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Master of Science Thesis:

ENERGY MANAGEMENT SYSTEM

A tool for optimizing energy consumption in a smart grid context

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To our families

Abstract

The sudden renewable energy sources penetration involving European Countries raised several problems connected to the electrical grid, forcing them to adopt new technological solutions. Smart grids are under study and development while new actors have to be introduced in the energy dispatching scenario. This thesis presents a software tool called Energy Management System whose role is to provide services whether to the grid and to the energy market or to the customers by coordinating distributed generation and power consumption by means of the application of Demand-Response. After a detailed introduction regarding the architecture and features, two different applications of this tool are analyzed in domestic and public contexts. Subsequently, this work focuses on the electric vehicle recharging infrastructure, one of the electric actors managed by such a system, describing a strategy for smart load shifting according to local energy availability, price and final users requirements with the purpose of supplying an acceptable level of charge service at the minimum cost.

Key words: Smart Grids, Demand-Response, load shifting, energy optimization, electric vehicle, charging station

Sommario

Il forte e repentino aumento di energie rinnovabili negli stati europei ha sollevato problemi relativi alla gestione della rete elettrica costringendo questi ultimi ad adottare nuove soluzioni tecnologiche. Molte ricerche si concentrano oggi sull'introduzione di Smart Grids mentre il settore dell'energia necessita di nuove figure. L'elaborato di tesi qui presente ha lo scopo di presentare uno strumento chiamato Energy Management System il cui scopo è fornire un duplice servizio alla rete e allo stesso tempo ai clienti finali coordinando la loro generazione distribuita con gli usuali consumi elettrici applicando tecniche di Demand-Response. Dopo un' accurata introduzione in merito all'architettura e le sue funzionalità, verranno presentate due differenti applicazioni di questo innovativo strumento considerando sia contesti domestici che pubblici. Successivamente il lavoro verterà sull'infrastruttura di ricarica dei veicoli elettrici, uno degli attori gestiti dal sistema, descrivendo una strategia per lo spostamento intelligente dei carichi considerando l'energia prodotta localmente, il prezzo di acquisto ed i bisogni degli utenti finali allo scopo di fornire un adeguato servizio di ricarica al minor costo possibile.

Parole chiave: Smart Grids, Demand-Response, spostamento dei carichi, ottimizzazione energetica, veicoli elettrici, colonnine di ricarica

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Abbreviations

Acronym	Definition
ASM	Ancillary Services Market
ACAP	As Cheap As Possible
ADR	Automated Demand-Response
ASAP	As Soon As Possible
ASM-D	Distributed Ancillary Services Market
BSP	Balancing Service Provider
CAES	compressed air energy storage
DAM	Day-Ahead Market
DG	Distributed Generation
DR	Demand-Response
DSO	Distribution System Operator
EIS	Energy Information System
EMS	Energy Management System
EU	European Union
EV-PG	Electric Vehicle Profile Generator
GME	Gestore del Mercato Elettrico
HVAC	Heating, Ventilating and Air Conditioning
ICT	Information and Communication Technologies
IDM	Intra-Day Market
IPEX	Italian Power Exchange
JSON	JavaScript Object Notation
LV	Low Voltage
MV	Medium Voltage
OPT	Optimizer
OWS	Optimization Web Service
PG	Profile Generator
PLC	Power Line Communication
PU	Production Units
PUN	Prezzo Unico Nazionale
PWM	Pulse Width Modulation
RES	Renewable Energy System
SCUOLA	Smart Campus for Urban Open Lab
SOC	State Of Charge
SS	Secondary Substation
TSO	Transmission System Operator
WB	WallBox

Chapter 1

Introduction

1.1 European energetic situation and issues connected

In recent years climate changes have occupied a central role in the social development of the countries all around the world. Mainly due to temperatures increase and greenhouse effects associated to the exponential rising of Carbon dioxide concentration in the atmosphere, new strategies have been applied in order to contain the global warming. In 1997 most of the nations gathered in a convention with the purpose of converging on several points regarding how to face the issue on a global scale: the Kyoto Protocol was drawn up and all the participants of the convention decided to reduce the emissions of CO2 and others greenhouse gases up to 9% within December 2012 introducing incentives and subsidies for enhancing “green” investments [1].

At the deadline of the agreement the EU introduced a new challenge for the Kyoto members gathered again for the so called COP15 in Copenhagen whose result was not the one expected: they didn’t find a compromise regarding a common strategy for the future and the climate changes topic, seen as a risk for the world economy, has been discarded [2]. Nevertheless the European countries decided to apply their new solution regardless the COP15 results with the idea of being promoters of possible future agreements [3]. The so called “REScoop 20-20-20” plan aims at replacing 20% of the final consumptions (electricity, thermal heating, mobility whether in domestic or in industrial contexts) with renewable energies such as photovoltaic panels, biogas, biomass, bio waste, onshore wind, offshore wind, small-scale hydropower, large-scale hydropower, solar thermal electricity, photovoltaics, tidal & wave energy, and geothermal electricity. Using these sources helps not only to reduce greenhouse gases emissions for energy generation and consumption but also to reduce the EU’s dependence on the fossil fuels importation (in particular oil and gas). Moreover it focuses on the improvement of technological efficiencies for reducing the energy demand up to 20% with the purpose of reducing the amount of CO2 released in the environment around 20% within the year 2020.

Due to the incentivations put in place by the European countries, Renewable Energy Systems (RES) has increased exponentially in recent years (fig. 1).

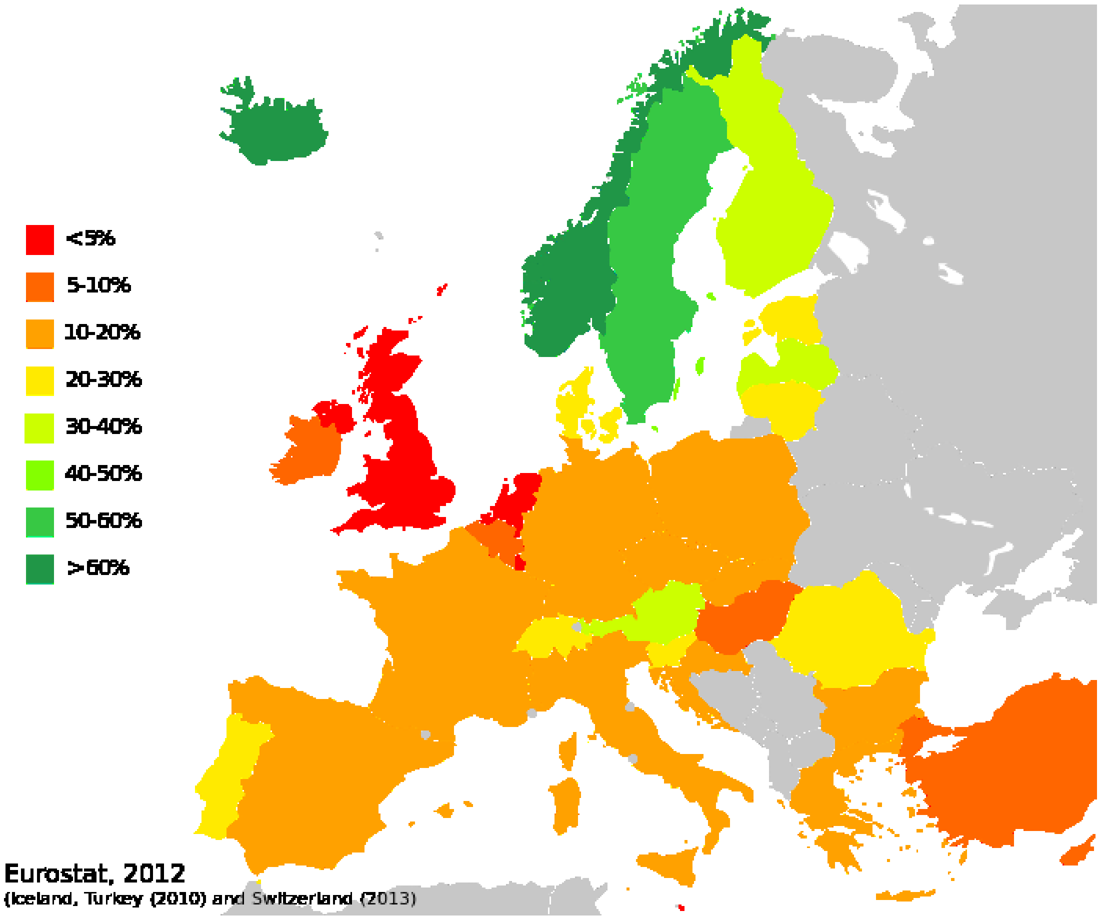


Figure 1.1: Share of renewable energies in gross final energy consumption by country [30]

Photovoltaics and onshore wind farms have been installed both by domestic users and industrial investors with the dual use of self consumption and grid injection: all the energy produced by RES connected to the transmission and distribution network and not used locally is automatically sold to the grid. In this way the distributed generations can share their green production with all the country receiving back an extra income.

Unfortunately this strategy has some drawbacks [4]: the unpredictability of the energy produced by Distributed Generations (DG) and in particular RES such as photovoltaics and wind turbines creates lots of issues for the national electric network and consequently on the energy market: in each second of the day the total amount of energy demand has to be equal to the total energy production. Traditional power generation technologies such as gas turbines can be scheduled almost in real time. This implies that even a small deviation in electricity demand prediction can be completely compensated by such a plant. However, the price associated to energy generated by programmable gas turbine plants is quite high, the generation process is quite inefficient and surely not renewable.

On the other hand Photovoltaic panels and wind farms produce green energy but they are always on when the primary source is available which makes them uncontrollable units: their generation strongly depends on weather conditions which can be predicted with a high level of uncertainties. The result is a fluctuating generation which creates imbalances (demand-offer misalignments). If in real time the production is lower than expected, the grid has to ask for an immediate reaction for covering the gap, usually provided by conventional plants such as gas turbines. On the contrary if the production is higher than expected the grid has to curtail the excess of production by disconnecting the RES units for network security reasons (reverse flow from medium voltage to high voltage transmission network). Since the main goal is to maximize the renewable production while exploiting all the available primary energy, the grid has to accept this intermittent behavior and looks for new solutions which aim to maintain the demand-production curve always balanced avoiding curtailments.

1.2 Smart grids and distributed generation

Further increase in RES penetration requires the presence of a “Smart Grid”:a grid is defined as “smart” when is able to harmonically couple different kinds of distributed generations (DG) with the centralized production avoiding security and integrity problems related to overgeneration and reverse flows by transferring the surplus of energy in others contiguous areas, predisposing energy storage systems and making the energy demand more flexible by offering money savings for the final users.

Lots of researches are now investigating new technologies for energy backup systems such as chemical batteries (e.g. Li-ion, sodium sulfur, Lead-Acid), pumped-storage hydroelectricity and compressed air energy storage (CAES) to be integrated into the network [5]. All these kinds of devices aim at compensating in real time the mismatch between the forecasted injection and the actual production. Moreover they enhance the hosting capacity (capability of accepting new distributed units like RES connected to the grid) reducing curtailments and increasing the programmability of the energy exchange profile. Unfortunately nowadays batteries are extremely expensive and their lifetime is usually too short. Pumped-storage hydroelectricity are more long-lived but they may suffer from a reduced water availability. Thus, with no reasons that justify the investments, their installation is still not encouraged.

Another way for reducing curtailments and imbalances is the so called Demand-Response technique [6]: according to the Federal Energy Regulatory Commission, Demand-Response (DR) is defined as “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized”.

The main goal of DR is to decrease electricity consumption or shift it from on-peak to off-peak periods depending on consumers’ preferences and lifestyles (fig. 1.2). Demand response activities are defined as “actions voluntarily taken by a consumer to adjust the amount or timing of his energy consumption”. Users are informed about hourly energy prices and incentives supplied in order to rescheduling the demand curve and makes it more flexible.

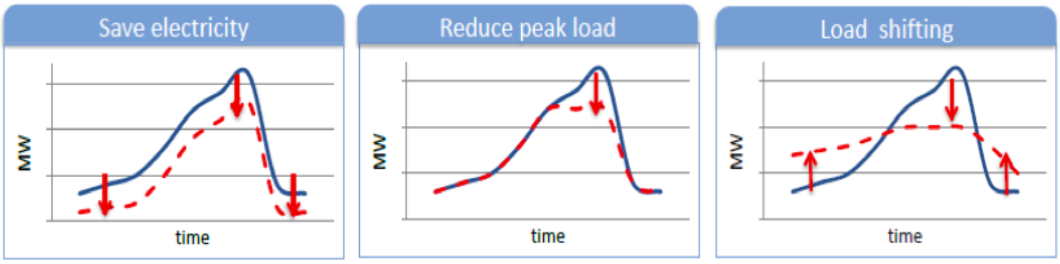


Figure 1.2: Demand-Response effects on the customers load curve [22]

For some electrical devices is not mandatory to be on in specific moments of the day: dishwashers, washing machines, electric vehicles battery can, up to some extents, be scheduled/postponed. The user who participates to Demand-Response accepts to anticipate or postpone the working time of deferrable devices in exchange for cost savings. Customers who traditionally pay a fixed rate for consumed energy (kWh) and requested peak load (kW/month) can set their thresholds and adjust their usage to take advantage of fluctuating prices. In order to comply with this service, devices able to read final user consumptions and hourly energy prices should be provided to the customers for making them more informed and presenting smart solutions for reducing consumptions and saving money (e.g. Smart Info device from ENEL) [27].

Moreover, in order to compensate imbalances and network instability the Distribution System Operator (DSO) would like to offer all the users a reward in exchange for a variation in energy withdrawal/injection thus making them participate as actors in the Ancillary Service Market (ASM).

1.3 Thesis scope and motivation

In order to face all this issues and enable Demand-Response, a new market actor has to be introduced. The Balancing Service Provider (BSP) has been presented as an interface able to create a link among different agents operating on the energy dispatching system. Its scope is to provide a service whether to the market/grid side or to the final users. By collecting and analyzing all the information and requests regarding energy prices, network security and distributed generation, it can provide suggestions or decisions which allows the customer to reduce bills costs. The tool used by the BSP in order to create this connection is called Energy Management System (EMS), a physical interface for making all the information available to the users.

In the following chapters we present an innovative EMS for the application and diffusion of Demand-Response. Due to their one-to-one correspondence, from now on we will refer to the BSP with the same nomenclature as for the EMS. As explain later in details, the scope of such a system is to manage the electricity consumption and production of a single house, a group of cooperative houses or of an institute in order to minimize the energy daily bills and improving efficiency of the electricity grid.

After a brief explanation in chapter 4 about the necessity of this new actor in the Italian context, chapter 5 will focus on the features and structure of the EMS. Chapters 6 and 7 will present two different applications of such a system underlying the different requirements and technological solutions. In chapter 8 some preliminary results of an EMS installation will be reported and discussed. Finally chapter 9 will provide some conclusions and introduce some future improvements for strengthening this innovative tool.

