive: 0.3 €

Incentive: 0.1 €

Figure 65 – The GUI provided by the DSO dashboard allowing to create a request, in term of power profile, and the related economic value.

The DSO dashboard is employed also for displaying the results of the optimisation process. In particular, the comparison between the power profile requested by the DSO and the optimised power profile of the district is shown in order to graphically assess the service provided by the ELSA system. In Figure 66, the chart showing the optimised power profile is deported.

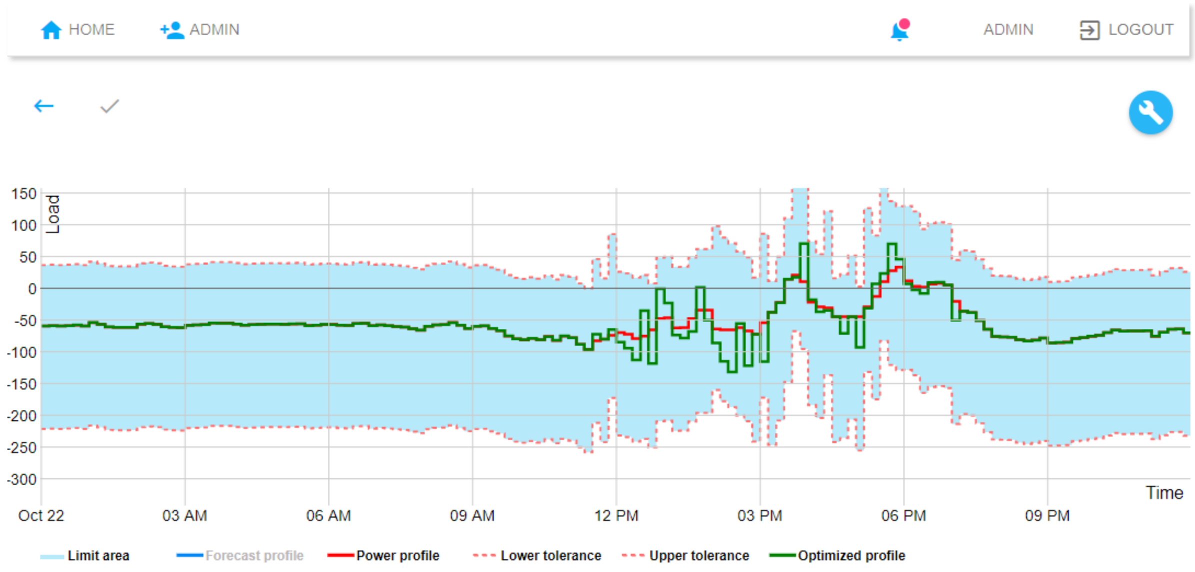


Figure 66 – The charts comparing the request of the DSO, along with its tolerance range, and the optimised power profile coming from the EDEMS within the DSO dashboard.

5.10 Software deployment

In order to install and deploy all the software components presented and discussed in this chapter, a detailed deployment activity has been performed. The ELSA architecture consists of several software interacting and exchanging information during different stages of the district operation, as clearly depicted in Figure 58 and Figure 60.

Each of these components requires a proper framework for being executed and the proper communication means have to be established for allowing data exchange. These software environment have been installed into different virtual servers located into Engineering Ingegneria Informatica S.p.A. data centre in Pont-Saint-Martin, Italy. In particular, two virtual machines have been set up for the ICT platform proposed for the ELSA system: one running the software tools regarding the DSO and the EEMSs (one EEMS for the PV system, one EBMS for the buildings, one ESMS for the batteries); another one running the district manager module and the EEMS of the EV recharging system. In Figure 67, a graphical representation of these two virtual machines is depicted.

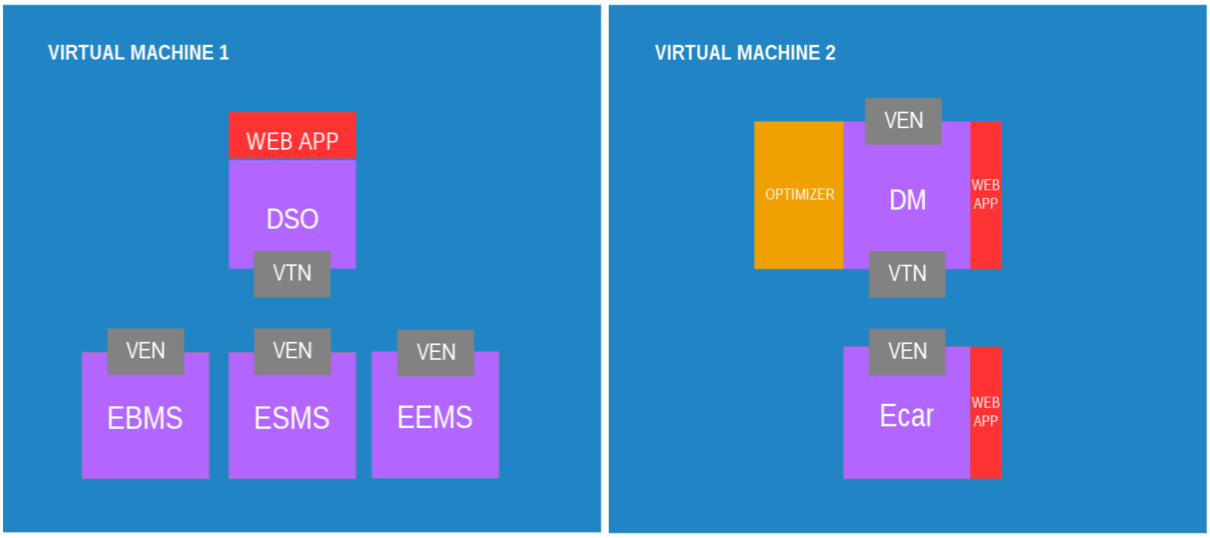


Figure 67 – Schematic representation of the virtual machines hosting the softwares of the ELSA ICT platform.

As discussed over the sections of this chapter, the integration and installation of the entire optimisation framework tool needs some third party components:

- Torquebox 3.0.2: allows to implement the Ruby language through which the VTNs of the openADR communication framework has been developed;
- Postgres 9: implements the persistence layers of the VTNs implementation;
- Tomcat 8.0: is an application server where the VENs implementation, the district manager module process, and all the web applications are run;
- Node.js 6.x: it is employed for running the EEMS applications and the server side of the web applications;
- MongoDB 3.2: is a NOSQL database instance employed for EEMS applications and the server side of the web applications;
- MATLAB Runtime 2015b: is the components allowing to run the evaluation performed by the optimisation algorithm.

5.11 Results

The results of the ELSA system discussed in this chapter have been tested in a simulation environment since the test campaign at the demonstrator site is not begun yet. Nevertheless, several tests have been performed in order to prove the effectiveness of the EDEMS in achieving the Project goals, see section 5.1.1, and, above all, in covering the use cases defining the service provision to the grid operator.

One of the most relevant goal of the Project consists in delivering technical services to the DSO. The criteria of the optimisation framework, which is the core of the ICT platform, are based upon the management of the flexibility provided by the battery system and from all the other flexible energy units of the district in order to provide services to the DSO. As already mentioned, three energy units out of the four ones installed inside the Terni test site are able to shape and modify their energy profile in order to provide flexibility services to the DSO: the battery system, the EV recharging station, and the building. At this stage, since no available actuator are installed at building premises, only the flexibility of the first two energy units are considered. The RES system, composed of two PV plant, is considered as an uncontrollable generation system.

In Figure 68, the flexibility provided by the battery system energy unit is shown for a 24 h execution of the optimisation process, considering a timestamp length of 10 minutes. As mentioned in the previous sections, the reference power of the battery system is set to zero for all the time horizon. This approach has been adopted because the batteries are considered totally dedicated to the flexibility service provision to the district and to the management tasks of the EDEMS; if a scenario in which the battery energy unit are committed to other energy activities, for instance for providing storage functionalities to a building, the reference power profile can be adapted to this behaviour and the flexibility is calculated accordingly. The flexibility limits are calculated by the dedicated modelling modules taking into account several operational conditions and current monitoring data retrieved from the battery system itself. It is clearly shown how this limits vary depending on the state of charge of the battery, given that the rated absorption and generation power values remain the same over the time horizon considered for the proposed simulation. The three coloured line in the graph represents the optimised solution selected by the DSS, the blue one shows the solution providing the best fitness towards the first objective function (F1), the red one shows the solution providing the best fitness towards the second objective function (F2), the green one shows the trade-off solution (A).