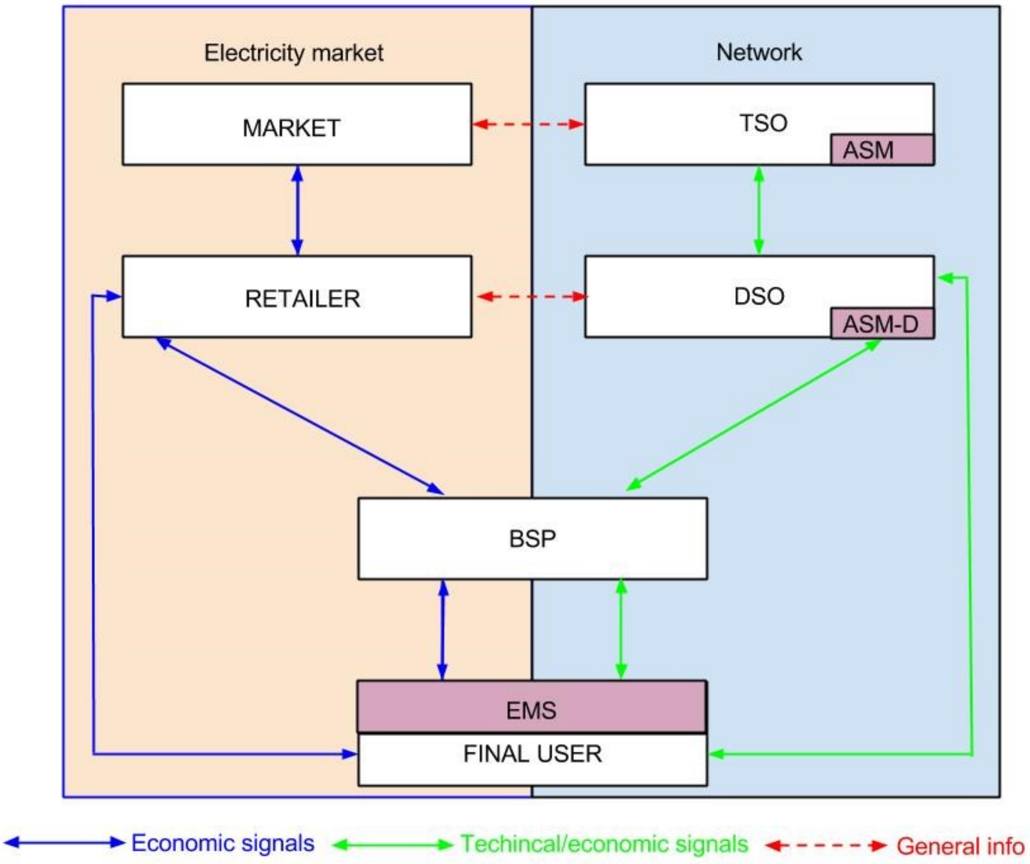


Figure 1.3: EMS location between the final user, electricity market and national grid

Chapter 2

State of Art

The research community has recently investigated several optimization methodologies for the energy management of residential, industrial and commercial scenarios, with real-time or day-ahead approaches. They are often based on the users' behavior profiling with the purpose of inferring the main habits and automatically act on them to reduce energy dissipation, e.g. by switching off stand-by devices [7][8]. The main drawback of the analyzed proposals with respect to the collected knowledge, is that data are stored with ad-hoc solutions that usually do not support data sharing and access by multiple entities. In the context of "Smart Office" scenarios, in [9] data from multiple sensors and actuators has been recorded for 6 years in a building of the EPFL campus. The collected data include room temperature, presence, lighting level, windows opening, blinds position, electric lights and heating power; weather data have been collected as well, and includes ambient temperature, solar radiation on a horizontal surface (direct and diffuse components), wind speed and direction and rain alarm. The main goal of the proposal is to validate control algorithms for the actuation of solar shadings, electric lighting and heating equipment. It was shown that such control algorithms were able to significantly reduce the energy consumption while maintaining the same comfort level or even improving it. In [10] the authors describe a case study about the refurbishment of a 1960's student accommodation. The refurbishment was predicted to possibly achieve a standard called Code for Sustainable; building information modeling and visualization are used for analyzing and comparing different design solutions. [11] presents a proposal to evaluate the role of Apps as an enabler of behavioral changes with specific aim of reducing energy consumption in buildings.

Our proposal includes an integrated data repository collecting all the relevant information gathered by different sources and available to be accessed by different actors.

A mixed integer linear model for the joint optimization of gas and electricity bills of a university campus building has been presented by Guan et al. [12]. The building is equipped with a controllable combined heat-power system, battery storage and a photovoltaic plant. The optimizer can run whether under assumption of "a priori" knowledge about future events, or assuming a "scenario tree", in which multiple possible future production/consumption patterns are considered, each one weighted with its probability of occurrence. This way, uncertainty about future energy usage is taken into account. Our approach also uses a linear program, but our EMS relies on energy production/consumption forecast models. Moreover, the optimization procedure is repeated multiple times during the scheduling horizon, and decisions are dynamically updated. Other recent works addressing Smart Office environments include studies on energy saving strategies for lightening management based on room occupancy (by Stojanovic et al. [13]) and some demonstrators deployed in office buildings aimed at the development of self-sustained distributed energy systems [14][15][16].

For what concerns residential environments, Bozchalui et al. [17] and Kriett et al. [18] provide optimization models for the usage of individual electrical appliances and combine multiple objectives such as the minimization of energy consumption, energy costs, carbon emissions, and peak load. Our proposed EMS also optimizes different objective functions, including energy costs, comfort of the buildings' occupants, and the fulfillment of Automated Demand-Response (ADR) requests from the Distribution System Operator (DSO).

Chapter 3

Background Notions

3.1 Need of a new character in the Italian Power Exchange

As a member of the European Union, Italy subscribed the “REScoop 20-20-20”. In 2010 a document reporting the strategy for the reduction of greenhouse gases (PAN: Piano d’Azione Nazionale) was published [19]. According to this document within year 2020 17% of the Italian energetic consumptions has to be covered by renewable energies for a production amount around 22,62 Mtep. In order to reach this goal a consistent increase in the national potentials exploitation will be required, in particular related to renewable sources for heating/cooling and the usage of biofuels in the transport field. The energetic plan reimburses 55% of an investment regarding heat pumps, solar panels and biomass plants through taxes deduction in ten years. Furthermore an yearly crescent percentage of biofuels will be sold in conventional gasoline and diesel.

Other nodal aspects to be considered are the strengthening and managing of the national grid, further simplifications regarding authorization documents and the development of international projects. A central role has been occupied by activities involved in information and promotion all around the country and by the regions’ interaction.

In 2015 the situation regarding the improvements is extremely promising [20] (fig. 3.1).

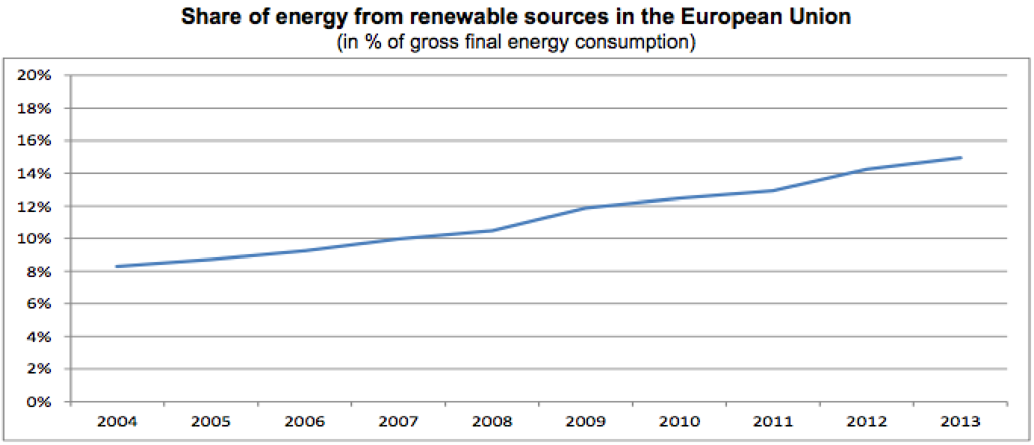


Figure 3.1: Share of energy from renewable sources in the European Union [20]

According to the recent data presented by EUROSTAT in 2013, 3 out of 28 European Union Member State have already reached the level required to meet their national 2020 targets: Bulgaria, Estonia and Sweden. Moreover, Lithuania, Romania and Italy are less than 0.5 percentage points from their 2020 targets. Conversely, the United Kingdom (9.9 percentage points from reaching its national 2020 objective), the Netherlands (9.5 pp), France (8.8 pp) and Ireland (8.2 pp) are the furthest away from their target.

Italy is putting lots of efforts in the diffusion of renewables covering in 2013 16,7% of the gross final energy consumptions (both thermal and electric) while it is still in late concerning the diffusion of the biofuels supply.

3.2 Network consequences of sudden RES penetration

This sudden exponential growth in green energy is mainly due to generous incentives provided by the Italian Government in favor of the installation of Photovoltaic (PV) panels along the peninsula.

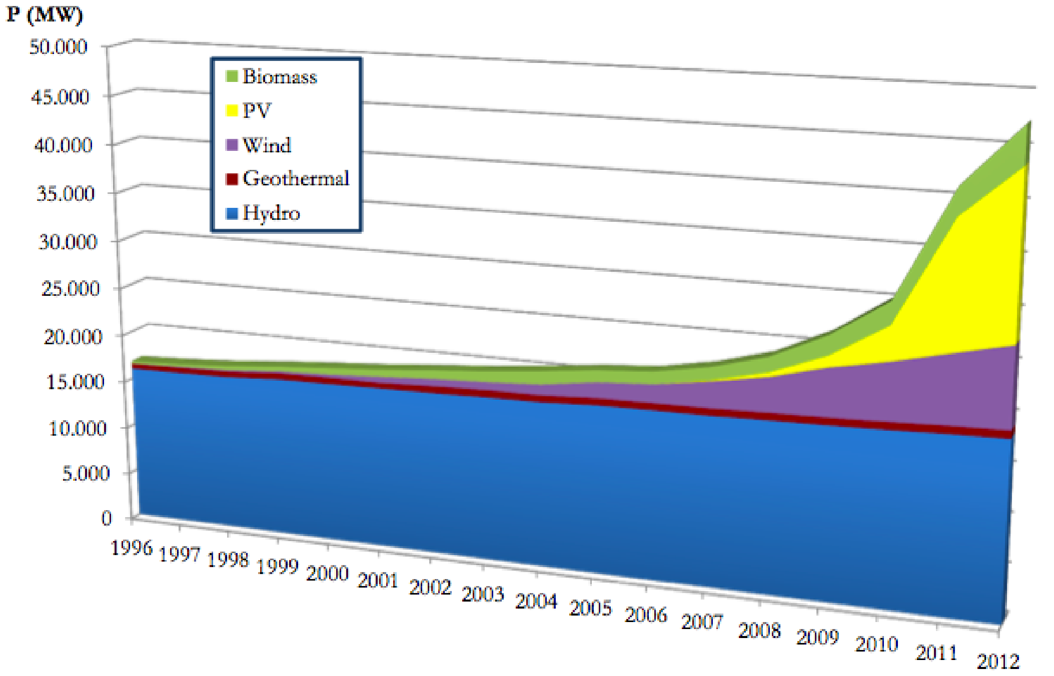


Figure 3.2: Gross power from renewables in Italy: rapid increase of PV installed due to incentives [28]

As can be clearly seen from fig. 3.2 between 2010 and 2011 Photovoltaic production underwent a steep increase due to a feed-in-premium incentive mechanism called “Terzo conto Energia” [22] which strongly promoted investments for domestic and industrial solutions. Unfortunately, even though such a revolution could seem to have just positive effects it actually has some drawbacks: the strengthening of the national grid was not as fast as the Photovoltaics propagation and this implied a suboptimal integration of distributed generations. Due to technical problems lots of renewable energy sources were not able to inject their production even though the primary energy was available: all the overgeneration of electricity in a specific area didn't have the possibility of flowing in other zones which required more. Most of the investors didn't see any income for the energy they couldn't produce for network congestions and the final goal of exploiting renewable sources was unjustifiably reduced. The same problem raised for wind farms installed on the transmission network. During year 2010 the loss of wind production was equal to 470 GWh, that represented the 5,6% of wind energy on the Italian transmission system.

In order to solve this issue lots of investments regarding how to potentiate the grid are now under study.

3.3 Market consequences of sudden RES penetration

Another problem strictly related with distributed generation affected the Italian Electricity Market.

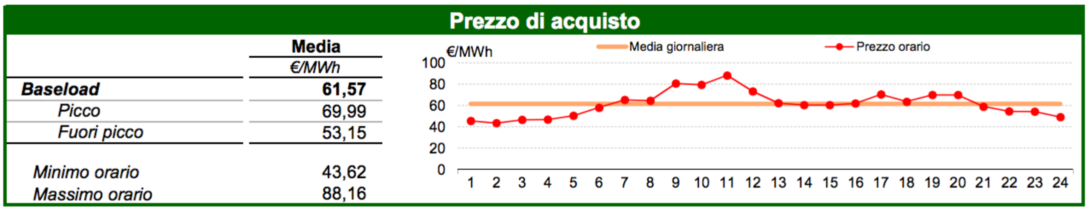
The IPEX, Italian Power Exchange, is mainly divided in three parts: the Day-Ahead Market (DAM) is responsible for energy trading between producers and consumers matching the demand and production curves in order to find the corresponding quantities of energy to be supplied a day in advance, allocate transmission capacity and locate the relative price. The participants are producers, consumers and brokers. it closes the day before the real consumption in the morning and the corresponding quantities are communicated to the producers through the Market Operator (In Italy Gestore del Mercato Elettrico, GME). In order to balance the "prediction" of the Day-Ahead Market and allow the producers to slightly modify their scheduling another market has been put in place: the Intra-Day Market (IDM). The last branch of the IPEX is the Ancillary Services Market (ASM) used for balancing the network in real time and apply power system constraints. It is ruled by the Transmission System Operator (TSO) which accepts bids and offers in order to relieve residual congestions and create reserves margins for balancing the demand gap. It pays production and consumption units for their availability to modify injections and withdrawals in critical moments of the day with respect to the cumulative program emerged from previous markets. The bids are paid at the offered price by TSO which tries to solve all the issues at the minimum cost. This cost will be transferred automatically to the final consumers' bills. Not all the Generation Units are allowed to participate to this market: usually programmable thermal plants are the main characters for their rapid reaction after a variation request. On the contrary uncontrollable RES units, by definition, have an intermittent production and can not participate. Moreover for their unpredictability, the Ancillary Service Market need is becoming more and more necessary for the stability of the network. The spread of non-programmable renewable sources is leading to a reduction in the hours of operation of thermal power plants that, among other things, are increasingly being used to cover the peak load. The presence of DG along the medium voltage and low voltage networks lines could even increase the voltage beyond the levels permitted by the EN 50160. Lots of researches are trying to solve the problem at the source by introducing devices like the Internal Protection Relays for frequency and voltage protection and improving communication of the distributed units with the whole system. To this end, wind farms shall be able to avoid the reduction of active power during underfrequency conditions and reduce, quickly and automatically, the active power during overfrequency conditions, without disconnecting from the network

For its pay-as-bid nature the Ancillary Service Market is extremely expensive and does not support renewables. Conventional plants, having less opportunities and incomes from the Day-Ahead and Infra-Day Markets, try to keep the price as high as possible in this market for compensating and nowadays TSO has no option but accepting and paying for this economically and environmentally expensive energy.

If the final consumers and distributed generations could receive signals regarding the network status they could modify their injections and withdrawals for avoiding an high exploitation of the conventional plants on the Ancillary Service Market reducing imbalances costs and even obtaining a revenue for helping the grid.

3.4 EMS introduction

Unfortunately nowadays customers have no access neither to real time network information nor to hourly energy market prices. They simply receive a bill from the chosen retailer which usually reports a flat and stable price for all the trimester. The energy price is calculated in this way: the intersection between Demand and Offer curves generates the Zonal Price, which is reported hour by hour and can be different according to the zone of applications.



Prezzo di acquisto

	Media *€/MWh*
Baseload	**61,57**
Picco	69,99
Fuori picco	53,15
Minimo orario	43,62
Massimo orario	88,16

Figure 3.3: Daily release regarding the Prezzo Unico Nazionale (PUN) [29]

The weighted average of the Zonal Price is called Prezzo Unico Nazionale (PUN), is hourly supplied and it corresponds to what the electricity retailers have to pay for buying electricity on the Italian Power Exchange (IPEX). As shown in fig. 3.3 The PUN can widely change during the day according to the cost associated to production in specific moments. Renewable Energy Systems (RES) can strongly reduce the electricity cost while conventional plants, forced to generate during peak moments in an inefficient way, are extremely expensive [21]. Nowadays the Retailers buy at the PUN the energy on the IPEX but usually provide to the end users flat contracts with monthly stable prices divided in bands of usage for simplifying the learning and reducing the risks associated to PUN fluctuations. Unfortunately with this strategy the user has no information about the PUN and cannot take advantage of its hourly variation.

A new Real Time Market establishment may allow the users to adjust their final consumption in a less expensive way, thus making the demand curve more flexible.

Because of all these new issues connected with RES penetration, the role of an Energy Management System (EMS) can become really important.

As shown in fig. 1.3, such a system is an interface between the final user (which can be seen as a simple consumer, a producer or a prosumer) the IPEX and the Network. The EMS, collects data about the user’s energy production/consumption, data from the IPEX regarding hourly price of electricity and grid requests coming from the Distribution System Operator for whether balancing or frequency and voltage control. Necessary condition for applying such a system is the introduction of a new Real Time Market in which the EMS can act as an energy broker buying electricity for the final user and network services in a flexible way. The EMS can even accept users’ commands: through a dedicated interface house owners can submit their preferences about the usage period of deferrable electric appliances and the recharge of their electric vehicle.

The final goal is an increase in flexibility of the demand curve through the application of Demand-Response and an improved stability of the network which can accept in this way more renewable distributed generations. On the other hand the end user can receive rewards for supporting the network balancing and stability.

The use scenarios can widely range from domestic installations (whether isolated or aggregated), to institutes, industrial contexts and mobility. The following chapters will explain in details the architecture and functionalities of the EMS according to different use scenarios

Chapter 4

Overview about the EMS

As shown before in fig. 1.3 the EMS is a tool able to provide an interface between the final user and the Balancing Service Provider (BSP). The latter is responsible for exchanging information regarding the electricity supply considering all the involved actors.