Figure 68 – The optimised solutions of the battery energy unit provided by the DSS. Green line: trade-off solution (A). Blue line: solution providing the best fitness towards the first objective function (F1). Red line: solution providing the best fitness towards the second objective function (F2).

In Figure 69, the flexibility limits of the battery system are shown along with the solution provided after the negotiation process. It worth mentioning that the flexibility limits here proposed are evaluated simulating the implementation of the negotiated power profile.

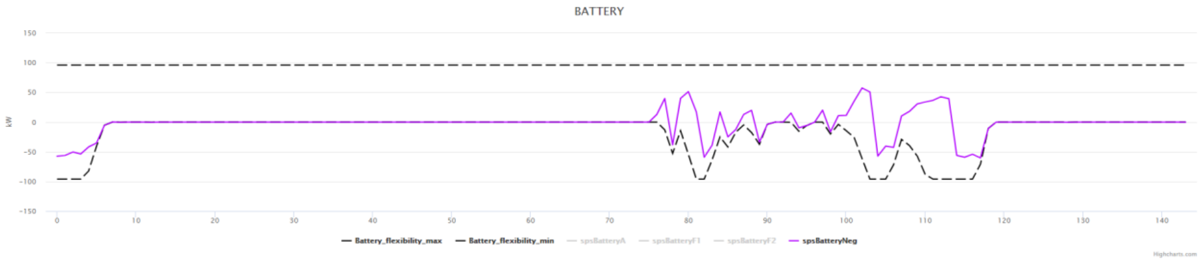


Figure 69 – The optimised solutions of the battery energy unit provided by the negotiation process.

In Figure 70, the flexibility provided by the EV system energy unit is shown. In this case, the reference power profile and the corresponding flexibility limits are evaluated by the modelling module and shared with the optimisation process. The power profiles are evaluated taking into account both the EV reservations and the updated status of the system by simulating it through its own model. As described in the modelling framework section, the reference power profile emulates the typical charging request queue aiming to recharge all the EVs in chronological order in accordance with the availability of the EV stations. The booking reservation system is in charge of allowing only the suitably recharge windows to the EV drivers. The evaluation of the flexibility limits relies upon operational consideration made on the basis of the upper recharge availability, in terms of EVs requesting for charge, and the lower recharge constraints, in terms of EVs that have to be charged for fulfilling operational targets. As shown for the battery system, the three optimised solutions provided by the DSS are displayed in the same charts of the corresponding power boundaries: the F1 solution, the F2 solution, and the A solution are shown in blue, red, and green bar, respectively. It worth noting that the area between the two flexibility limits do not represents the set of all the operational point that the system can implement, but this area identifies all the possible profiles that can be performed inside the EV system. This means that the status of the system, updated timestamp by timestamp, is crucial for determining the available EV unit power values.

Figure 70 – The optimised solutions of the EV system energy unit provided by the DSS. Green bar: trade-off solution (A). Blue bar: solution providing the best fitness towards the first objective function (F1). Red bar: solution providing the best fitness towards the second objective function (F2).

In Figure 71, the flexibility limits of the EV system are shown along with the solution provided after the negotiation process. It worth mentioning that the flexibility limits here proposed are evaluated simulating the implementation of the negotiated power profile. Moreover, in this case, the negotiated profile is the only one whose technical feasibility has been verified through the negotiation process.

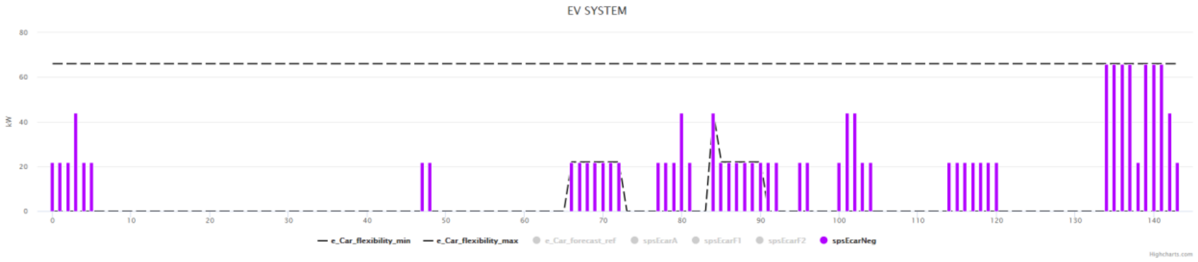


Figure 71 – The optimised solutions of the EV system energy unit provided by the negotiation process.

The modelling tasks related to the EV system allows to evaluate also the reference forecasted power profile, which is shown in Figure 72.

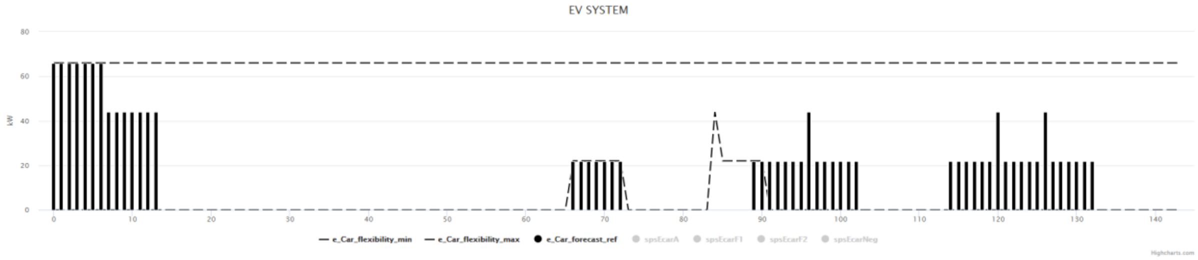


Figure 72 – The reference power consumption profile of the EV system energy unit provided by the modelling process

The flexibilities given by these energy unit collaborate on creating the aggregated power profile of the overall district. In Figure 73, the charts reporting the district power profiles are shown. In these chart different profiles are shown. Firstly, the profiles reported in the upper chart represent the availability of the district to provide flexibility. The forecast power profile of the entire district is evaluated taking into account the forecasted power production of the PV plants energy unit, the forecasted power consumption of the buildings energy unit, and the reference power profile of the EV system energy unit. No contribution from the battery energy unit is considered at this stage. The upper and the lower flexibility of the district are evaluated by considering the unconstrained flexibility capabilities of the energy units: the flexibility of each energy unit is considered at its maximum in order to address ideally all the flexibility that could be provided by the system. This approach has been adopted for having a preliminary assessment of the available flexibilities of the overall district, also for guiding the DSO on creating a suitable requests on the basis of the declared flexibility capability. The blue, red, and green lines represent the three solutions provided by the DSS. The profiles reported in the lower chart refer to the requests sent by the DSO. By means of the DSO dashboard, the DSO sets a reference request profile for service provision which is accompanied by an upper and a lower tolerance limits. These limits define the area inside which the request of the DSO is considered fulfilled, also in terms of rewarded money. This tolerance range is set by the DSO defining the limit profiles manually of by simply setting a tolerance percentage. Within these profiles, the purple line refers to the power profile of the entire district provided after the negotiation process, put in comparison with the violet dashed limit that reports the reference forecasted district profile.


DISTRICT PROFILE

DISTRICT PROFILE

DISTRICT PROFILE

DSO REQUEST

Figure 73 – The optimised power profiles of the district reported in comparison with the district forecast and the DSO power request. Green line: trade-off solution (A). Blue line: solution providing the best fitness towards the first objective function (F1). Red line: solution providing the best fitness towards the second objective function (F2). Purple line: negotiated solution.

It is clearly shown how the optimised solutions manage to reduce the distance between the forecasted profile before the optimisation and the request of the DSO, exploiting the flexibilities put at disposal of the EDEMS by the battery energy unit and the EV recharge system. Depending on the management criterion adopted by the DSS, the solutions presented are more or less close to the request of the DSO; in particular, the profile representing the F2 solutions (red line) is characterised by the lowest value of the second objective function that parametrises the distance between district power and DSO request is the closest to the DSO profile.

The behaviour discussed above clearly depicts the capability of the district to shape its power profile in order to meet requests from an external actor. This functionality has been designed and developed for fulfilling the two use cases covered by the EDEMS, addressing the peak shaving and the PV power smoothing services. The former aims at flattening and reducing the power consumption of a power profile. Thanks to the usage of storage devices, the peak demand can be shifted to a different time period of the day. Reasons can be lower prices or grid congestion. Besides the storage usage, peak demand might also be reduced employing a different energy generation unit, such as DG systems. The DSO requests for a peak shaving service since a surplus of power consumption in the district is detected. As for the PV power smoothing, this service consists in the ability to store PV extra production in the storage devices in order to mitigate and smooth fluctuating power output. The service is implemented storing electricity when the output of PV system is higher than the reference power request from DSO. The DSO requests the PV power smoothing service when it forecasts that the power injection of the PV energy unit will exceed the expected load consumption of the other energy units of the district.

In Figure 74 and Figure 75, the provision of both services is shown. In Figure 74, the forecasted consumption profile of the district presents significant peaks over the addressed time horizon, so the DSO requests for a flat power absorption over the day, for instance shifting loads from peak hour. The optimised solution manages to respond to the DSO request and reshape the overall district energy behaviour by exploiting the energy flexibility of each energy unit.

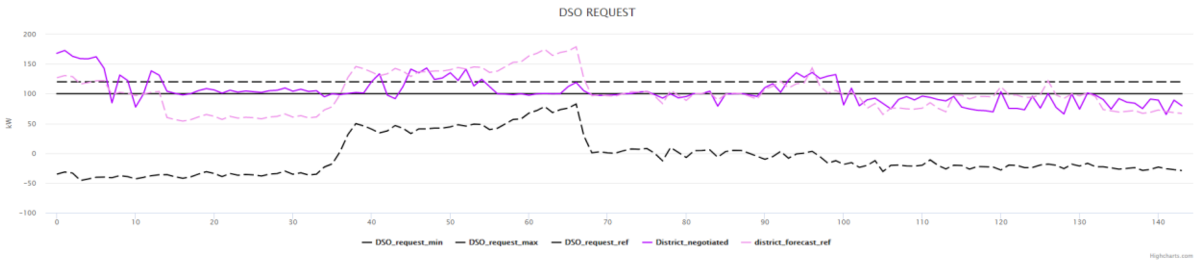


Figure 74 – The negotiated power profiles of the district reported in comparison with the DSO power request and the district reference forecast for the peak shaving service. Purple line: negotiated solution. Violet line: district forecast.

In Figure 75, the overall power profile presents some negative power flows, thus in some hours of the day the district injects power towards the MV grid because the power generation exceeds the power consumption. The DSO requests for a profile that stays as far as possible inside the positive section of the chart. Also in this case, the optimised solution manages to achieve this goal by shifting the load consumption in the hours where there is exceeding power for PV plant, or simply by charging batteries.

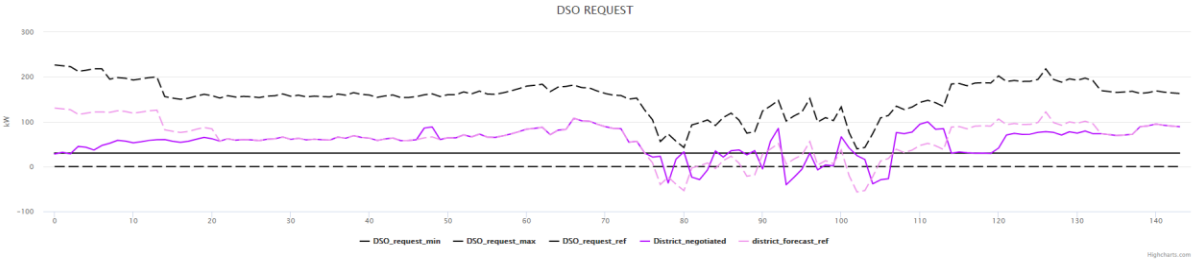


Figure 75 – The negotiated power profiles of the district reported in comparison with the DSO power request and the district reference forecast for the PV power smoothing service. Purple line: negotiated solution. Violet line: district forecast.

The data shown in the previous charts have been evaluated by the optimisation, modelling, and forecasting modules of the ELSA ICT architecture and subsequently have been displayed and proposed through the dashboards provided to the DSO and the district manager. All the input data of the optimisation process are conveyed by means of the OpenADR standard, as well as the output sent to each energy unit. The data exchanges occurring in this process are performed by the report and event exchange between the VTN and VEN implementations. The proposed simulations, to which the data depicted above refer, have been performed by employing these components that showed their responsiveness and effectiveness during all the tests conducted for assessing the functionalities of the communication framework.

These results shows how the ICT platforms of the modern power systems can seamlessly exchange various typology of information among several actors of the smart grids, such as grid operators and aggregators, RESs systems, EV recharge stations, storage devices and smart building, or industrial equipment. As a matter of fact, these actor are interested in communicating electrical values and parameters, price signals and economic data, service requests, notifications and negotiation signals. Both the DSO and the energy units are involved in exchanging electrical parameters, mainly power values, battery state of charge and other monitoring data. Moreover, the DSO is also committed in sending requests in shape of power profiles and service provision. The economic data about the money rewarded to the district manager, in terms of payment for technical services, and to the energy units, in terms of incentives for the flexible behaviours, are exchanged by OpenADR as well. Finally, all the energy units give feedbacks and notification about the acceptance of flexibility requests, as the district replies back to the grid operator with availability of providing that service in that time window. All these communications are performed over well-established and easy accessible means, e.g. internet protocols, so it is demonstrated the availability of the technological background for implementing smart grid implementations.

The ELSA concept aims also at paving the way for the creation of business models able to give economic value to the smart grid solution related mainly to the storage technologies. The ELSA system implementation proposed in this work envision a service-oriented business model in which the flexibility of the smart energy district gains economic relevance by means of tailored incentives rewarded by the stakeholder requesting for it. Two incentives schema are proposed and implemented. The first one addresses the grid operator, covering the role of DSO, that requests for peak shaving and PV power smoothing service to the district manager. The provision of this service is rewarded by establishing a fixed incentive for a selected time windows (proposed by the DSO and measured in euros) during which the district manager is paid by means of the whole amount of the incentive if it manages to exploit the flexibility of its energy units in order to fulfil the DSO request inside the tolerance range. These moneys represents the gross economic benefits of the district manager. In its turns, the district manager, by the operations of the EDEMS, requests flexibility services to the energy units that are able to provide these kind of behaviour. Each energy unit, in declaring the limits of flexibility actions that it can deliver, communicates also an incentive to be paid in order to leverage the provision of this service. This incentive aims at rewarding the amount of power variation performed by means of their internal device or appliances, and is measured in euros per kW. After the negotiation process, the district manager is asked to reward the flexibilities provided to the related energy units; this amount consists in the costs of the district management. The difference between the above presented gross benefits and these costs represents the net economic benefits of the district manager. In the view of a business model tailored to the activities of the district manager, this approach manages to create a suitable economic leverage for affording the expenditures for equipping the district context with storage devices and smart energy systems able to modify their behaviour in the view of providing flexibility. Moreover, this business model allows revenues even after the payback time, consisting in a valuable economic source. In the charts in Figure 73, it is clearly shown the difference between the benefits and costs of the district management.

Chapter 6

Conclusions

6. Conclusions

This chapter reviews all the topics discussed along the present thesis, highlighting the main outcomes and their relevance in many of the heartfelt issues of today discussion about smart energy efficiency and consumption reduction. The innovation carried out by the proposed studies tackles many well-known issues about smart grid technologies and management approaches for providing services to distribution grid in the shape of flexible energy behaviour. Moreover, the economics and business models of such smart implementation are taken into account as well. The results of the two implemented test cases related to the flexibility platforms depict the effectives of the combination made by the innovative devices and the tailored business models. They are here proposed for demonstrating how two different energy contexts, greatly represented in modern smart grids, benefit from the usage of smart flexibility platforms aimed at managing the usage and the optimisation of the energy resources. Finally, the future advancements and new approaches for the proper management of modern energy contexts are proposed, depicting the main research areas in which these innovations will be brought.