On the Network side the Transmission System Operator (TSO) is in charge of monitoring that the balance of energy production and demand for the dispatching service is always respected. It can ask for energy rescheduling in real time only through the Ancillary Service Market (ASM). As discussed in chapter 3, the Production Units (PU) which can participate to this market are all the programmable conventional plants connected to the transmission grid and all the non Renewable Energy Sources (RES) plants with a capacity bigger than 10 MW able to vary their production within 15 minutes [22]. All these PU provide this kind of service in exchange for a congruous reward.

The TSO cannot communicate directly neither with Distributed Generations (DG) nor with the low voltage (LV) and medium voltage (MV) final users: all the information has to pass through the Distribution System Operator (DSO) except for critical situations regarding network stability (see RIGEDI protocol for MV units) [23]. Due to the high cost associated to ASM utilization in a new context the DSO could act as an aggregator of DG services with the purpose of participating directly into the same market: by submitting requests to all the DG connected to its network it can create a new Market (ASM-D) whose aim is to provide reserves and sell them to the TSO on the traditional ASM. The final user could in this way obtain a corresponding revenue according to a load shift or injection modification and the TSO would have the possibility to buy cheaper and greener energy reserves. By receiving signals from the DSO the Balancing Service Provider (BSP) by means of an EMS could evaluate the convenience of accepting energy rescheduling with respect to the one defined before.

For what concerns the Market side, the final user is never informed about the energy costs detected on the Italian Power Exchange (IPEX). Retailers buy electricity on the Day-ahead Market and sell it to the customers with standardized contracts. Usually this contracts offer a fixed price without reporting the fluctuation imposed by the IPEX. In a new scenario the final user could be informed directly by the retailers about the hourly price volatility or even be part of the IPEX itself. An EMS could withdraw from retailers the trend of an entire day and evaluate how to reduce customers’ costs associated by modifying and shifting their electric loads.

4.1 Functionalities

An ***energy management system (EMS)*** is a system of computer-aided tools used to monitor, measure, and control electrical consumption and production. Such a system can be used to centrally control devices like HVAC units and lighting systems across multiple locations, such as retail, grocery and restaurant sites. Energy management systems can also provide metering, submetering, load shifting and monitoring functions that allow facility and building managers to gather data and to make more informed decisions about energy activities across their sites.

The EMS has been designed considering all the functionalities listed above with a particular focus on:

- Load shifting: capability to move electrical loads considering energy price, user preferences and generation forecast.
- DSO requests monitoring: capability to monitor DSO requests to reduce/increase withdrawn/injection. The EMS evaluates if accepting a request is economically convenient for user or not considering generation forecast and comfort constraints.

4.2 Input and Output

Figure 1.3 shows the location of the EMS within the smart grid environment. In this figure we can identify input and output of the system and the involved actors: BSP sends time-varying tariffs and DSO requests.

The data provided by the BSP are those that mostly influence the EMS decisions. Thus, we identified two scenarios:

1. **Market driven**: decisions are based on time-varying tariffs
2. **DSO driven**: decisions are based on DSO requests.

In the market driven case the EMS knows time-varying tariffs and schedules programmable loads in convenient moment of the day.

In the *DSO driven* case the EMS receives requests from the distribution network like power injection increase or withdrawal reduction and evaluates if the incentive proposed for loads modification can justify a rescheduling of the controllable devices.

The EMS output is a set of actuation signals that set the operation of the controlled installations.

4.3 Optimization goals

The EMS supports different operational modes which provide a different level of involvement between network and user. In fact, in normal operating mode, the installed the EMS at user’s premises defines set point of loads and generators considering the desired comfort level and the energy price (DAM and ASM) in order to optimize the operation of the entire system according to the optimization goal set by the user (maximum comfort, greater economic return, mixed based on all the previous two).

Maximum comfort goal: the EMS defines the set point of loads and generators in order to ensure maximum availability and functionality of all the equipment in accordance with the needs of the user, obtained whether through the processing of the historical energy usage data or on real-time commands from the user. In this scenario the EMS will not provide services to the network (only emergency actions will be available) and economic signals coming from the market will be ignored.

Maximum economic return goal: the EMS defines the set point of loads and generators in order to ensure maximum revenue for the user through active participation to the market; loads will be modulated considering price information coming from the market (DAM). In this scenario user’s needs will be ignored, so this means that equipment may be controlled ignoring the real-time commands from the user.

Mixed goal: the EMS combines "maximum comfort" and "maximum economic return". Considering the historical energy usage data and the energy price the EMS defines the set point of loads and generators in order to maximize a weighted sum of comfort and economic return. In order to provide network services the EMS will consider the availability of the user to change his own consumption pattern in exchange for an economical reward.

4.4 Case Studies

In the following we introduce two case studies in which an EMS is in design/implementation phase. We adopted a bottom-up design approach by integrating the EMS with existing systems. In some cases, the conservative approach of hardware and software introduces inefficiencies. For example in SCUOLA project the data regarding recharging station for electrical vehicles are gathered by Ducati before being transmitted to the EMS. So the main purpose of these implementations is not to realize the perfect software but to manage and merge different systems under a single macrosystem.

The EMS was designed based on the requirements of the following two case studies.

4.4.1 Fortiss Smart Energy Living Lab

The Fortiss Smart Energy Living Lab is envisioned as a smart microgrid node. The so called prosumer (i.e. a system that can produce, consume, and store energy) focuses on commercial or office environments and is an example for adaptive control and responsive behavior. Based on the current and predicted generation of renewable energy and on the available storage capacity, it is possible to control office appliances in order to achieve a better utilization of energy. Imagine a sunny day, which leads to an overproduction of the solar energy generation. Once the batteries of the storage bank are fully charged, the surplus could be used to cool down the server room more than usual. Hence, the server room has not to be cooled down for a longer period of time. Alternatively, taking the current energy prices into account, the excess energy can be feed into the network to achieve an economic profit. Another scenario related to dynamic energy prices is the switching between islanded and grid connected mode. Again, mechanisms for efficient energy use can be used to avoid prolonged high price periods.

Smart Energy Living Lab requirement is a market driven EMS. Our goal was the design and implementation of a component of the EMS as a web service. Such component, named Optimizer, is responsible of defining the optimal energy consumption schedule of the Fortiss building.

4.4.2 Smart Campus as Urban Open LAbs (SCUOLA)

SCUOLA project have as its main objective the study and design of a new smart network architecture achieving the most advanced capabilities for electric service, integrating the management of distributed generation, storage systems, the charging infrastructure for electric vehicles, buildings and citizens.

A detailed view about the project is presented in Chapter 6, here we are just focusing on requirements. Some milestones of the project:

- Introducing innovative photovoltaic panels with integrated storage system and contemporary heat production.

- Realization of a new service of demand response which allows the DSO to ask the citizens for a support in case of need offering them an economical reward.
- Introducing electric vehicle charging infrastructures which can be managed with the network rules and integrated in home energy management systems.
- Presentation of a new service which allows the citizens to be informed about their actual energy consumption and production for questions connected to environmental issues.

SCUOLA requires both a *market driven* and a *DSO driven* EMS. Our goal was the realization of two components of the EMS: the energy Optimizer and a recharging Station Manager for electric vehicles. The SCUOLA project includes the deployment of two demonstrators:

1. Institute
2. Domestic

In demonstrator 1 the final user interacts with both the retailer and the BSP so this demonstrator requires both a *market driven* and *DSO driven* EMS. In demonstrator 2 the final user interacts only with retailer so the requirement is for a *market driven* EMS.

Chapter 5

Case study Fortiss Smart Energy Living Lab

5.1 Overview

The Optimization Web Service (OWS) provides optimization services for the Energy Management System (EMS), which is responsible for collecting measurements and instructing actuators within the managed environment.

The OWS locally runs a database to store the data received from the EMS, which are subsequently used as input for the optimization process. Moreover, the database stores optimization results for the EMS. This approach has some advantages:

- The EMS can whether send a single data value or multiple values at each call
- The EMS can update single data in real-time and ask for further optimizations on demand

It is responsibility of the EMS to provide all the necessary data. Once all data are available at the OWS, the EMS can submit a request to start the optimization process.

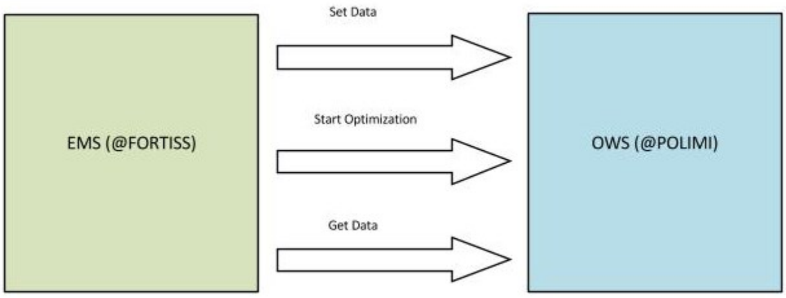


Figure 5.1: Interaction between EMS (Smart Energy Living Lab) and OWS (Politecnico di Milano)

We chose a stateless communication type between EMS and OWS and to guarantee a proper level of security we chose HTTPS protocol. At each interaction with the OWS, the client has to provide authentication data (username and password).

5.2 Architecture

We chose a LAMP architecture to cover OWS functionalities. LAMP is an open source Web development platform that uses Linux as the operating system, Apache as the Web server, MySQL as the relational database management system and PHP as the object-oriented scripting language (sometimes Perl or Python is used instead of PHP).

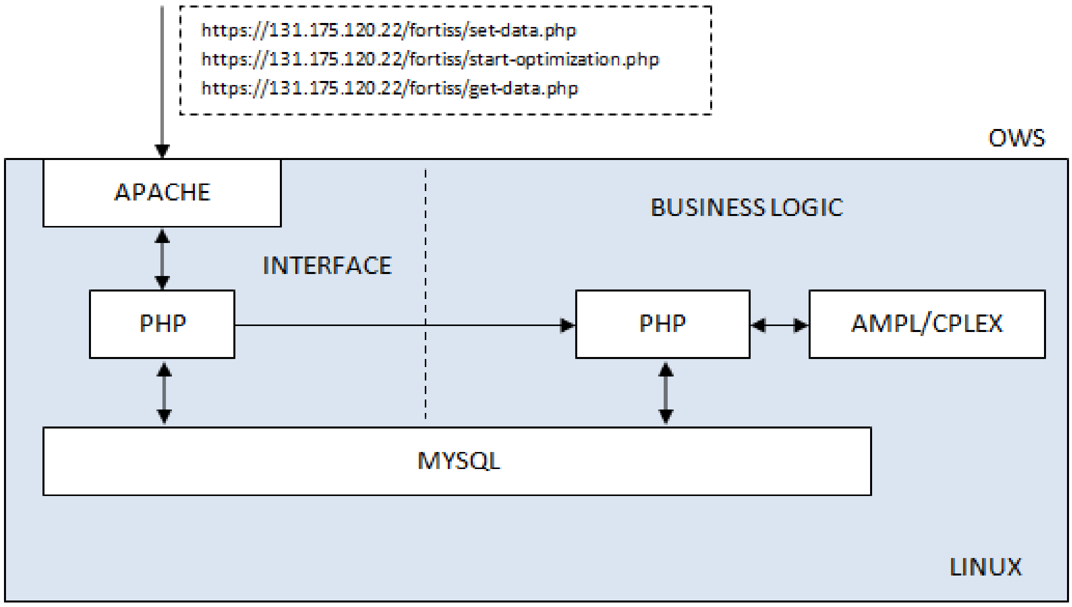


Figure 5.2: OWS software components and logical split between interface and business logic

Fig. 5.2 shows software components and interaction between them. Also we can see the separation between interface component and business logic component.

5.3 Interaction

The client interacts with the OWS through actions. In table 6.1 the possible actions are listed.

Table 5.1: Actions exposed by OWS

URL (ACTION)	PROTOCOL	METHOD	DESCRIPTION
https://131.175.120.22/fortiss/get-data.php	HTTPS	POST	Action to retrieve data
https://131.175.120.22/fortiss/set-data.php	HTTPS	POST	Action to insert/update the DB
https://131.175.120.22/fortiss/start-optimization.php	HTTPS	POST	Action to start optimization

5.3.1 Sequence Diagrams

The following figures show the main processing steps regarding get-data.php (fig. 5.3), set-data.php (fig. 5.4) and start-optimization.php (fig. 5.5)