6.1 Innovation proposed

Modern power systems are facing enormous changes in almost all the fields related to the energy generation, consumption, storage, and management. These innovations are accompanied by smart approaches and techniques implemented in the energy systems, as well as new models for addressing the smart behaviour of such energy resources. These topics are threated in details in the first three chapters of this study, addressing cutting-edge technologies, modern communication means, new stakeholders, smart management techniques, and, above all, innovative flexibility implementations.

The main outcomes reported in the present work have been achieved by combining all these aspects in the research activities performed in the INGRID project and the ELSA project, both funded by the EU.

These projects firstly propose new breaking-through storage technologies at different distribution grid scales: one installed within a plant equipped with industrial devices, one installed within an urban energy district. As for the former storage system, the INGRID system deploys an innovative solid-state hydrogen storage based on magnesium hydrides. This modern technology represents the key aspect of the INGRID plant allowing high performances at its inlet, which is strictly connected to the electricity consumption, and at its outlet, which is strictly connected to the electricity generation. Moreover, the process of hydrogen absorption ensures high dynamics and storage density, allowing significant storage capability. The storage system, supported by the devices in charge of handling the hydrogen before the storage, the WE, and after it, the FC, is suitable employed for providing flexibility to both the MV and LV grids by modulating both electrical power consumption through the WE and electrical power injection through the FC.

Also in the context of the ELSA project, the main technological innovation is represented by the storage system. The ELSA concept relies upon the implementation of a storage system consisting of a set of 2nd life-batteries recovered from EVs. The storage requirements of an EV are too high to be fulfilled by these storage devices that are in any case properly suitable for providing storage and flexibility services to residential energy units such as building, on-roof PV plants, EV recharge stations, etc. The storage system, consisting of a pack made by several Li-ion batteries and auxiliary devices, provides high dynamics at both inlet and outlet and proper power capability in order to deliver significant flexibility behaviours to the district management. Actually, the storages are considered as an energy unit directly accessible and controllable at district level as well as the main source of flexibility as a service.

For both the considered Projects, the storage device plays the central role in the smart energy management of the proposed smart flexibility concept. Their functionalities deliver the greatest part of the flexibility put at disposal of the management systems. These implementations demonstrate how the modern smart energy contexts can easily access to new storage technologies that, properly scaled, can cover the services required by various different kinds of energy-related stakeholders.

Moreover, each of the Project demonstrator presents the installation of modern power system technologies in order to demonstrate their effectiveness on smart grid implementations and the possibility of smart managing them. Both of the demonstration sites have an EV charging system participating actively in the management approach of the entire energy system. In the INGRID system, the electromobility program proposed is considered as a part of the balancing services offered to the DSO at LV grid level, representing a constraining request for the energy management process. The EV system envisioned for the ELSA project proposes a private electro-mobility renting program employing a fleet of ten EVs available at the parking lot inside the demonstrator site itself. This recharging system delivers flexibility to the district management and participates actively in both technical and economic management criteria of the EDEMS. These two electromobility implementations demonstrates the possibility of adopting these kind of programs in two different shapes. In the former case, the concept of a charging station available for charging purposes is proposed, whose energy consumption is related to the flow of active EVs circulating in that area. Moreover, the possibility of creating a recharging service for the electric buses employed within public transport services is under investigation. In the case of the ELSA project, the concept of an EV renting service is studied showing how, in urban area, tailored recharging service can be provided to private parties owning an EV fleet while fostering energy management of the district and new business models related to the flexibility service provision.

Both of these implementations show the great impact that electromobility can have in the modern power system and, focusing on the specific topic of the present study, it is demonstrated how they can also support energy management tasks.

The solutions proposed for the two smart grids here discussed tackle and properly handle the topic of RES integration into distribution grid. As a matter of fact, both the Projects allow to face the issues due to the power injection of PV plants. One is connected outside the INGRID system facilities, immediately downstream the MV feeder supplying the plant itself. It has been shown how the INGRID system is able to smooth the peak of power injection from these generation units by activating the WE and modulating its power absorption. The other PV plant is equipped within the infrastructure of the ELSA demonstrator itself, installed above the roof of parking shelters. The issues related to the power generation peaks of these systems are avoided by the smart management of the flexibilities resources of the district: on peak hours, both batteries and EV system are asked to be activated in charging mode and to increase the power absorption, respectively.

The innovation brought by the researches shown in this thesis address also the field of new communications means allowing the actors of modern power systems to exchange data related to the management, monitoring and control tasks. In this view, the researches focused on two significantly different contexts: a plant where industrial devices and the corresponding equipment are installed, an urban district where typical residential facilities and energy units, such as households, offices, and storages, are installed. The communication and monitoring systems of the industrial plants represent a well-established technology and a plenty of complex architectures are available. The innovation of the proposed solution relies upon the creation of a communication framework through which the management and optimisation process can easily exchange data with the equipped industrial device, such as the PLCs installed within the WE and FC. As shown in section 4.4, the data regarding the optimal configuration of the plant are evaluated by means of powerful computing tools, e.g. MATLAB, and then are made available to the plant communication system, consisting of OPC server and PLCs, through Java libraries developed on purpose that allow to read and write tags of the OPC server itself. This architecture shows how it is possible to exchange data with complex third-party industrial communication system and access to it also by means of ICT framework dedicated to the smart management of the energy resources developed with open source and easily available environment.

The urban district proposed within the ELSA project demonstration site fits perfectly with innovative communication standards tailored on smart grid implementations; OpenADR, is one of these standards and its employment can provide great advancements in the creation of smart communication architectures allowing to exchange information about energy management and, above all, economic trading of the addressed energy. The OpenADR has been employed for the ELSA system and adapted to the ICT framework developed for managing all the energy resources of the district. By means of the events and reports functionalities of this standard, all the information between the DSO and the EDEMS as well as between the EDEMS and all the energy units have been properly handled and encapsulated in OpenADR messages. The ELSA implementation demonstrates how the functionalities of the OpenADR standard can be exploited by many actor of modern power systems and can be integrated within many ICT environments for exchanging significant management, monitoring, and control data.

Besides the advanced technologies implemented into the two test sites, many innovations have been carried out by proposing new stakeholders participating in the energy management process. Both the proposed solutions envision the active participation of the grid operators in the shape of DSO: this body, in charge of managing the distribution system infrastructure and of addressing its technical issues, can formulate technical service requests to the EMSs controlling the energy resources connected to that distribution grid. Moreover, the possibility of rewarding the provision of these services is proposed as a new feature of these actors. As a matter of fact, the DSO could be forced to sustain significant costs for empower and smarten the infrastructure of the distribution grid in order to face technical issues due to the presence of modern energy system. In this view, it prefers to reward the actors able to partially solve these technical issues instead of undertaking expensive infrastructure interventions. This approach leverages the creation of tailored business model and provides new features to this stakeholder.

Another important stakeholder envisioned for the proposed smart grid scenarios is the district manager. It is responsible of the energy management of an energy system, such as the energy district of the ELSA system. This figure acts as an interface between the requests made by an external stakeholder and the owners of the energy systems of the district, in order manage all the energy behaviours of the district as a whole by gathering and coordinating the energy resources operating inside the district. This coordination activity takes into account not only the technical management aspects, related to the optimal scheduling of the power consumption and generation of the energy units, but also the economic aspect. The district manager is indeed in charge of handling money transactions between the external stakeholders and the energy resources inside the district: the incentive for flexibility services are rewarded by the district manager directly to the energy units, while it is paid by the DSO for the provision of grid services. As mentioned in the previous chapters, the difference between these two amounts of money represents the net benefits of the district manager. The results of the ELSA project shows how the adoption of a district manager simplifies the management of the energy resources of the district and provides actors such buildings users or small RES system owners with easy access to the smart grid solutions. Moreover, the business model allowed by the intervention of the district manager can support the economic sustainability of the smart grid implementation for all the involved stakeholders.