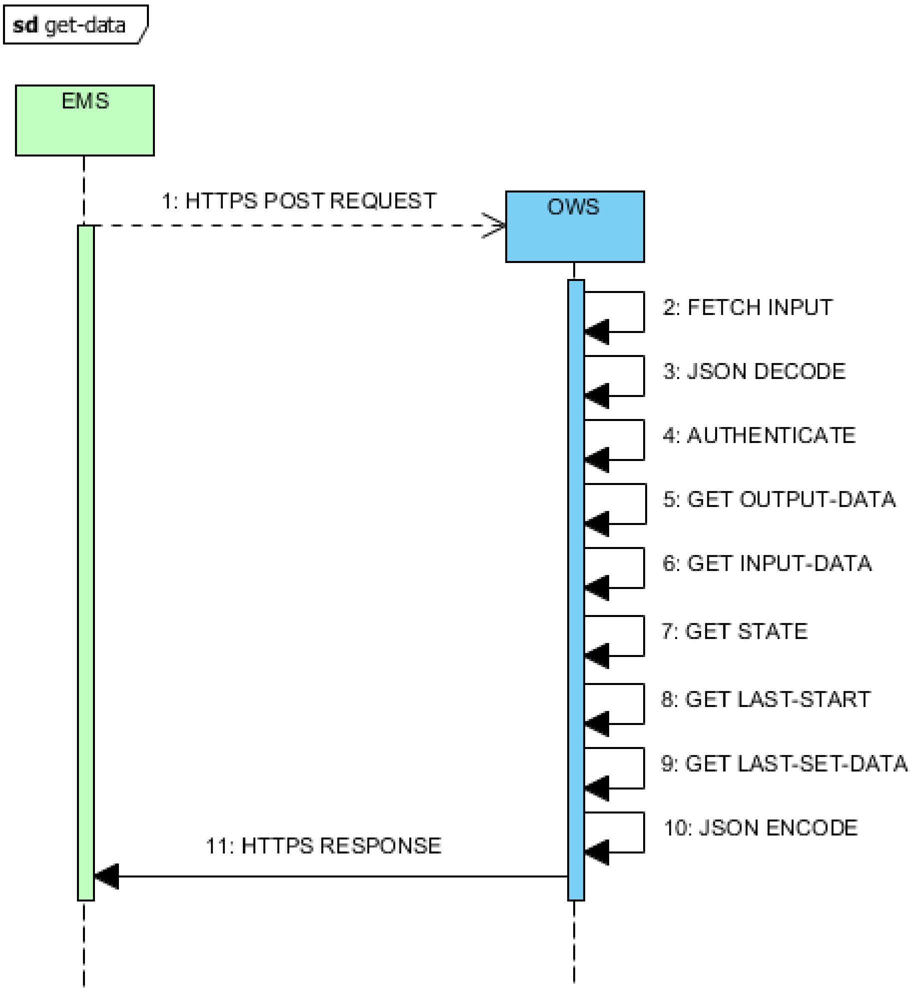


Figure 5.3: OWS get-data action main processing steps

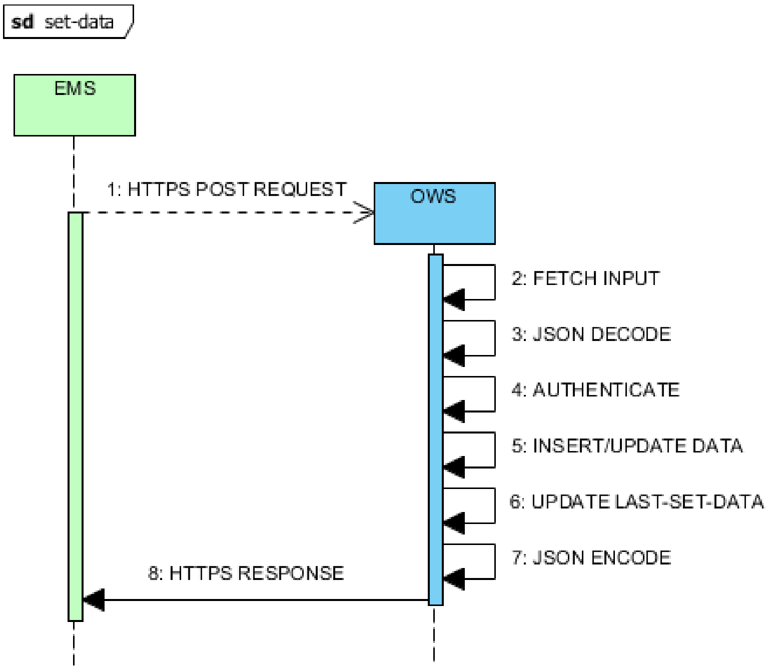


Figure 5.4: OWS set-data action main processing steps

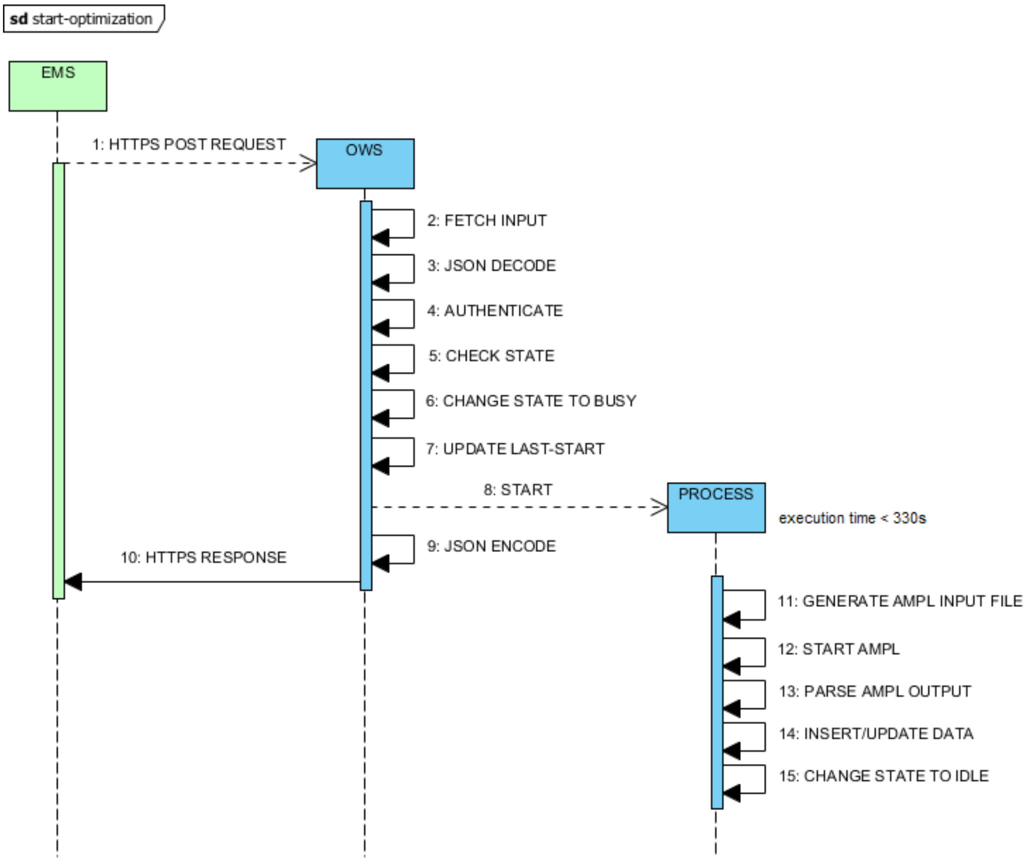


Figure 5.5: OWS start-optimization action main processing steps

5.3.2 Deterministic Automaton

The interaction has been designed in order to allow for one optimization per time. If a start-optimization request is submitted to OWS then no further start-optimization will be accepted till the end of the optimization (busy state). In busy state the EMS is allowed to submit only get-data and set-data requests. The maximum time in busy state is limited to 330s.

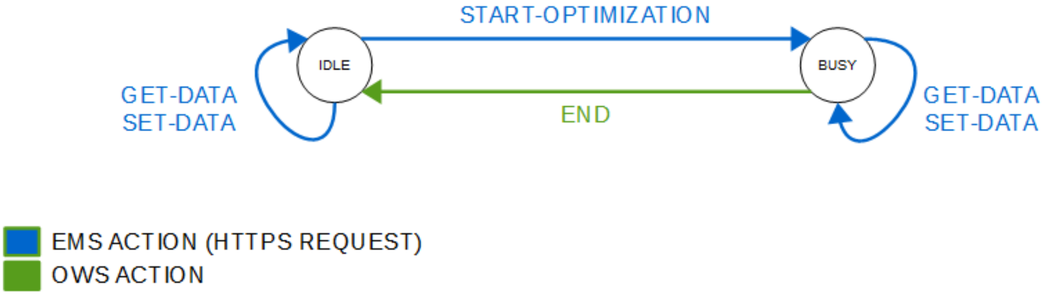


Figure 5.6: OWS automaton

5.4 Data exchange: JSON format

The EMS and the OWS exchange data in JSON format. JavaScript Object Notation (JSON) is an open standard format that uses human-readable text to transmit data objects consisting of attribute–value pairs. It is used primarily to transmit data between a server and web application. The structure of the exchanged JSON objects depends on performed action. The associations between actions and JSON structures are shown in tables 5.2, 5.3 and 5.4.

5.4.1 JSON Objects Description

Table 5.2: OWS START-OPTIMIZATION action JSON structures

https://131.175.120.22/fortiss/start-optimization.php

HTTPS POST REQUEST OBJECT

```
# main json object
{
 "authentication" : {
          "password" : "fortiss",
          "username" : "fortiss"
 }
}
```

HTTPS POST RESPONSE OBJECT

```
# main json object
{

}
```

```
# errors
If errors occur:
{
 "error" : "Error: Authentication Failed"
}

or

{
 "error" : "Invalid action: …"
}

otherwise:

{

}
```

Table 5.3: OWS GET-DATA action JSON structures

https://131.175.120.22/fortiss/get-data.php

HTTPS POST REQUEST OBJECT

```
# main json object
{
 "authentication" : {
            "password" : "fortiss",
            "username" : "fortiss"
 },
 "input-data" : [ "pv_pred", "undef_pred", ... ],
 "range" : {
            "begin" : "2014-07-19 01:45:00",
            "end" : "2014-07-19 02:00:00"
 },
 "output-data" : [ "y", "z", ... , "def_ch" ]
}
```

HTTPS POST RESPONSE OBJECT

```
# main json object
{
"output-data" : {
            "y" : [...],
            "z" : [...],
        ...
},
"input-data" : {
            "pv_pred" : [...],
            "undef_pred" : [...],
        ...
 },
"state" : "idle",
 "last-start" : "2014-08-01 00:04:23"
"last-set-data" : "2014-07-31 23:56:12"
}
```

HTTPS POST REQUEST OBJECT

some details

"input-data" is an ARRAY of STRINGS
"output-data" is an ARRAY of STRINGS
"range" is an OBJECT with 2 FIELDS: "begin" and "end"

HTTPS POST RESPONSE OBJECT

```
# detailed element (vector)
...
"y" : [
            {
            "timestamp" : "2014-07-19 01:45:00",
            "value" : 885.71
            },
            {
            "timestamp" : "2014-07-19 02:00:00",
            "value" : 1130.19
            }
            ],
...
```

HTTPS POST REQUEST OBJECT

```
# possible input
...
"input-data" : [ "pv_pred", "undef_pred",
"plug_pred",
"b","bc","br",
...
]
...
```

HTTPS POST RESPONSE OBJECT

```
# detailed element (matrix)
...
"def_ch" : [
            {
         "timestamp" : "2014-07-19 01:45:00"
            "def1" : 0,
            "def2" : 0,
            "def3" : 0,
            "def4" : 1,
            "def5" : 0,
            "def6" : 0
            }, ... ],
...
```

Table 5.4: OWS SET-DATA action JSON structures

https://131.175.120.22/fortiss/set-data.php

HTTPS POST REQUEST OBJECT	HTTPS POST RESPONSE OBJECT

```
# main json object
{
 "authentication" : {
            "password" : "fortiss",
            "username" : "fortiss"
 },
 "input-data" : {
            "pv_pred" : [...],
            "undef_pred" : [...],
       ...
},
}
```

```
# main json object
{

}
```

```
# detailed element (vector parameter)
...
"pv_pred" : [
            {
            "timestamp" : "2014-07-20 01:45:00",
            "value" : 115.82
            },
            {
            "timestamp" : "2014-07-20 02:00:00",
            "value" : 0.404494
            },
       ...
       ,
            ],
...
```

```
# errors
# If errors occur:

{
 "error" : "Error: Wrong Structure"
}

# otherwise:

{

}
```

```
# detailed element (matrix parameter)
...
"plug_pred" : [
            {
           "timestamp" : "2014-07-20 02:45:00"
            "def1" : 0,
            "def2" : 0,
            "def3" : 0,
            "def4" : 1,
            "def5" : 0,
            "def6" : 0
            },
       ...
       ,
            ],
...
```

5.4.2 Input Data

In order to perform the optimization some input data are required. In table 5.5 a detailed list about input parameters required by the mathematical model is presented. In this table we can also see the JSON objects data type and their structures.

Table 5.5: OWS input data details and descriptions

NAME	TYPE	OBJECT FIELDS	FIELD TYPE	DESCRIPTION
pv_pred	ARRAY[OBJECT]	timestamp	STRING	forecasted solar panel production
		value	NUMBER	
undef_pred	ARRAY[OBJECT]	timestamp	STRING	forecasted energy consumption of undeferrable loads
		value	NUMBER	
plug_pred	ARRAY[OBJECT]	timestamp	STRING	1 if app d is expected to be plugged at time t, 0 otherwise
		def1	NUMBER	
		…		
		def6	NUMBER	
def_b_pred	ARRAY[OBJECT]	timestamp	STRING	forecasted battery level at initial plug-in time of defer app
		def1	NUMBER	
		…		
		def6	NUMBER	
b	ARRAY[OBJECT]	timestamp	STRING	battery level at start-optimization request
		value	NUMBER	
ec_bought	ARRAY[OBJECT]	timestamp	STRING	cost of bought energy
		value	NUMBER	
def_bc	ARRAY[OBJECT]	timestamp	STRING	battery capacity of defer app
		def1	NUMBER	
		…		
		def6	NUMBER	
bc	ARRAY[OBJECT]	timestamp	STRING	battery capacity
		value	NUMBER	

NAME	TYPE	OBJECT FIELDS	FIELD TYPE	DESCRIPTION
zdef_br	ARRAY[OBJECT]	timestamp	STRING	battery charge/discharge rate of defer app
		def1	NUMBER	
		…		
		def6	NUMBER	
br	ARRAY[OBJECT]	timestamp	STRING	battery charge/discharge rate
		value	NUMBER	
def_bm	ARRAY[OBJECT]	timestamp	STRING	battery minimum charge level of defer app
		def1	NUMBER	
		…		
		def6	NUMBER	
bm	ARRAY[OBJECT]	timestamp	STRING	battery minimum charge level
		value	NUMBER	
ec_sold	ARRAY[OBJECT]	timestamp	STRING	income from sold energy
		value	NUMBER	
peak	ARRAY[OBJECT]	timestamp	STRING	maximum amount of bought/sold energy and load per time slot
		value	NUMBER	
lost	ARRAY[OBJECT]	timestamp	STRING	lost energy per time slot
		value	NUMBER	

5.4.3 Output Data

The optimization process returns a set of variables that indicate the optimal operation mode. In table 5.6 we enlist such variables. In this table we can also see the JSON objects data type and their structures.

Table 5.6: OWS output data details and descriptions

NAME	TYPE	OBJECT FIELDS	FIELD TYPE	DESCRIPTION
xc	ARRAY[OBJECT]	timestamp	STRING	amount of energy charged into the battery at time t
		value	NUMBER	
xd	ARRAY[OBJECT]	timestamp	STRING	amount of energy discharged from the battery at time t
		value	NUMBER	
must_ch	ARRAY[OBJECT]	timestamp	STRING	1 if battery must be charged at time t
		value	NUMBER	
y	ARRAY[OBJECT]	timestamp	STRING	energy bought at time t
		value	NUMBER	
z	ARRAY[OBJECT]	timestamp	STRING	energy sold at time t
		value	NUMBER	
def_ch	ARRAY[OBJECT]	timestamp	STRING	1 if deferrable app d is charged at slot t, 0 otherwise
		def1	NUMBER	
		…	STRING	
		def6	NUMBER	
isl	ARRAY[OBJECT]	timestamp	STRING	1 if working in islanded mode, 0 otherwise
		value	NUMBER	

Chapter 6

Case study SCUOLA project

6.1 Overview

In November 2013 the public Administration of Milan and Brescia funded project called Smart Campus as Urban Open LAbs (SCUOLA) with the purpose of promoting smart grids applications. The main goal was to investigate innovative generation from renewables technologies for green energy generation, a way for improving building thermal and energy efficiency and the role of telecommunications technologies to improve citizens' livability and city participation. The central actor involved in this project is the Italian electricity network which aims to an higher level of smartness in order to integrate more and more distributed generation units for electric power supply, heating and cooling and coupling them with new energy backup systems and conventional plants. Citizens are the beneficiaries of this improvements and thanks to the urban infrastructure and resources' sharing (like urban sensors, protections, automations), the cost associated is relative low. Here in details the cornerstones of the project:

- Monitoring and managing network resources for coordinating distributed generation and the other loads through smart devices settled in the Secondary Substation (SS) for improving the quality of the service.
- Introducing innovative photovoltaic panels with storage system integrated and contemporary heat production.
- Introducing new heat pumps with augmented efficiency with a backup system for storing thermal potential.
- Introducing electric vehicle charging infrastructure able to be managed with the network rules and be integrated in home energy management systems
- Realization of a new service of Demand-Response which allows the Distribution System Operator to ask the citizens for a support in case of congestions, unbalancing or security problem on the network.
- Presentation of a new service which allows the citizens to be informed about their actual energy consumption and production for questions connected to environmental issues.

- Analyzing the results of the previous applications for evaluating the level of improving and repeatability for different contexts.

All the innovative elements mentioned before will be installed in the city of Brescia and Milan and accurately tested for several months.

The main participants for the implementation of SCUOLA are two institutes, Politecnico di Milano and Università degli Studi di Brescia, four companies well known in the energetic field and seven small and medium enterprises coming from Lombardy. Campuses of the two universities will be the location for demonstrators realization and future tests.

Innovative ICT sponsored by these emerging enterprises can hence be used and investigated in an academic environment which represents a place under continuous research and development.

The solutions under study are mainly two different contexts in which the coordination and coupling of heterogeneous power absorbers and generators can have a positive influence on the whole system. These two scenarios have been chosen due to their widespread nature in all the developed society and their possible repeatability.

The first case analyzed is a domestic context with an high technology level which can hypothetically represent, in a close future, a realistic independent home building connected to the low voltage network. The house selected for applying the innovative solutions presented in SCUOLA is a villa located in the province of Brescia.

The second case regards a complete different kind of final user: the two universities of Milan and Brescia has been investigated, thus including medium voltage customers in the evaluation of performances of such a system.

6.2 Architecture

With respect to the FORTISS case, for the SCUOLA project several improvements and changes has been applied even though the logic structure has been preserved. The whole physical system has been modeled as a set of ***Locals***. A Local can be whether a physical space or an abstract concept. Every Local has an ***Observable Environment***, which represents a collection of ***Observable Entities***. An Observable entity can be whether a conventional physical quantity (e.g. temperature, humidity, solar radiation) or an abstract one.

An ***Electric Plant*** works on a non-empty collection of Observable Entities of a specific Local and is responsible for their modification during all the day. It can act on the physical system through the ***Electric Actors*** aggregated.

An Electric Actor is a subsystem strictly related to a device or a collection of devices whose scope is to absorb and/or supply electric energy for a specific purpose. All the charging stations of the system compose the Electric Actor for the vehicle charging subsystem. The heat pumps used for heating and cooling are grouped in the Thermal subsystem which is again an Electric Actor.

The atomic unit of time is the so called ***Timeslot*** which correspond to a specific and fixed number of seconds. A collection of timeslots is called **Time Horizon.**

Each Electric Actor can provide a collection of eligible ***Power Profiles*** which are vectors containing, for each Timeslot, the quantity of available/required power. Varying the choice of a Power Profile, the Observable Environment, through the action of the Electric Actors, can change significantly.

A ***Demonstrator*** is a collection of Electric Actors referred to Electric Plants which have to compete for the primary source needed. Scope of an Energy Management System (EMS) is to act as a referee for a fair share of the primary source among all the Electric Actors.

The EMS is mainly composed by two actors: the Optimizer (OPT) and the Profile Generator (PG). The solution adopted is briefly summed up in fig. 6.1

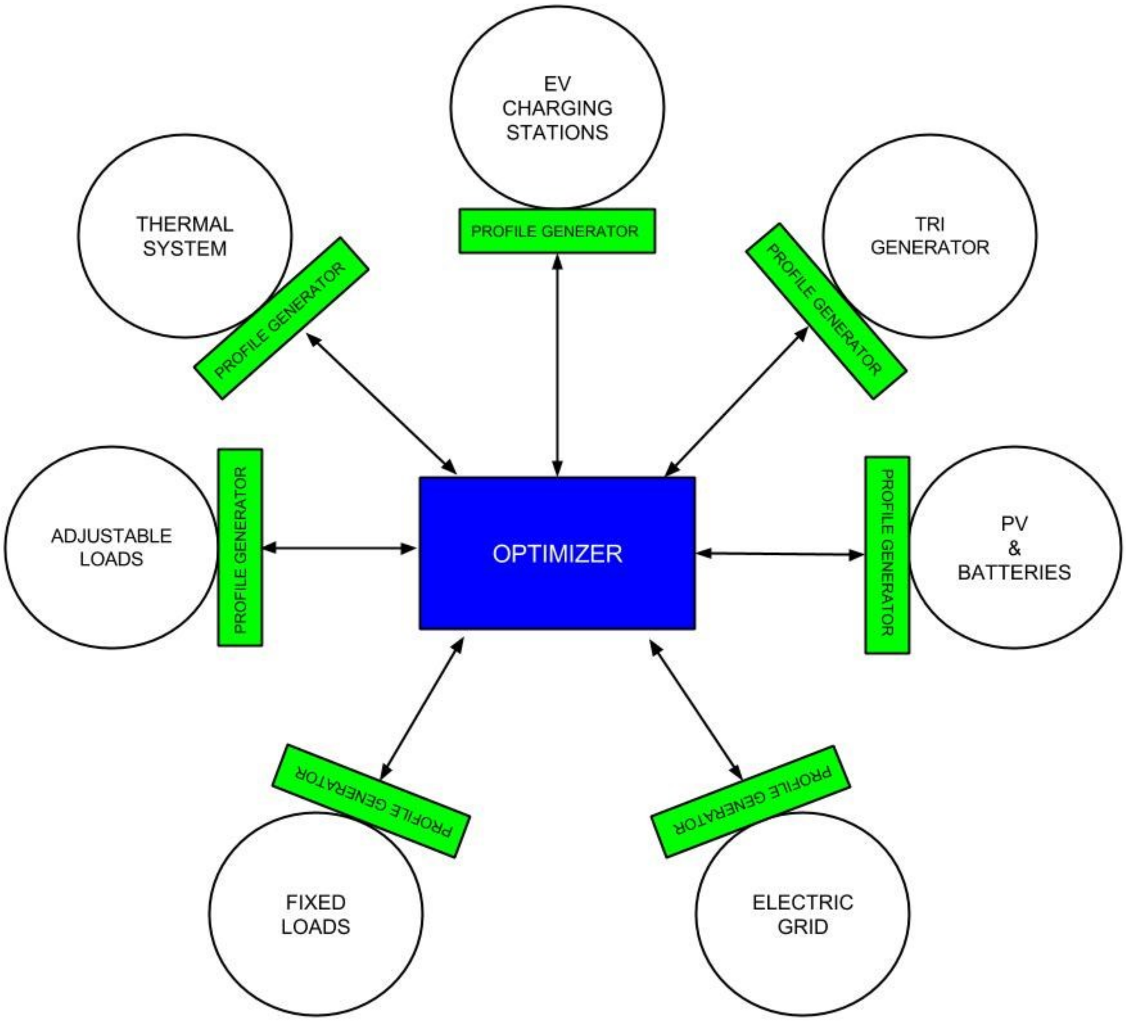


Figure 6.1: Conceptual scheme regarding the EMS architecture for the SCUOLA project: White circles represent the Electric Actors to which correspond a specific Profile Generator (in green). The optimizer (in blue) collects all the information coming from

The ***Optimizer (OPT)*** can be seen as the core of the whole system: it includes a ***Solver*** part for the computation of the optimal energy usage schedule and a ***Business Logic*** able to activate all the procedures, acquire all the necessary data for computation, manage and control the behavior of the other system components and provide them the solver results.

The Optimizer communicates directly with the ***Profiles Generators (PG)*** of the system: for each electric actor, which could be a generator or an absorber a Profiles Generator has been created with the aim of subdividing the amount of work and different requirements of the subsystem for the generation/consumption estimation. Each Profile Generator is in charge of creating and presenting different possible active Power Profiles spread along the subsequent hours. The Optimizer (in particular the Business Logic) will decide to start an optimization process once a timeslot (or a time horizon set as default) has elapsed and the calculation will find out, for every subsequent timeslot, the best Power Profile among all the profiles passed by the Profile Generator of the Demonstrator from the call moment till the end of the day (h.23:59).

Every Profiles Generator acts as a web service able to answer to specific requests coming from the Optimizer, which acts as the only client of the system. The communication protocol between the Optimizer and a generic Profiles Generator is reported in the next section.

6.3 Interaction Optimizer-Profile Generator

Once the Business Logic decides that is time for running a new optimization procedure, it alerts all the Profiles Generators of the electric actors it wants to include in the computation through a request of ***start***. Once the start request received all the involved Profiles Generators reset their previous results, finish their own calculations and get ready for the next requests. At this point the Optimizer can ask for new active power profiles: it calculates upper and lower limits for active and, eventually, reactive power for each time scheduled according to forecasted power availability and physical limitations imposed by the devices. Hence, it submits to the involved PGs a new request, ***set-power-band*** reporting their specific power limitations. Once accepted, every PG, using internal algorithms, computes multiple feasible power profiles by relying on information regarding statistical and historical data, users input on real time requirements and limitations imposed by the Optimizer. For each timeslot of the time horizon it has to report the value of the set point as active power expressed in kilowatt hour and a corresponding value of ***comfort*** : the definition of comfort varies according to the considered PG. For example the concept of comfort for the Profiles Generator associated to the heating and cooling actor rests upon the level of satisfaction reported by the end users regarding the living conditions of the room (temperature, humidity) while the one associated to the electric vehicle profiles considers comfort as the distance between the feasible schedules which can be obtained when the EMS is not running and the forecasted set points.

Once all these profiles are available the PG saves them in a local database associating to each of them an identification number ***n*** and concludes the computation. Later the Optimizer can ask for retrieving these results through the command ***get-profiles*** and/or ask for new profile generations with different power limits.

After having received enough profiles from all the Profile Generators participating to this calculation, the Business Logic of the Optimizer elaborates the collected data and weights the corresponding comfort levels coming from different sources in order to make them comparable. Then it withdraws the PUN hourly prices saved by the Real Time Market simulator into the ***Energy Information System*** (EIS), which represents a central database for collecting all the important system data. All the data are sent to the Solver.

Here an Objective Function which minimize costs maintaining an acceptable level of global comfort is applied and the algorithm is able to select, for each electric actor, the profile which better fits. It is important to note that limiting the amount of generated profiles to a subset of all the feasible ones implicitly introduces some sub optimality in the computation of the global energy usage pattern. Such compromise is necessary to ensure acceptable computational times of the Profile Generators and to limit the volume of the exchanged data.

Finally the Optimizer communicates the selected profiles through the corresponding identification number *n* to all the PGs which will then manage the actuation part.

When the Optimizer decides to run a new calculation it can decide to avoid the inclusion of some Profiles Generators. The reason is connected to the hysteresis of the system: some PG may generate provides profiles with a rate that is not compatible with the needs of the other PGs. For example the PG associated to the heating/cooling can schedule its consumption every hour due to latencies imposed by the heat pumps. On the other hand the Electric Vehicle PG needs to update the optimizer with a higher rate in order to cope with unexpected connection requests and power supply. For this reason the Optimizer will inhibit some PG from the

calculation applying the profile chosen for that PG at the last call. The Business Logic has to keep a table which associates to every PGs the corresponding number of timeslots after which the Optimizer is allowed to ask for new profiles.

All the data regarding historical choices and configurations, devices' datasheet, users input and hourly Market prices will be stored in the EIS and used for next computations and for developing an ***observatory*** for monitoring purposes. Figure 6.2 shows the general architecture of the presented EMS.

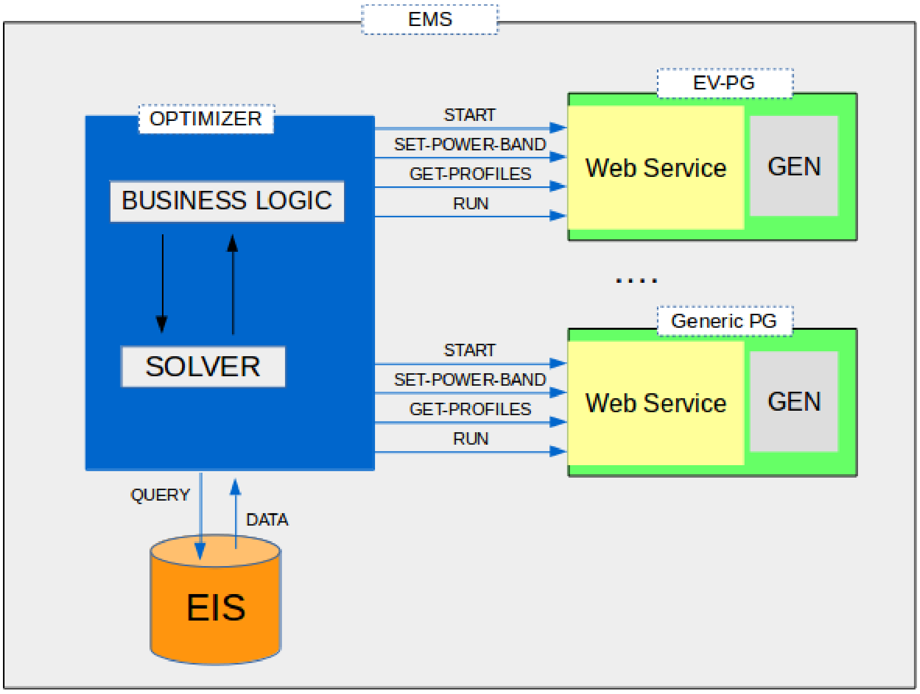


Figure 6.2: EMS description and subsystems' interaction

6.4 Protocol

6.4.1 Input and Output data

As mentioned before every Profile Generator (PG) provides a web service to the Optimizer (OPT). The communication channel established between PG and OPT is used for communicating the following data:

- Minimum and maximum active power (p_t^{MIN} and p_t^{MAX} $\forall t \in T$ where T is the vector containing all the Timeslots) and reactive power (q_t^{MIN} and q_t^{MAX} $\forall t \in T$). These thresholds are computed by the OPT and sent to the PG.
- Power consumption estimated for the profile n, $p_{n,t}$ $\forall n \in N$, $\forall t \in T$ where N is the collection of identification numbers for the profiles. These values are generated by the PG.
- Comfort value for the profile n, $c_{n,t}$ $\forall n \in N$, $\forall t \in T$. These values are generated by the PG
- Identification number of the generated profile, n. These values are generated by the PG
- Expenses not connected to the electrical consumption, $F_{n.}$ These values are generated by the PG

6.4.2 Methods

All the function made available from the web service are here reported:

- ***START()***: The OPT expresses its intention for a new optimization process. The PG cancels all the previous profiles and reset the identification number *n.*
- ***SET-POWER-BAND(p_t^{MIN}, p_t^{MAX}, q_t^{MIN}, q_t^{MAX}):*** The OPT asks for a new profiles generation imposing some limits on the active (p) and reactive (q) power for each timeslot of the time horizon chosen. A new identification number n will be associated to every generated profile.
- ***GET-PROFILES()***: The OPT asks for withdrawing all the generated profiles.
- ***RUN(n*)***: Through this command the OPT orders the PG to actuate the profile with the identification number equal to *n**

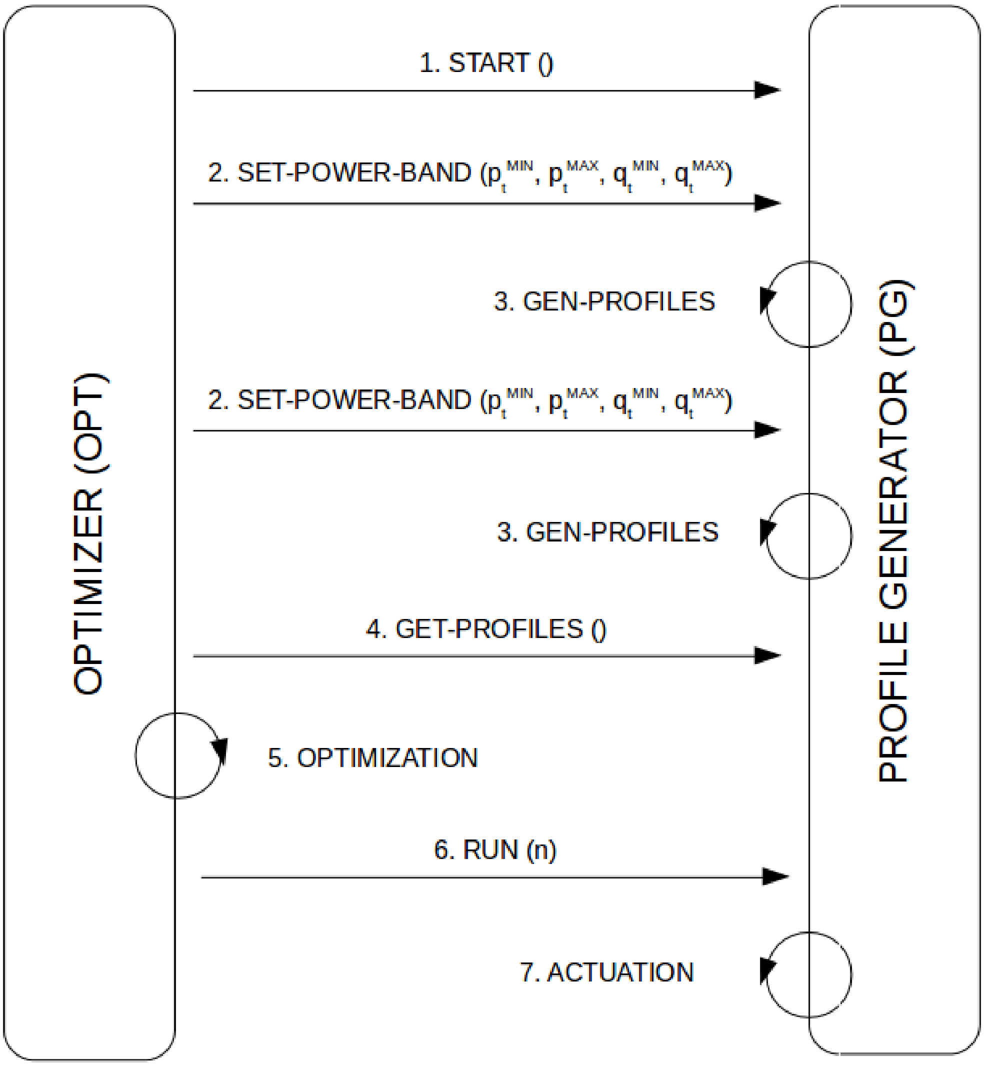


Figure 6.3: EMS communication between the Optimizer and the Profiles Generator

Figure 6.3 shows a typical interaction of the two systems:

1. The OPT sends the PG a START() request to communicate the beginning of the calculation. As a consequence whether the OPT or the PG cancel their previous profiles.
2. The OPT sends the PG a SET-POWER-BAND(p_t^{MIN}, p_t^{MAX}, q_t^{MIN}, q_t^{MAX}) command so that the PG can define a new set of profiles based on the acquired information.
3. The PG actuates its decision algorithms and generates the required profiles associating them an identification number n.
4. The OPT sends a GET-PROFILES() command for retrieving all the profiles generated from the PG.
5. The OPT identifies the profile with the identification number n* which better fits the Objective Function.
6. The OPT sends a RUN(n*) command to the PG for communicating the selected profile n*

If the OPT realizes that new profiles have to be calculated with different thresholds with respect to the previously communicated ones, step 2 and 3 are repeated. Note that during these steps the identification number is never reset.

6.5 Generic Profile Generator architecture

6.5.1 Deterministic Automata

For driving the communication in an correct way avoiding possible conflicts, a processing status has been defined for the PG. This status is uniquely determined and describes the requests that can be satisfied at the current processing time. Figure 6.4 introduces the Finite State Automata realized for a generic PG.