Supported by a rich literature research, the main technical, economical, and policy-related topics of the provision of flexibility services have been addressed. Great emphasis is put on technical, economic, and market aspects of the flexibility services. The changes that the modern electrical grid is experiencing are the main driver for exploiting at its maximum the possibility of receiving flexibility services and for researching on more affordable and reliable flexibility techniques and actions able to provide effective services to the power system stakeholders. The benefits of such initiatives are numerous and involves many aspects of the energy field: energy efficiency, grid operation, users’ engagement, and environmental issues. Many bodies are now fostering on legal and regulatory level for creating a suitable environment for increasing the commitment of both flexibility providers and flexibility users. The innovation brought by the solutions proposed in this thesis is represented by an advanced ICT solution aimed at managing flexibility services, that are properly modelled and delivered according to the energy context taken into consideration. The flexibility optimisation of the energy resources characterising the modern power system has been fully discussed and explored in all of its relevant aspects.

For both the Projects here presented, the flexibility provision is the key engine of the smart management. As for the INGRID project, the flexibility is provided by the controllable power consumption of the INGRID plant equipment, especially from the WE. This device is able to modulate its power consumption with high dynamic performances in order to face the flexibility required by the service envisioned for the INGRID system. Besides some operational parameters, the flexibility is modelled in reference to the maximum and minimum rated power consumption values of the WE in normal operational conditions, allowing the entire system to follow power profile requests at MV connection point. The ELSA project presents an urban district where the flexibility is provided by aggregating the flexibility availability of different energy units, in particular the battery system and the EV system. In this case, the flexibility is modelled in order to take into account the energy behaviour of each single unit, employing tailored modelling modules aimed at evaluating the flexibility limits referring to the operational status and the management choice of the energy unit owner/manager, that can decide to what extend its unit can provide flexible services to the district manager. The aggregation of these flexibility, performed by the district management, is then provided to the DSO in order to define the provision of suitable services to the grid operators.

The management of the flexibility put at disposal by the energy systems controlled by the ICT framework developed is performed by smart optimisation algorithm, in charge of innovating the traditional approach of energy resource coordination by taking into account several goals and objectives at the same time. This approach allows to provide optimal operational configurations that manage to cover several aspects of modern power systems processes. Supported by a wide and acknowledged literature research, a heuristic optimisation framework has been chosen in order to take into account the complexity of smart grid operations, the presence of different energy carriers, the non-linearity of many controlling functions, and, above all, the possibility of handling various control criteria. As discussed in the previous chapters, a genetic algorithm has been appointed for these purposes, the Non-dominated Sorting Genetic Algorithm II, based on Pareto optimality concepts, that are fundamental in the management of more than one objective function. The results provided by the developed optimisation framework demonstrate how the economical, technical, and operational criteria can be handled and optimised simultaneously by properly designing the framework itself and defining suitably all the objective functions as well as the equality and inequality constraints of the optimisation problem.

Finally, a key innovative aspect of the proposed study is the adoption of a multi energy carrier approach for modelling complex energy context. In particular, the possibility of exploiting technical and economic advantages from the optimal management of the interaction between two energy carriers, electricity and hydrogen, has been modelled and assessed within the researches performed for the INGRID project. It has been clearly shown how the storage of electricity in the form of hydrogen allows to provide technical service to the DSO: flexibility services towards the MV grid by modulating the power absorption of the WE; balancing services towards the LV grid by modulating the power generation of the FC. Moreover, the interaction with a third energy infrastructure has been addressed, thus the possibility of injecting hydrogen in its gaseous form into the gas distribution network. It is clear how the smart management of a multi-carrier hub brings technical and also economic benefits to all the involved stakeholders.

6.2 Results

The results achieved in the two test cases reported in this work show the possibility of exploiting flexibility in very different energy contexts with the aim of providing technical services to the grid operators and of maximising the economic benefits of the actors involved.

The INGRID project provides a great amount of flexibility by operating an industrial plant able to absorb from the MV grid up to 1 MW. This flexible behaviour is exploited for coping with the peak of RES power generation that occurs in that portion of the grid. The results provided by the flexibility platform on both the offline evaluations and the field test campaign demonstrate how the flexibility provided by the modular power absorption of the INGRID plant, mainly due by the WE, manages to cover the power peak and reduce the reverse power flow phenomena towards the transmission system by means of the optimisation of the energy and storage operation inside the plant.

The Figure 48, here proposed again, shows how the INGRID plant reactively responds to the power profile set by the control infrastructure and, above all, how the power absorption of the INGRID plant manages to significantly modify the power profile of the HV/MV station with respect to the power profile measured downstream the connection point of the INGRID plant itself. It is clearly shown how reverse power flow phenomena are almost totally avoided thank to the intervention of INGRID system.

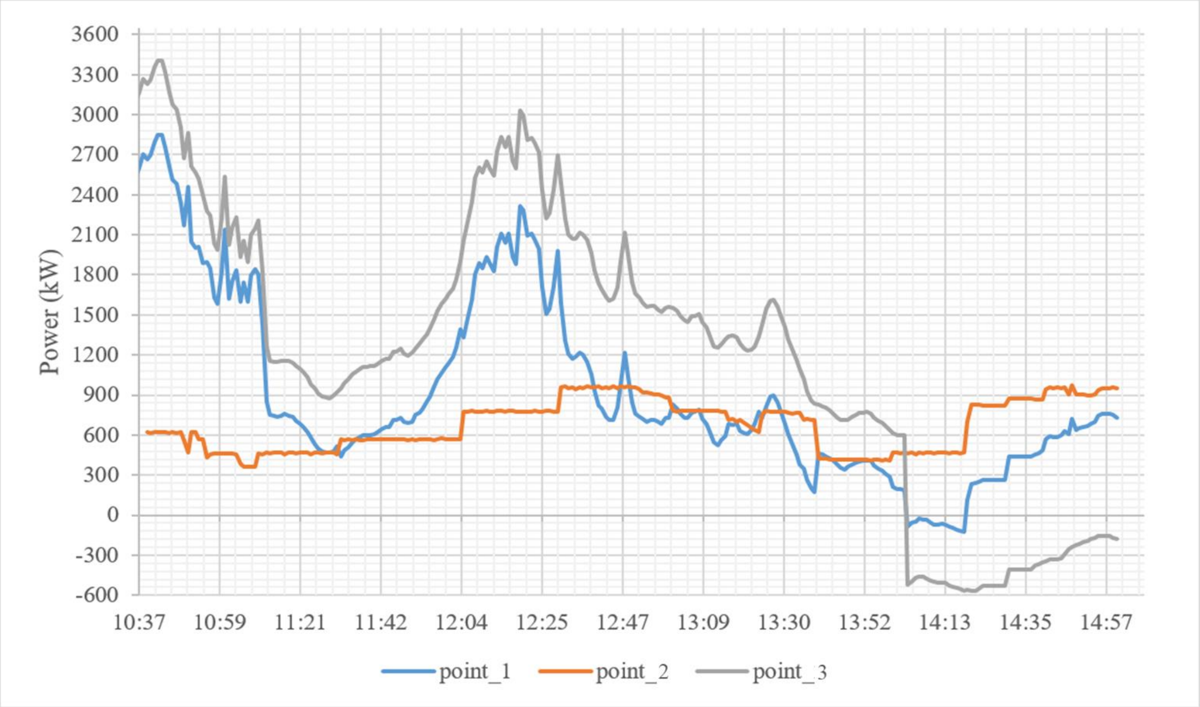


Figure 48 – The INGRID demonstrator substation power levels during Test 3.

Moreover, the economic aspect is taken also into account, trying to maximise the economic revenues of the INGRID system operations. The main cost sources are related to the purchase of electricity form MV grid to be stored in form of hydrogen. The economic revenues of the plant are due to the sale of hydrogen stored into the dedicated channel of the plant and to the sale of electricity at LV level to the EV customers by means of the FC. The incentives rewarded by the DSO for the provision of services at MV level are taken into consideration only for simulation purposes. In this way, the best technical operational configurations provided by the EMS are always characterised by a proper business sustainability in order to minimise the expenses and maximise the incomes of the plant.