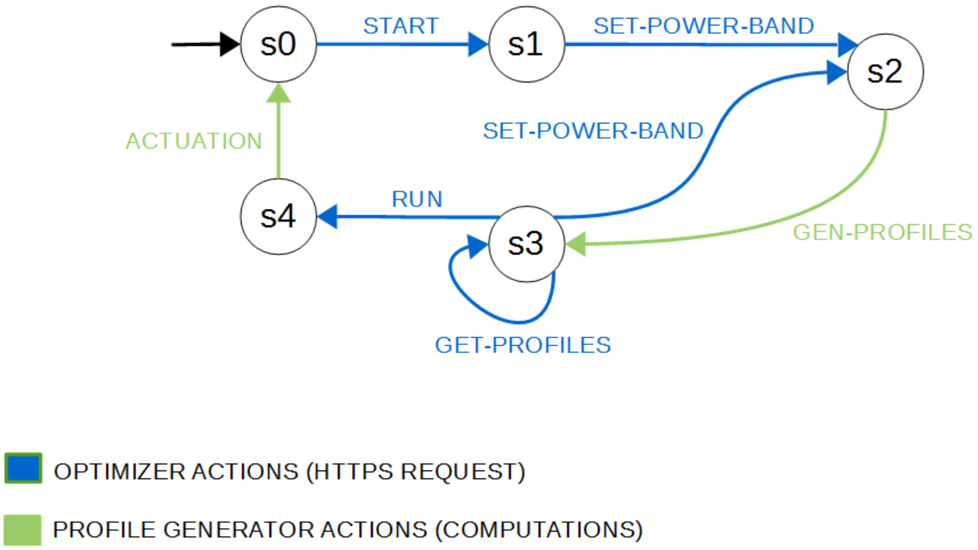


Figure 6.4: Finite State Automata for a generic Profile Generator (PG)

The blue lines represent HTTP requests made available fro the Web Service of the PG to the OPT.

Conversely, green lines indicate PG local procedure. It is possible to reach a generic S_j status from a S_i status only through an HTTP request or the conclusion of a local computation with subsequent acknowledgement message (ack). The current status is entirely managed by the PG which will always check its value before accepting a request submitted by the OPT.

PG status changes are here reported:

S0: Before the beginning of the optimization process the PG status is S0 waiting for new requests. At this point the OPT declares its will for a new calculation. The PG status moves from S0 to S1 and an acknowledgement message is sent back (e.g. an empty message if no problem occurs, a code otherwise).

S1: Afterwards the OPT generates the power limits for each timeslot from the current moment till the end of the day (timeslot containing h.23:59) and sends them to the PG through the SET-POWER-BAND(p_t^{MIN}, p_t^{MAX}, q_t^{MIN}, q_t^{MAX}) request. PG changes its status from S1 to S2. Again an acknowledgement message is sent back to the OPT.

S2: PG runs the GEN-PROFILES procedure whose purpose is to create a new set of power profiles with an associated level of comfort. In this status it is not able to satisfy other requests coming from the OPT. Once the computation is concluded all the generated profiles are saved into the local database and the PG status changes from S2 to S3.

S3: Once reached this status 3 possible alternatives can occur:

1. The OPT asks for a new profile generation with different power limits: a second SET-POWER-BAND(p_t^{MIN}, p_t^{MAX}, q_t^{MIN}, q_t^{MAX}) request is sent to the PG which switches its status back to S2. The identification number n is not reset.
2. The OPT wants to retrieve all the profiles generated through the GET-PROFILES() command. In this case the PG status doesn’t change. This implies that later either a SET-POWER-BAND(p_t^{MIN}, p_t^{MAX}, q_t^{MIN}, q_t^{MAX}) or another GET-PROFILES() can be submitted.
3. The OPT reports the chosen profile among the ones supplied through the RUN(n*). PG status moves from S3 to S4 with a subsequent acknowledgement message.

S4: Once the desired profile n* has been received, the PG runs the ACTUATION procedure and finally moves its status back to S0, closing the communication.

6.5.2 Methods

Besides all the protocol commands, a few service functions have been defined in order to simplify the communication and manage exceptions:

- GET-STATE(): returns to the OPT the current status of the involved PG.
- RESET(): sends the status of the selected PG to S0.

All the functions defined for the communication are reported in tab. 6.1 and tab. 6.2

Table 6.1: EMS-PG service functions

ACTION	PERFORMED BY	EXPOSED BY	PROTOCOL	METHOD	FORMAT
GET-STATE	OPT	PG	HTTPS	POST	JSON
RESET	OPT	PG	HTTPS	POST	JSON

Table 6.2: EMS-PG protocol functions

ACTION	PERFORMED BY	EXPOSED BY	PROTOCOL	METHOD	FORMAT
START	OPT	PG	HTTPS	POST	JSON
SET-POWER-BAND	OPT	PG	HTTPS	POST	JSON
GEN-PROFILES	PG	-	-	-	-
GET-PROFILES	OPT	PG	HTTPS	POST	JSON
RUN	OPT	PG	HTTPS	POST	JSON
ACTUATION	PG	-	-	-	-

6.6 JSON Objects Description

All the information exchanged between the Optimizer and a generic Profile Generator have to respect some requirements for a controlled communication. Since the Profile generations can have different implementation origins, a language-independent data format has been chosen. Due to the PG webservice behavior JSON format has been selected.

Table 6.1 and 6.2 show all the method structures available for the Optimizer. Each of them will be submitted through a POST request. For each call to the PG webservice a JSON file will be generated for communicating login credentials and any data useful for the method return. All the request will receive a response through an acknowledgement message which still consists in a JSON file.

Tables from 6.3 to 6.6 reports the general structure of the JSON file generated for each requests.

Table 6.3: PG START action JSON structures

HTTPS POST REQUEST OBJECT	HTTPS POST RESPONSE OBJECT
# main json object **{** **"authentication" : {** **"password" : "OPT",** **"username" : "OPT" },** **}**	**# main json object** **{** **}**
	# errors **# If errors occur:** **{** **"error" : "Authentication failed"** **}** **# otherwise:** **{ }**

Table 6.4: PG RUN action JSON structures

HTTPS POST REQUEST OBJECT	HTTPS POST RESPONSE OBJECT
# main json object **{** **"authentication" : {** **"password" : "OPT",** **"username" : "OPT"** **},** **"n" : 7,** **}**	**# main json object** **{** **}**
	# errors **If errors occur:** **{** **"error" : "n value does not exist"** **}** **otherwise:** **{** **}**

Table 6.5: PG SET-POWER-BAND action JSON structures

HTTPS POST REQUEST OBJECT

```
# main json object
{

"authentication" : {
            "password" : "OPT",
            "username" : "OPT"
},


"ranges" : [
       {
           "timestamp" : "2015-01-22 12:00:00",
           "p_min": 400,
           "p_max": 1000
       },
       {
           "timestamp" : "2015-01-22 13:00:00",
           "p_min": 500.5,
           "p_max": 900
       },
       ...
       ,
]

}
```

HTTPS POST RESPONSE OBJECT

```
# main json object
{

}
```

```
# errors
# If errors occur:

{
 "error" : "Inconsistent values"
}

# otherwise:

{

}
```

Table 6.6: PG GET-PROFILES action JSON structures

HTTPS POST REQUEST OBJECT

```
# main json object
{

"authentication" : {
            "password" : "OPT",
            "username" : "OPT"
},

}
```

HTTPS POST RESPONSE OBJECT

```
# main json object
{

"profiles" : [
  {"n" : 1,
   "F" : 75,
   "profile" : [
          {
           "timestamp" : "2015-01-22 12:00:00",
           "p": 988.2,
           "c": 85
          },
          {
           "timestamp" : "2015-01-22 13:00:00",
           "p": 744.33,
           "c": 75
          },
          ...
             ]
  },
  {"n" : 2,
   "F" : 10,
   "profile" : [...]
  }
]

}
```

```
# errors
If errors occur:

{
 "error" : "Authentication failed"
}

otherwise:

{

}
```

As reported in the tables, all the request JSON files contain a first information regarding the authentication of the client (the Optimizer) followed by the needed data. The acknowledgement message can be an empty JSON file in case everything has been concluded correctly, or a file reporting error codes.

6.7 A particular case: Electric Vehicle Profile Generator

6.7.1 Electric Actor description

All the case studies belonging to the SCUOLA project have to deal with a charging station for electric vehicle. Such a device has to be taken into account by the EMS for the optimization processes. Each electric vehicle has charging dynamics which in principle are different from the other vehicles. Battery status depends on several variables: temperature, aging, level of battery at the moment of plug connection, etc. Moreover technological improvements allow new charging strategies which are totally different from the ones currently implemented. In Italy, mainly due to these dissimilarities and the lack of a commonly accepted standardization, the charging infrastructure had to face lots of issues. Moreover electric vehicles are still extremely expensive and can not yet compete with the thermal engine counterpart in terms of autonomy. The result is a lack of demand which leads to a slow development of the electric mobility sector. All these difficulties should be sooner or later overcome as done in many other European Countries through the application of green incentives.

The typical behavior of a lithium battery used in an electric vehicle is shown in fig. 6.5.

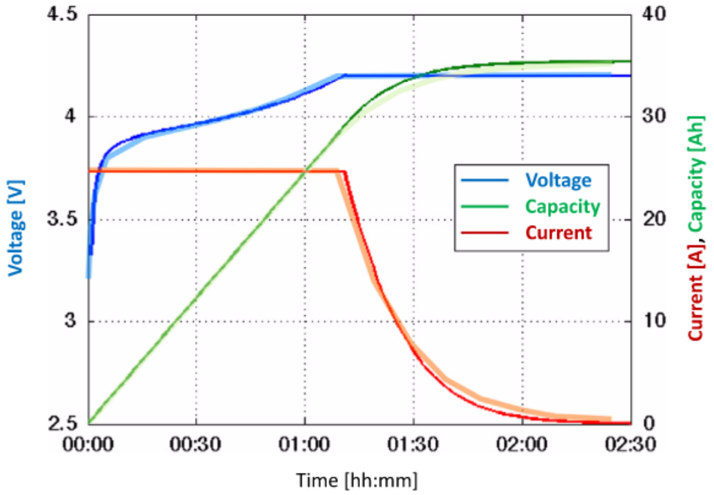


Figure 6.5: Voltage, current and capacity behavior during a lithium battery charge for an electric vehicle [26]

Starting from a complete discharge level of lithium battery, the voltage value increases almost linearly while the current is stable. Once reached around 80% of the total capacity the current starts to decrease exponentially while the voltage is kept constant. The corresponding power profile associated to this chart is constant till the inversion of the two quantities around 80% and starts then to decrease with a steep rate. Once a minimum level of power absorbed is reached, the battery control system disconnects the unit from the network. The time required for a complete charge depends on the amount of supplied power which can vary according to the system infrastructure and the battery technology. It is important to note that once almost the 80% of the total capacity is reached, the time required for charging the remaining 20% is quite high and comparable with the time used for reaching the first 80%. This is due to the nature of lithium cells and not to limitations imposed by the vehicle. Battery capacity varies with vehicle models but is usually around 20-25 kWh (some elite cars can reach the 80-90 kWh).

The main problem related to the interaction between the charging station and the electric vehicles is the almost complete lack of communication: by connecting the car to the plug the cable is just able to recognize if the two sides are connected correctly. According to the reference standard IEC 61851(ISO/TC/SC 69 Electric road vehicles & electric industrial trucks) [24] no other data can be exchanged between the two entities. In particular the level of battery can never be known by the charging station. With no information about this value it is not possible to predict accurately neither the remaining energy to be supplied nor the corresponding reaching time. Moreover it is not possible to read the charge status directly from the battery before reaching the 80% of the capacity. A possible expedient could be an accurate battery model to estimate the current state of charge, in order to replace the missing information from the real system. But such a model requires to know the initial level of batteries. This data cannot be directly read from the charging station but has to be reported by the vehicle user through a dedicated interface. If this information is missing, the charging station can only know if the battery level is lower or higher than 80% by simply reading the amount of supplied power. Hopefully in the future standards on digital communication between the electric vehicle and the station (e.g. ISO 15118 ISO/TC 22/SC 3 Electrical & electronic equipment, 2013 [25]) more data, including general system and battery status, will be exchanged.

For the SCUOLA project all the information readable by the charging station can be accessed by the EMS whose scope aim is to control and schedule the power supplied to the managed electric vehicles of the whole system. Due to their difficult predictability some statistical data regarding users’ habits and needs has been considered. In the next chapters a detailed description of the EV-PG will be presented for both the campus and the domestic case.

6.8 Domestic Case: Low Voltage User

6.8.1 System description

As mentioned before, in the SCUOLA project two different scenarios have been considered. The first is a low voltage user in a domestic context.

The plant scheme is reported in fig. 6.6. Before the intervention, photovoltaic and thermal panels were already in place. New Indra Smart Meters were put in place in series with the existing conventional meters for collecting in real time all the consumption measurements associated to the electrical devices of the house (lightning, refrigerators, washing machine, dish washer,...). The collected data are then sent to an Indra Concentrator which gathers and aggregates all the information and communicate the results to a cloud service through a gateway provided by ADB. Upstream smart plugs have been installed.

For what concerns the generation using the 4.5 kWp photovoltaic plant, a new Inverter has been installed with more advanced capabilities which can respond to all the requests coming from the Distribution System Operator. Downstream another Indra smart meter has been installed for measuring all the production, usage and injection of renewable electricity. All these data are then sent to the same Indra concentrator.

The tenants own two electric cars: a Zoe by Renault and a Model S by Tesla. In order to satisfy their needs related to the recharge of the electric vehicles, a Wallbox made by Ducati Energia has been installed. It is able to supply up to 7kW of electric power and can communicate with an ADSL Wifi Router through an RS232 serial port. Once reached the router all the information are sent to the Ducati control center for monitoring and scheduling.

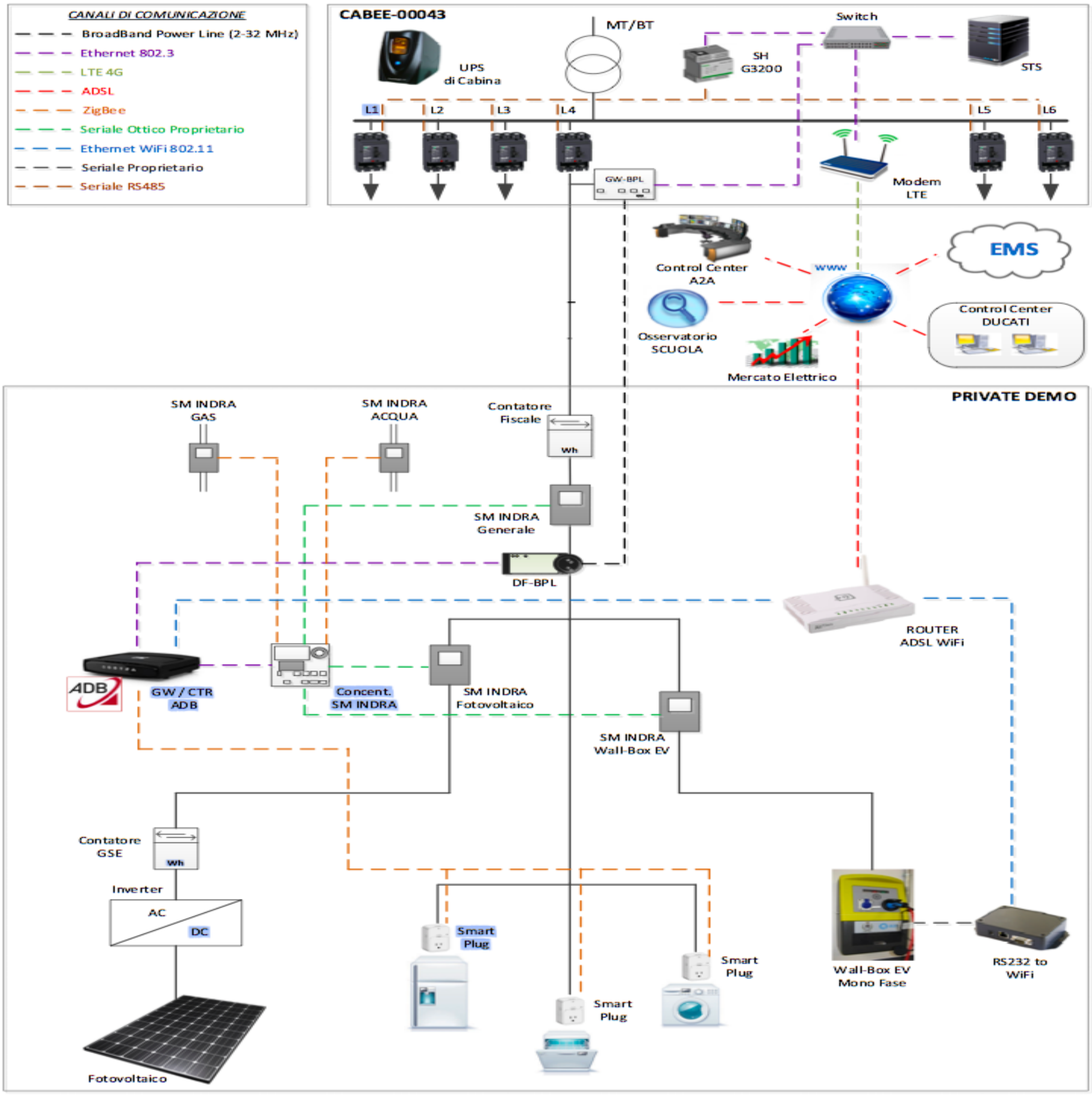


Figure 6.6: Plant scheme for the domestic case [31]

Here the Gateway operates as a filter for actuation: the charging station (called WallBox for the Domestic case) is equipped with an automatic remote tripping which allows the Gateway to disconnect the electric vehicle if problems connected with the stability of the system arise.