In the context of the urban energy district of the ELSA project, the effect of the smart management provided by the flexibility platform is twofold: firstly, the ICT tools allows to coordinate several flexibility resources and optimise their exploitation; secondly, the efforts on aggregating this resources focuses on provide grid services to the DSO. The small amount of flexibility provided by each energy unit of the envisioned ELSA system is cumulated with that of the other resources and smartly managed in the view of providing significant grid services. Actually, in the case of the ELSA concept, the system flexibility allows to modify the energy behaviour increasing both power injection, mainly by means of the battery system, and the power absorption, by means of the battery and the EV systems.

As discussed in section 5.2, the two grid services envisioned for the Italian pilot of the ELSA project are peak shaving and PV power smoothing: the former aims at reducing power absorption during peak load hours by properly reducing and shifting the energy consumption of the district energy units as well as exploiting battery discharging capability; the latter aims at smoothing the power injection during high solar irradiation hours over a day, by properly increasing and shifting the energy consumption of the district energy units as well as exploiting battery charging capability. In this view, the ELSA system has been tested in order to prove that the functionalities of the ICT framework proposed as EDEMS of the addressed context are able to cover the use cases consisting in the provision of the services described above.

In Figure 74 and Figure 75, here reported again, the results of the tests performed for assessing the fulfilment of DSO service request are shown. In particular, the requests of the DSO have been structured in order to be coherent with peak shaving and PV power smoothing services. In the former case, the forecasted power profile of the district is characterised by high consumption peaks, so the power request of the DSO has been drawn inside the flexibility limits of the district in order to reduce these peaks and flatten the power profile of the entire district. In the latter case, the forecasted power profile of the district presents a reverse flow towards the MV grid caused by the power injection of the PV plants, so the DSO request has been shaped in order to keep the power profile of the district on the upper side of the chart while remaining inside the district flexibility limits.

Figure 74 shows the optimised solutions provided by the optimisation framework in a test where the EDEMS is asked to shave consumption peaks. It is clear how the system is able to modify its behaviour in order to flatten the power consumption profile and avoid peaks over the addressed time horizon. In Figure 75, the optimised results of the EDEMS are shown in the case of excess of power production from PV plants. It is clear how the system is able to properly manage the power generated by the RESs inside the district in order to cope with reverse power flows by shaping the power profile of the district.

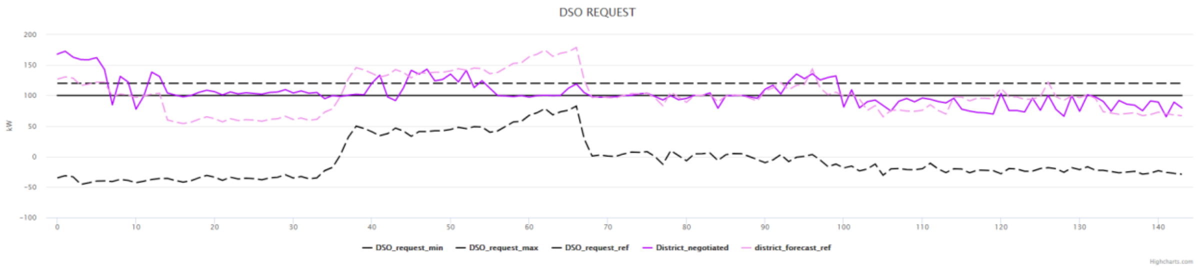


Figure 74 – The negotiated power profiles of the district reported in comparison with the DSO power request and the district reference forecast for the peak shaving service. Purple line: negotiated solution. Violet line: district forecast.

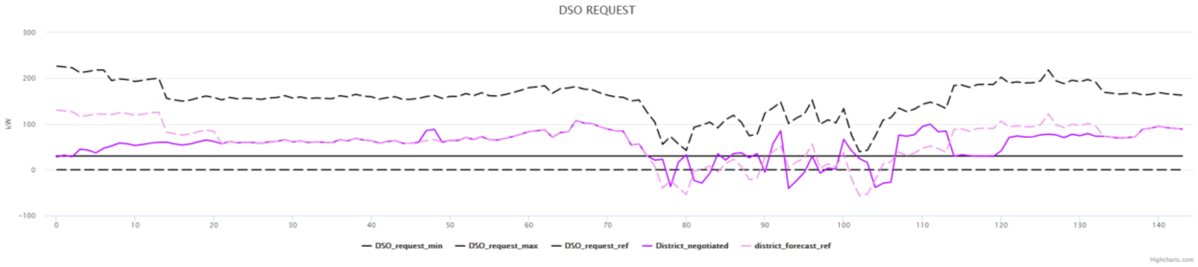


Figure 75 – The negotiated power profiles of the district reported in comparison with the DSO power request and the district reference forecast for the PV power smoothing service. Purple line: negotiated solution. Violet line: district forecast.

The economic aspect of district management has been taken into account by the optimisation process in order to maximise the economic benefits of the district manager. The test performed for assessing the technical services provision provided also significant results about this aspect. Actually, as shown in Figure 63, the amount of money rewarded to the energy units is lower than that received by the DSO for technical service provision, so that a viable economic structure is guaranteed for the implementation of such system.

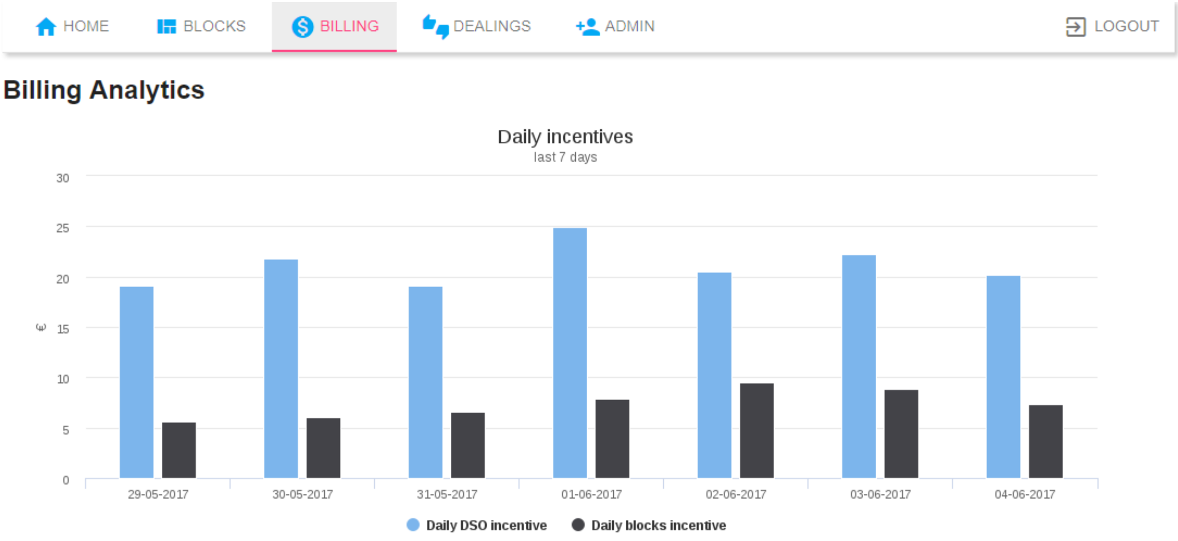


Figure 63 – The daily incentives paid by the DSO to the district manager and by the district manager to the energy units in the "Billing" tab of the district manager dashboard of the ELSA system.

6.3 Impacts on the addressed energy contexts

The economic, social and environmental impacts of the solutions proposed in the researches here presented are not in the scope of the present work and will be the topics of further future investigations. Nevertheless, this section aims at providing a general overview about the footprint, the effects, and the acceptance of the smart energy systems developed in this thesis. These considerations gain more and more momentum since the proposed solutions are installed and developed in real energy system and all the aspects mentioned above are actually affected by their operation.