Finally an Energy Management System (EMS) has been installed to coordinate the energy production and consumption, improving the efficiency of the house and minimizing the energy bill. For this solution the EMS has been realized as a software participating to the cloud service supplied to the house using a market driven approach (thus neglecting network signals): as shown in previous chapters, the goal of such a system is to combine all the information coming from the Italian Power Exchange (IPEX) and the house owner in order to find the best strategy for scheduling energy utilization during all the day. The EMS also acts as a forecasting system based on historical and statistical data regarding user habits and needs. The system is even able to receive specific input signals from the tenants which can in this way inform and pilot the EMS for the current day. For what concerns photovoltaic panels' production, a forecasting system based on weather conditions is used for predicting hourly energy availability. Moreover, a new Market based on hourly electricity price has been simulated to enable the end users (or the EMS itself) evaluate when to schedule their energy withdrawal and injection. Such a Market is not yet available in Italy but is under investigation.

6.8.2 EMS interaction

For the domestic case the stakeholders of the SCUOLA project decided to include the EMS implementation directly into the cloud service offered by ADB. Due to the need of providing an additional service without compromising the integrity of the whole electric system, two layers have been realized for the electric vehicle WallBox. The first is a ***Stability Layer.*** This layer is responsible for monitoring all the Electric Actors of the Demonstrator trying to avoid, if possible, the disconnection from the grid caused by an overconsumption. The second layers called ***Optimization Layer,*** regards the possibility of modifying all the set points of the electric devices of the building as a result of an EMS economic oriented optimization. This layer can be used only if the Stability Layer is not compromised.

The physical interface between the Stability and the Optimization Layer is the Gateway: it evaluates at regular intervals if the choices made by the EMS for the WallBox can be satisfied or not according to the electrical limitations of that moment.

When the Optimizer decides to launch a new optimization procedure, a start request is sent to all the Profile Generators chosen for the current computation. Each of these reads all the required data from the Energy Information System (EIS) and from internal data storages and produces all the feasible Power Profiles with an associated comfort value which will be later sent back to the Optimizer. Once the selected profiles are returned, the actuation phase begins. in particular the Electric Vehicle Profile Generator sends all the vector containing power set points to the corresponding Gateway. Here all these values are stored and at once per second the power value to be imposed to the actuators for the current Timeslot. will be compared with the power limits necessary for the correct power balance of the whole system.

The Gateway imposes the minimum power amount between the two following values:

$$P_{set} = MIN\ (P_{OL} ; P_{SL})$$

where P_{set} represents the overall power level imposed to the actuators, P_{OL} is the power chosen by the Optimization Layer and P_{SL} the power imposed by the Stability Layer.

In order to better explain this concept a use case is here reported: at a certain moment of the morning the photovoltaic plant is producing 1kW of power. The contractual maximum absorption is 4.5kW and in the considered moment such amount is reached due to the power consumption of several electric devices. The EMS will set the Wallbox power at 1kW, which equals the production by the photovoltaic plant, thus recharging the vehicle connected with that rate. If a new device is then turned on the overconsumption of energy coming from the network would let the domestic smart meter trip in a while. Thanks to a fast response local controller installed into the Gateway, the WallBox meter trips before the domestic one, thus interrupting the electric vehicle charge. As a consequence 1 kW produced by the photovoltaic plant is now available and usable for other electric devices,hence avoiding disconnection of the house from the grid. The solution implies that the electric vehicle will be always charged with the remaining power coming from the energy balance of all the other actors. Figure 6.7 reports the interactions between all the agents mentioned up to now.

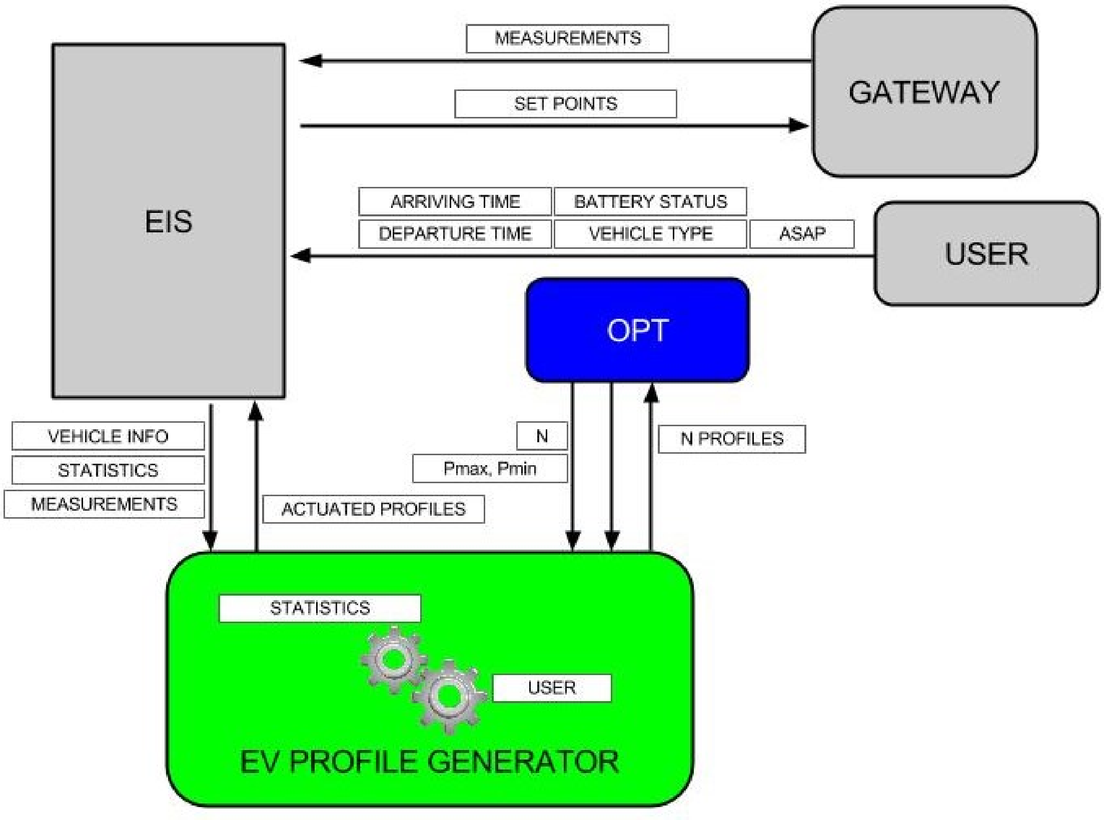


Figure 6.7: Systems interactions for the domestic case.

For the domestic case the Electric Actors are:

- the 4,5 kWp Photovoltaics seen as a Generation Actor
- the 4,5 kW Smart meter which gathers all the electric devices
- the 7kW Electric vehicle WallBox

In the next chapter the Profile Generator of one of these Electric Actors will be discussed in detail.

6.8.3 Electric Vehicle Profile Generator for the Domestic Case

In a scenario with only two vehicles the predictions made by the Electric Vehicle Profile Generator EV-PG are difficult to be reliably formulated using statistical data. Moreover for this Electric Actor small errors in the estimation of energy supply can heavily affect the energy balance of the whole Demonstrator.

The first issue to be addressed is the time and frequency on which the vehicle is plugged in: EMS needs to know when and how long the user will be connected to the WallBox in order to modify or shift the energy injection time during the day. Unfortunately this information can exhibit remarkable fluctuations according to the user’s lifestyle.

For this reason, the EV-PG has been designed in order to learn day after day the tenants' vehicle recharge patterns. EMS can deduce this information whether from the past data or from input coming directly from the user. According to the collection of historical data stored in the Energy Information System (EIS) the EV-PG can compute some statistics and estimate for the day of interest the time interval in which the electric car is supposed to be connected to the WallBox. From the same data it can even deduce the average energy amount to be scheduled for the recharge. With this two information mixed with the power thresholds coming from the Optimizer the EV-PG is able to create different Power Profiles by simply modifying, shifting and subdividing the power curves whose total area has to be equal or less than the amount of energy required according to the corresponding comfort level. For this PG comfort has defined as the ratio between the level of charge reached with the optimization process and the level of charge which would have reached if the EMS was not turned on. In other words it can be associated to the efficiency of the recharging system. If the car is plugged in for a sufficient time to provide an entire charge up to 100% but due to EMS choices at the end of the period considered the battery level only reaches 80%, the comfort associated to that profile is 80%.

The EV-PG can even accept input from the users: If the tenants know how long the vehicle will be plugged in, they can send this information through a dedicated interface (web service, smartphone application, etc.). In the same way they could even report the vehicle model and battery status at the moment of connection. All this data are stored into the EIS. If input from the user are available the EV-PG does not consider the historical data under the assumption that the new data acquired are more reliable.

Figure 6.8 shows all the profiles received and generated by the EV-PG when the optimizer decides to run a new optimization under the assumption of having a timeslot equal to 60 minutes.

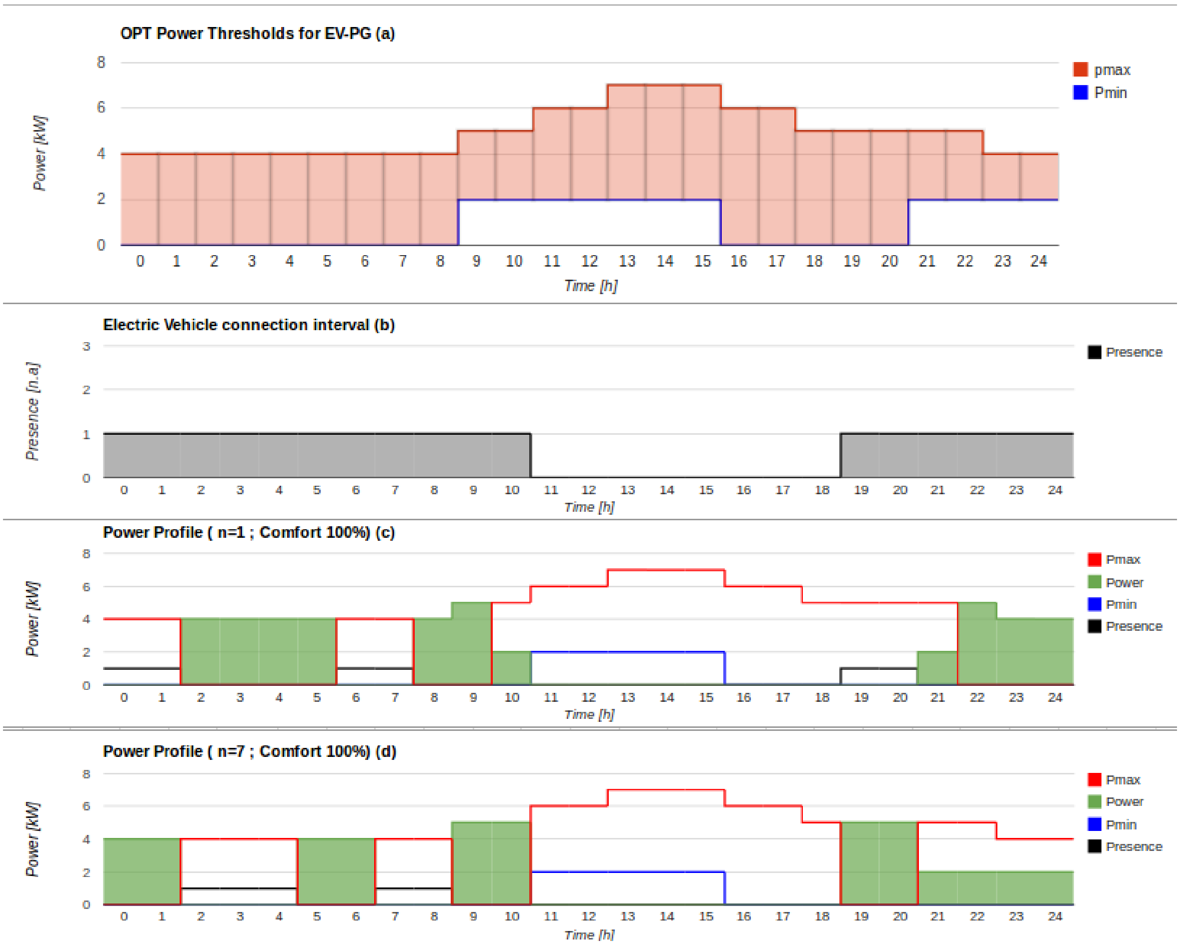


Figure 6.8: General sequence of profiles managed by the EV-PG during an optimization process. Timeslot = 60 min. Profile (a) reports the thresholds received from the Optimizer, (b) is the presence profile of the vehicle connected to the WallBox according

The EV-PG receives the maximum/minimum power thresholds from the Optimizer. Then, according to statistical data coming from the EIS or user input it generates a profile reporting the time intervals in which the car is supposed to be connected to the WallBox. Finally, knowing the total energy required (obtained by formulating some hypothesis or through an explicit acknowledgment of the battery status), it can generate some feasible Power Profiles with an associated level of Comfort.

Due to the different choices the profile generator can make according to the available information, a data flow diagram has been reported in fig. 6.9 for better illustrating the different use cases.

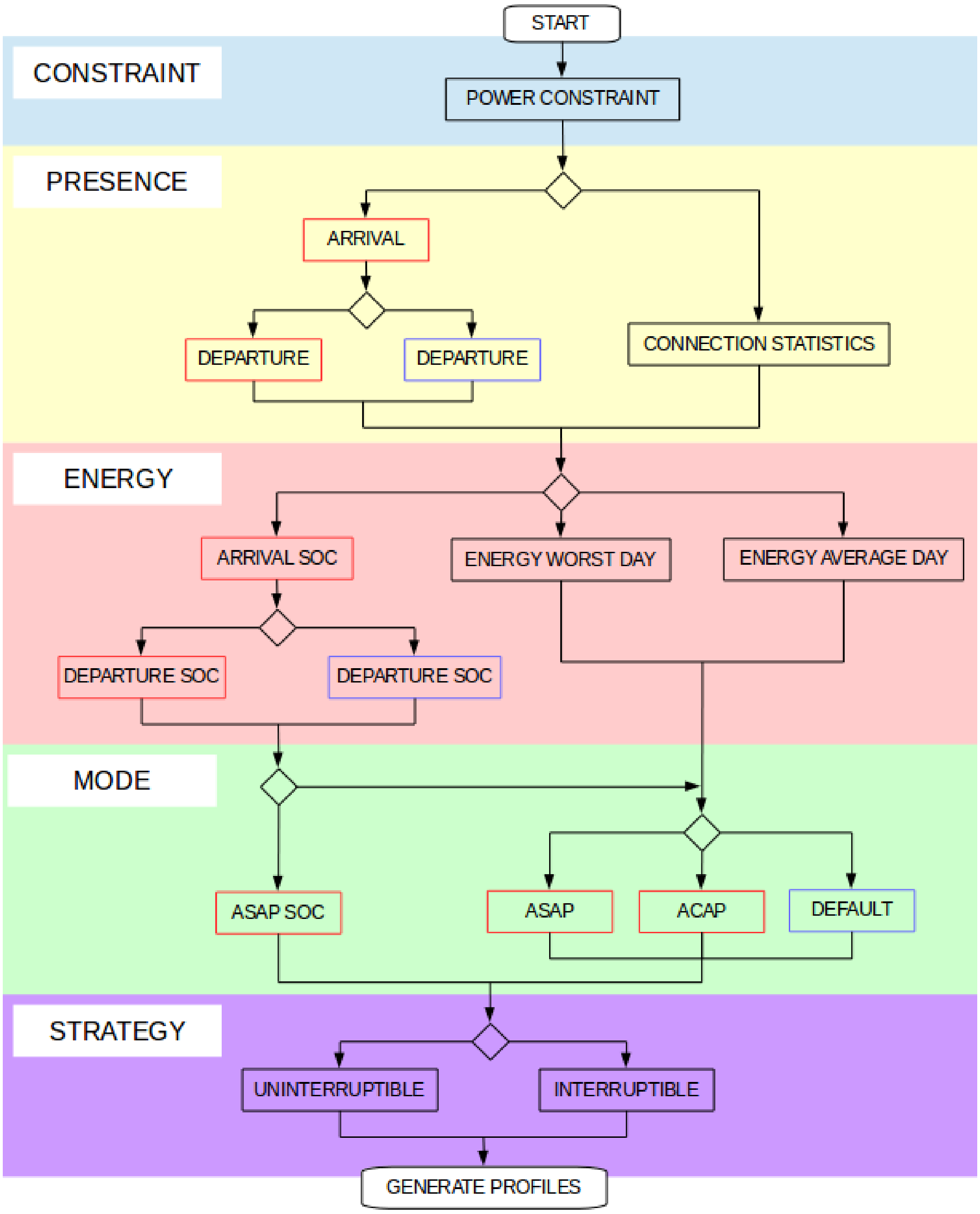


Figure 6.9: EV-PG data flow diagram for the aggregation of the information

Figure 6.9 shows the combinations of possible scenarios which influence the choice for the profiles generation. The EV-PG, following the path of the data flow diagram from the top to the bottom, can univocally identify how to aggregate the available information.