6.3.1 Impact on the main stakeholders

As widely discussed in chapter 0, many actors and stakeholders are involved in both the provision and exploitation of flexibility services. The test cases presented show how the grid operators are considerably committed on requesting technical services to the smart energy systems, mainly in order to face grid issues such as reverse power flows or power peaks over their infrastructure. In both INGRID and ELSA projects, a grid operator is part of the Project consortium, leading the assessment of the technical services to be studied and provided by the demonstrators; in particular, e-distribuzione S.p.A. and ASM Terni S.p.A. are the two appointed grid operators responsible of the distribution grid of the area of Foggia, where the INGRID demonstrator is located, and Terni, where the ELSA demonstrator is located, respectively. They cover indeed the figure of the DSO, which is in charge not only to evaluate the technical status the distribution network and the related issues, but also to undertake concrete actions for solving and coping with these issues. These figures has been impacted since they were asked to envision a mechanism of service request towards a third party, seen as a grid customer, in order to solve grid technical issues. This request is shaped as a desired power profile at the connection point of the smart energy system consisting in the INGRID and ELSA demonstrator. Moreover, an early incentive framework has been proposed: the DSOs are not only in charge of sending request, but are also expected to pay the provision of this service and to communicate the related incentives and/or rewards to the interested actors in order to allow an economic customer side optimisation aimed at both providing these technical services and maximising customer economic benefits. In spite of the lack of proper regulations and laws addressing these incentive mechanisms, these researches aims at studying the economic viability of such smart energy solutions and, above all, to foster and support the decision making bodies on designing a regulatory framework tailored on these kind of power system applications.

Other relevant stakeholders involved in the provision of the flexibility services are the owners of the energy systems able to provide flexibility to the whole grid. As a matter of fact, great emphasis is put on the opportunity of gathering flexibility contributions from users and grid customers whose energy behaviour is usually static and related to typical absorption and/or generation patterns. In this view, these actors are asked to strongly commit themselves for smartening their energy usage and improving its efficiency. Firstly, from an economic standpoint, they are required to install and equip their energy systems and/or appliances with smart devices able to monitor and control the energy behaviour with respect to the management criteria addressed by the flexibility platform. This entails also the purchase of systems allowing to enhance the flexibility capability of their systems, such as local storages, controllable heat pumps, etc. Moreover, they are also asked to change their habits and daily routines in order to shape the energy behaviour of their systems and modify the above mentioned patterns. These tasks impact obviously their comfort and their usual approach to the energy consumption and/or generation. The leverage for these kind of actions is represented by the economic incentives rewarded by the stakeholders requiring for grid services, shaped in order to cover the economic efforts and ensure money revenues, but also by the awareness of the customers on the energy efficiency aspects, in the view of improving the usage of energy resources, reducing the human impact on the environment, and smartening the modern power systems. The customers involved by the solutions proposed by the INGRID and ELSA projects belong mainly to two categories, due the great differences of the proposed energy contexts. The formers is characterised by an industrial stakeholder, owning enough space and resources to host a solution such the INGRID one and having enough capability for sustaining the financial efforts. Such a stakeholder is impacted for both smart managing its internal energy resources and gaining economic benefits from the flexibility exploitation. In the case of the ELSA project, the stakeholders are various and range from residential user to small enterprises; within the demonstrator discussed in this thesis, the most impacted stakeholders are the battery system owner, the EV system owner and, the building user. The first two actually sustain the efforts for equipping their devices with smart metering and actuator systems. The building user, even though at this stage is not able to modulate its consumption, is putting many efforts on designing smart building features characterised by controllable appliances, accompanied by a study on typical consumption behaviour to be shaped accordingly.

The two Project addressed in this research are characterised by storage technology breakthroughs. As a matter of fact, the system capability of providing flexibility services relies upon these storage devices. The opportunities of finding a low-cost, reliable, and secure technology providing local and/or centralised storage service is the driver of many manufacturers in the field of power system technology. The INGRID and ELSA projects can count on the innovative storage devices aiming at ease and smarten the management task, besides offering their energy capacity. The two involved manufacturing stakeholders are McPhy Energy and Renault S.A.S., respectively, for the INGRID and ELSA demonstrators. These stakeholders are strongly impacted by the implementation of smart actions such as the flexibility platforms addressed in the present study. Firstly, the results of the commissioning, test, and demonstration phases provide a plenty of relevant data for improving and driving the technology research in that particular device. Moreover, the Projects results are crucial for proving the effectiveness of these storage system and represents a suitable proof of concept for the commercialisation of these products.

6.3.2 Impacts on society

The widespread implementation of smart energy systems over the distribution network is strictly connected to societal aspects that represent the level of awareness, acceptance, and commitment of the society on all the topics related to the benefits and issues of such kind of innovation. The acceptance by the society has always been a crucial aspect on the advancement and diffusion of new technologies [242]. The society, and in general the customer, is characterised by high unpredictable behaviours that cause great design and investment uncertainties to the manufacturers that want to propose innovative technologies, solutions, and/or paradigms. In this view, the success of the roll out of smart energy technologies is strongly linked to the evaluation of the impacts on the society and their acceptance.

Generally, a high share of the people is well disposed towards green energy technology and implementation, as well as towards smart energy and efficiency technologies or actions. These innovation is seen as an improvement of human activities towards the environment and as a general enhancement of technological capability in controlling every day activities, for instance controlling smart appliances from a smartphone or monitoring dynamic real-time energy prices. Besides small groups and movements standing against the installation of new green technologies, for instance wind turbines because of the visual impact on the landscape and the risk for birds, the main obstacles is the real commitment of the customer of adopting a smart energy action within their premises. This is due to the lack of clear regulatory framework, uncertainties of economic sustainability, low confidence on the offers of the energy retailers, etc. In section 2.3.1, more details about the social acceptance are highlighted.

The proposed flexibility platforms envision the contribution of an effective smart consumer, engaged on providing concrete services exploiting the technology innovation provided by the Projects solutions. A typical industrial consumer that could fit the INGRID system implementation can be concerned about the dangerous operational management of a gas system related to the hydrogen flow, to the high pressure and temperature recorded within the storage devices, and to the transport issues of the storage blocks. Moreover, the economic sustainability of the investment could also be an aspect to be taken into account. The main doubts of the urban users that could be involved in the implementation of an ELSA energy district are related to the risks of the installation of Li-ion batteries within the area where the district facilities are located, the possibility of losing user comfort in order to fulfil service requests and to respond to the district manager, as well as the transparency and clarity of the economic relationship, for instance in terms contract of flexibility service provision, with the district manager.

Due to the fact that individuals are more open to accept technology innovation if the technology replicates and considers their values, that could be social, environmental, economic, etc., the main efforts performed by the Project activities consists in disseminating the benefits and the positive results of the implementations proved by means of the demonstrator campaigns. In this view, several dissemination events have been attended by the Projects partners [243] [244], such as conferences, fairs and exhibitions, congresses, institutional events with local and national authorities, EU initiatives, etc. Since smart energy technologies and services, such as storage devices or ICT systems, are more likely to succeed when they are directly based on users' preferences and fulfil a clear function in the everyday life of consumers, many events have been arranged for informing citizens and people living in the area nearby the demonstration test site. The main goal of these events is to allow participant to get familiar with both technologies and their risks, highlighting all the countermeasures performed for reducing them. Moreover, the all the benefits carried out by the implementation of such actions have been shown by means of multimedia supports, demonstrations, small-scale reproduction of the devices installed, etc. The active participation allows to enhance feelings of attachment and identification to a product, a good, or a service, usually driving to a stronger engagement. Thus, products and services that are presented to the society using this kind of approach are more likely to succeed because their added value is more evident to the user.

6.3.3 Impacts on environment

The impacts on the environment due to the implementation of the proposed solutions are mainly related to the benefits provided by the smart energy services and to the environmental footprint caused by all the phases of the demonstrations life.

The services envisioned for both the INGRID and ELSA projects aim at integrating RES generation systems into the distribution grid by smoothing the production peaks, that leads to avoid RES curtailment, and by storing the energy produced by the green sources in order to reuse it when the absorption of the same amount of energy from the grid is more environmental impacting, thus during consumption peaks. This approach allows to reduce the usage of fossil fuels through a twofold effect: by avoiding the energy generation of traditional power plants and by reducing the employment of high polluting peak power units during peak hours. Moreover, the possibility of using the energy generated by the RES systems locally allows to reduce the injection of this power into the distribution grid or into the transmission one in the case of power reverse flow. This leads to lower losses on the power system lines that are related to lower polluting emissions.

Without going through the detail of a proper Life Cycle Assessment that considers all the phase of the system from “cradle to grave”, here are proposed some consideration about the impacts related to the activities performed for the overall implementation of the proposed energy contexts.

As for the INGRID system, the phases of the plant life considered are those regarding the manufacturing, installation and erection of the plant, those regarding the tasks of real operation and use of the plant, and those regarding the activities performed at the end of life of the plant itself. The most critical impacts are caused by the tasks related to the use phase: the electrolytic process of hydrogen generation impacts significantly on the environment because of the energy required for its production. The categories of environmental impact that are most affected by this process are those related to the ecosystem quality. The three main services that could be provided by the INGRID system are the provision of services to the MV and LV grids, the sale of hydrogen to a third party customer, and the usage of hydrogen for electromobility programs. The best behaviour in terms of reduction of the environmental impacts of the system is related to the third one, mainly because of the lower emissions achieved by the usage of EVs.

The considerations related to the ELSA system take into account almost the same phase shown before, except for the provision of the battery system itself. Actually, there is a phase of manufacturing and installation of the system (whose impact has to be shared with the assessment performed for the electromobility program, thus the first intended use of the battery system), a phase of extraction of the batteries from the EVs where they have been employed, an operational phase of the ELSA system and, finally, the phase related to plant dismissing and end of life operations. According to the two services provided by the ELSA system, PV power smoothing and peak shaving, the best environmental behaviour is related to the reduction of the curtailment of electricity from RES generation systems and, thereby, a reduction of the use of electricity from fossil sources. The comparatively low share of environmental impact of the battery pack suggests that the impacts of an ELSA system is mainly determined by the use phase and by the changes caused by the ELSA system in the energy mix used at the site of installation.

6.3.4 Impacts on economics

The economic study about sustainability of the smart energy projects is a very complex fields characterised by high uncertainties and low regulatory references. Nevertheless, in this section, a high level overview of the most relevant aspect to be taken into account is provided, highlighting which are the main cost and perspective revenues items of the proposed smart energy solutions.

The INGRID concept entails the erection of an industrial energy context. The costs related to this kind of application are both capital costs and operational one. The former represent all the initial investment costs to be incurred to acquire, install and set up the storage facility. Capital costs include as well project planning, permitting, site construction, component assembly and delivery, facility set up. High capital costs are currently one of the major barriers, together with a not favourable regulatory framework, preventing storage applications and hydrogen energy storage to be successfully deployed at commercial level. The operational costs represent all the yearly expenses incurred by storage facility owner/operators to operate the storage system, once such a system has been constructed, assembled and set up on the selected test site. Operational costs include electricity purchase, water consumption, maintenance due to degradation and gradual efficiency losses.

Since the costs related to the plant are very high, various and simultaneous revenue items are considered, in order to compensate costs and provide a potential economic viability. As matter of fact, the storage of hydrogen allows multi-revenue generation and could be a suitable candidate for making commercially viable storage applications. The following revenues could be considered to offset costs:

- DSO-tailored service provisioning revenues;
- limiting renewable feed in for curtailment minimisation and renewable integration;
- peak shaving for congestion relief, electromobility optimisation and distribution grid reinforcement deferral;
- voltage regulation ancillary service for local balancing;
- wholesale electricity traders (arbitrage);
- Hydrogen Feedstock Selling, valued through the different possible end usages (industrial, refuelling, gas grid injection).

It worth noting that, at the current stage of energy storage innovation, several revenue items are quite uncertain and do not support a widespread commercial deployment of hydrogen energy storage applications. For instance, the price spread between purchasing and selling electricity is gradually decreasing and is not anymore sufficient to cover high costs and efficiency losses and accordingly generate profit for hydrogen storage price arbitrage applications.

The ELSA system proposes an application tailored for urban district where existing energy units have to be modernised and new devices have to be installed. The main costs are the capital ones; the operational costs are neglected due to the low impact of the maintenance costs related to the equipment providing the ELSA services. These capital costs are related to the installation of the battery systems that can be more or less expensive in accordance to the existing devices: for instance, an ex-novo installation could be cheaper than a retrofitting one because of the cost of the new inverter. Other capital costs are expected to buy and install PV systems and smart metering, sensing and actuating devices.

The revenues expected for the ELSA system are related to the purchase of ancillary service to tailored markets. It worth mentioning that, in several countries, no proper ancillary market frameworks have been created but most of them are studying the most suitable solutions for integrating ancillary services in the energy trade.

Considering the opportunity of delivering energy services to the grid operators, the storage systems are compared and handled as energy generation units. The services that could be provided are:

- energy arbitrage;

- increasing of self-supplied local energy;
- peak shaving;
- solve congestions and overload issues on the grid due to updated cumulative injection and withdrawal programs;
- an improvement of predictability and uniformity of power injection profile;
- time deferral of investment to the power capacity enhancement;
- participation in the recovery of the electricity system in case of black out.

Moreover, the storage systems of the ELSA concept are also envisioned for the provision of power services, used to stabilise the grid when there is an imbalance between the energy demand and the energy supply. Indeed, storage systems could be exploited by the grid operator in order to:

- solve congestion during the planning phase;
- provide the primary, secondary and tertiary power reserve;
- provide balancing service in real time.

The application of storage systems for energy services provision in case of residential self-consumption, is not suitable for economic sustainability because very high return times of the investment exceed the battery life-time. In the case of power services, the ELSA solution demonstrates a viable economic sustainability. In particular, the geographic areas with the greatest potential are the southern ones, because the penetration of non-programmable renewable installations is high and the energy demand and supply management presents critical issues.

6.4 Future steps

The topics discussed and analysed within the present study address a very heartfelt research field that has been explored by several bodies all over the world in the last decades, especially for its impacts on sustainable development and environmental issues. In this exciting environment, many innovative solutions concerning new technologies, management approaches, markets evolutions, etc., support the great efforts of scientific community, and not only, on changing the actual way of processing and employing energy resources. It is clear how the quality of the innovation proposed depends on the ability of proposing solutions and related research topics updated according to the newest scientific trends.

In this view, many further innovative areas are already under investigation for increasing the functionalities provided by the ICT flexibility platforms addressed in the reported research activities and for improving their effectiveness and reliability. One of the most impacting improvement under investigation concerns the design of a higher control level able to manage the energy operation of several EMSs. This can be performed by creating an energy federation among several platforms that, besides optimising the operation of their system, are able to take into account higher level goals managed at federation level. Such an approach allows to handle larger technical or economic criteria and to achieve more significant impact on both network infrastructures and energy markets. For instance, the possibility of coordinating several energy systems providing flexibility under a unique management process enables significant services also for TSOs and allows to gather enough capacity for participating to the actual ancillary services and wholesale markets.

Another key aspect bringing smart innovation to the field of energy management is the possibility of adopting decentralised control system. Actually, the platforms proposed in this thesis are based upon a centralised algorithm that handles all the optimisation criteria on a unique control process aimed at sending control signals to the managed energy resources. A decentralised approach is characterised by several local management processes that implement simpler logics with respect to the centralised one but that gain effectiveness thanks to the data exchange between the decentralised decision centres, establishing a cooperative or competitive management process. Many frameworks and algorithms have been proposed in this fields, such as the multi-agent systems, consensus algorithms, and game theory based processes, and their implementation in smart energy ICT platforms is under investigation.

The technical innovations could also affect significantly the management functionalities of an ICT platforms, mainly in terms of static and dynamic performances provided to the smart energy system. In this view, the main technology innovations are reported in the field of energy storage, whose researches propose year by year new improved storage devices and mechanisms. The possibility of adopting such technology is investigated by now, for instance great emphasis is put on the implementation of flow battery technologies in smart grid context, or on the employment of improved materials within typical electrochemical batteries.

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