Black boxes represent the EV-PG choices if no external requests are available.

Blue boxes are the default values selected during the EMS setup phase.

Red boxes represent the user input which will be supplied through a proper interface (smartphone application) every time a recharging service will be demand.

User input, if available, are considered more relevant with respect to historical data. Each input is optional: if a value is missed EV-PG will use statistics or default values. The information the vehicle owner can provide are:

- ARRIVAL: timestamp that indicates when user expects to plug the vehicle.
- DEPARTURE: timestamp that indicates when user expects to unplug the vehicle.
- ARRIVAL SOC: integer value that indicates the State Of Charge at ARRIVAL time.
- DEPARTURE SOC: indicates the desired State Of Charge at DEPARTURE time.
- ASAP: indicates that the user wants the vehicle charged As Soon As Possible.
- ASAP SOC: indicates that the user wants to have the vehicle charged As Soon As Possible up to the percentage of battery level reported. After this threshold, the EV-PG can allocate the remaining energy needed according to cost optimization strategies.
- ACAP: boolean value. Indicates that the user wants to charge the vehicle As Cheap As Possible in the estimated or reported connection interval.

Some input data are mandatory for selecting specific optimization modes: ASAP SOC is meaningful only if ARRIVAL SOC is available.

The mode selected by the user or set as default value must be unique.

The mode is not the only parameter which can be set as default.

User can set preselected values for DEPARTURE, DEPARTURE SOC and DEFAULT, used by EV-PG when that input is missing in a recharge request.

The data flow diagram is composed by 5 layers. Here below a detailed explanation:

Layer 1: CONSTRAINT

This layer regards the power thresholds imposed by the optimizer (Pmax, Pmin). For each timeslot, the profiles proposed from the EV-PG to the optimizer have to be between this two values.

Layer 2: PRESENCE

This layer defines the physical connection interval for the recharge which corresponds to the user available time to recharge the vehicle.

If the user does not supply this data, the EV-PG will try to guess the user presence time according to historical data (provided by Ducati Energia) updating the prediction with real time information.

On the other hand if this data is directly reported by the user, the EV-PG will compute all the profiles according to this parameter, regardless of the historical data. Even in this case the prediction will be later controlled and adjusted in real time.

Layer 3: ENERGY

Here the EV-PG needs to withdraw information about the amount of energy to be scheduled. For the domestic case, under the assumption that the final user has just a single charging point (WallBox) and a single electric vehicle to be managed, if no external input are available the EV-PG will base its computation on the historical data considering the worst case i.e. the complete charge of the battery from 0% to 100%. Differently if the user indicates, through the dedicated interface, a desired minimum level of charge guaranteed once he disconnects the vehicle plug, the EV-PG, according to the results of layer 1 and layer 2, will do the best to satisfy the request. In this case the information regarding the battery status at the moment of plug connection is compulsory.

The EV-PG will join layer 3 with layer 1 and layer 2 for scheduling the energy to be supplied.

Layer 4: MODE

Layer 4 is responsible for the user choice of service demanded. 3 cases have been identified:

A. **As Soon As Possible (ASAP)**: once connected the user is asking for starting the recharge of the vehicle immediately in order to reach as soon as possible the highest level of charge in the time available.
B. **As Soon As Possible till % (ASAP%)**: the user demands for an immediate recharge till a specific battery status (indicated through the interface). Once this value is reached the EMS will manage the remaining part according to the most economically convenient solution. For making this mode available the user must indicate the battery status at the arrival time (once he connects the plug).
C. **As cheap as possible (ACAP)**: The user is asking for the economically most convenient solution. According to the result of layer 2 the EMS will decide how to allocate the energy withdrawal for the time available. For this mode the user has to accept that, if something goes wrong with layer 2 (uncorrected prediction for presence time based on historical data or user input related to arrival-departure time which does not correspond to reality) the vehicle could not be (completely) charged at the disconnection time.

If the user does not indicate the desired mode, a **default** value (chosen during set up phase or simply considering the last choice applied) has to be considered.

Layer 5: STRATEGY

This layer takes into account the result of the previous layers and decide a strategy for allocating the energy required during the day in order to feed the Optimizer (OPT) with different profiles. 2 strategies has been figured out (fig. 6.10):

A. **Uninterruptible**: Once started the charge is supposed to be continuous till reaching 100% battery status or disconnecting the plug. Different profiles will be simply generated by shifting the starting moment (keeping in mind that from layer 1 there are different power limits for each timeslot).
B. **Interruptible**: The charge can be suspended for some time slots: the energy can be injected into the battery only in specific timeslots of the day in which the energy price is low and/or the local generation (e.g. photovoltaics) is high. This strategy is more accurate than the previous one but it could generate a very large amount of profiles. Moreover the applicability of a scenario in which the charge process is continuously turned on and off has to be studied.

The choice of the strategy to be adopted is not the task of the final user but has to be evaluated by the EV-PG itself.

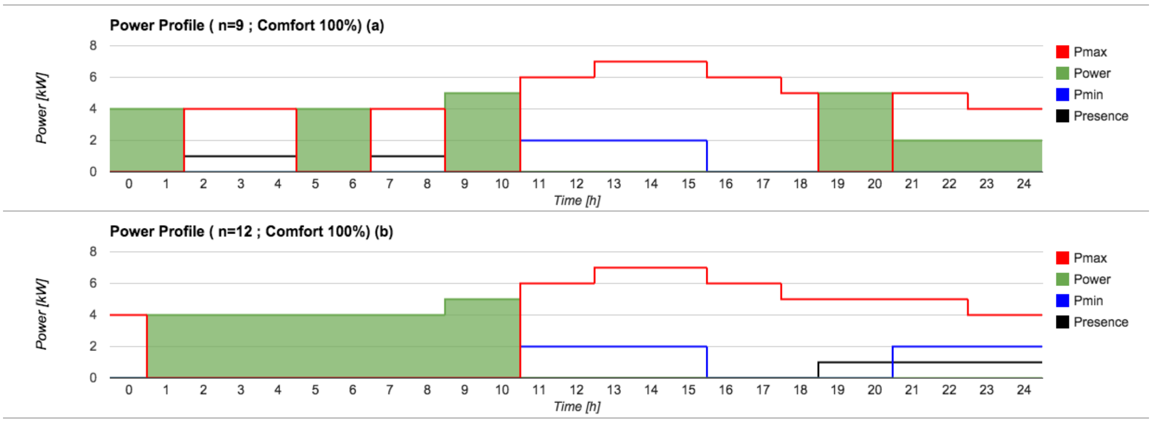


Figure 6.10: Two different strategies for scheduling the recharge: (a) interruptible, (b) uninterruptible

6.9 Institute Case: Medium Voltage User

6.9.1 System Description

The other two Demonstrators taken into account in this document are two buildings owned by Politecnico di Milano: Building 20 and 25. The former is mainly composed by rooms used for students' lessons while the latter hosts professors' offices and laboratories. A general system diagram for the two demonstrators is reported in fig 6.11. Due to the similarity of the two plant schemes in the following all the analysis will only discuss the details of building 25 as a generalization of the case study.

The Electric actors involved in this system are:

- 10kWp concentrated photovoltaic plants with an energy storage system.
- thermal heating and cooling provided by high efficiency electric heat pumps for all the building
- Electric vehicle charging station directly connected to the secondary substation able to supply up to 22kW per vehicle and managing two cars at the same time
- Undeferrable loads used for office needs (laptops, printers, lightning,...)
- Distribution System Operator (DSO) requests of injection/withdrawal reduction for network stability.

Moreover, with respect to the domestic case the limitation imposed by the smart meter is no more present due to an high power threshold which theoretically allows to withdraw from the network any amount of active power.

For the institute case the main novelty regards the introduction of a new Electric Actor responsible for taking into account DSO needs related to grid management: it could ask the final user for a reduced energy consumption or an augmented network injection of the energy produced locally for a time interval reported in advance. On the other hand, thanks to a new inverter used for photovoltaics, it could also ask for a reactive power injection used for frequency stability and voltage control. In case the final customer decides to accept the request and respects it, he/she will receive an economic incentive.

Another important aspect to consider for this Demonstrator is the need of managing whether the electric or the thermal demand: the heating and cooling system is supplied by electrical heat pumps which can produce and even store their energy by exploiting containment tanks already in place. If this was not sufficient or simply not convenient, an auxiliary gas boiler can be activated for supporting the thermal production.

Even the Electric Actor concerning vehicle battery charging is quite different with respect to the Domestic case: The station is equipped with 2 three-phase sockets that allow for a simultaneous charging of two vehicles. Each three-phase socket can supply to the vehicle a maximum power of 22kW (400 VAC - three-phase – 32A) to perform a fast charging and manages the Vehicle charging in according to the “Mode 3” communication standard, in PWM (Pulse Width Modulation) or PLC (Power Line Communication) standards. In addition, a single-phase one socket supplying 3,6 kW (230 VAC – 16A) is available, which can perform a slow charging again in according to the Mode 3 standard. The single-phase socket can be used alternatively to the three-phase one. The station has a fiscal electricity meter which records vehicle consumption and it is also able to collect data related to charging time, arrival and departure time. All the collected data are sent to and stored by the control center Ducati Energia through a GPRS module directly installed into the station. The user who wants to use the service has to be authenticated by the station (usually by means of a magnetic card). Scope of such an Electric Actor is to recharge the vehicles owned by the institute and utilized for its purposes promoting green mobility among all the employers.

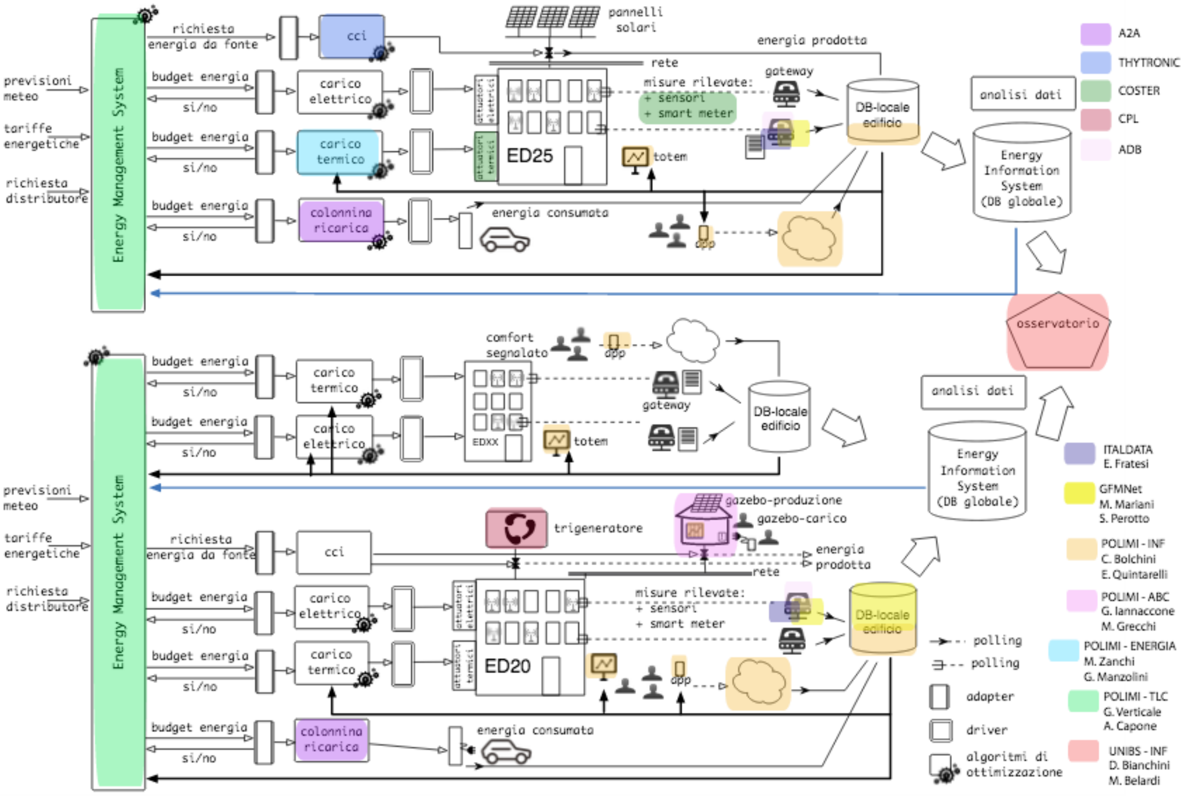


Figure 6.11: General plant scheme for the institute case, courtesy of prf. Cristiana Bolchini [35].

6.9.2 EMS interaction

For the Institute case the goal of the Energy Management System has been further refined: according to the hourly electricity market price variation and the availability of energy produced locally, the EMS has to find out the most convenient solution for managing all the involved Electric Actors. Moreover it has to include in the Objective Function the reward associated to DSO requests regarding network stability for evaluating if accepting such requests could increase the overall institute income/saving. Thanks to high scheduling flexibility of some categories of electrical loads (heat pumps, washing machine, dishwasher), the EMS can occupy a central role in coordinating different needs imposed by electricity market, national grid and final customer. The architecture chosen for this Demonstrator is the same presented in the previous section: The EMS is mainly divided in three parts: The Optimizer is responsible for running the optimization process by means of a dedicated Solver. All the Electric Actors have a Profile Generator designed for providing possible generation/consumption scenarios according to some power thresholds which may be imposed. All the relevant data about the selected schedules and Power Profiles are stored in an energy Information System (EIS) for subsequent elaborations and analysis. In addition the EMS has now to evaluate the thermal needs by choosing which systems (whether electric heat pumps, gas boiler or a combination of the two) is more convenient considering all the variables connected (gas price, latencies, extra costs, incentives). Possible DSO requests will be saved into the EIS and will play a role in the optimization process as additional power limitations imposed by the Optimizer.

6.9.3 Electric Vehicle Profile Generator for the Institute Case

As explained before the charging station available for the two Buildings is quite different with respect to the WallBox used for the Domestic case. Thanks to its direct connection with the network via specific socket and plug and a dedicated circuit, it is able to supply two different levels of power: one is a single-phase socket which can reach up to 3,6 kW for a slow charge. The other is a three-phase socket with a power limit equal to 22 kW. Time required for a complete 20 kWh battery-charging is respectively 6-8 and 2 hours.

The reason of this choice comes from the different kinds of electric vehicles on the market: some old model batteries have just the possibility to be charged at a slow rate while last commercial cars can support both the modes. A fast recharge, if feasible, has the advantage of having the car ready sooner, but it implies some issues related to battery lifetime. Thus, the owner can choose the recharge mode according to his priorities.

The station has two equal sides. Each side is equipped with a single-phase and a three-phase socket which are mutually exclusive (if one is activated, the other of the same side cannot be used). When two cars are connected the total power available for the charging station is divided according to this strategy:

- If one car is connected to the 3,6 kW socket while the other is asking for 22kW, the charging station will give the maximum power to the single-phase one and the remaining part will be injected in the three-phase.
- If both the cars are asking for a 22kW the charging station will subdivide equally the power available.

Depending on the cable type the charging station will automatically recognize which mode is allowed for the connected vehicle.

For the test phase the institute will use two Zoe by Renault with a fast-charge system. For the initial test phase some hypotheses have been formulated in order to simplify the intricate verifiable scenarios: the two cars used are supposed to have exactly the same charging behavior and capacity. Moreover the possibility of a simultaneous connection has been neglected. Under these hypotheses, the same algorithm used for the Domestic case can be applied. The only differences regard the boundary conditions due to different physical power thresholds and the consequent time required for the complete charge. The EMS can obtain real time information regarding the charging status of the station and imposing power set points simply communicating with the Ducati Energia control center. Again the user (which in this case could be a driver or the system administrator depending on the policy applied) will be able to communicate with the Electric Vehicle Profile Generator through a dedicated interface sending information regarding battery status, presence interval and recharging mode (ASAP, ASAP %, ACAP, see section 7.8.3). Thanks to the fast charge up to 22 kW the EMS will be able to schedule the peak loads more efficiently in convenient moments of the day with a high flexibility (fig. 6.12).

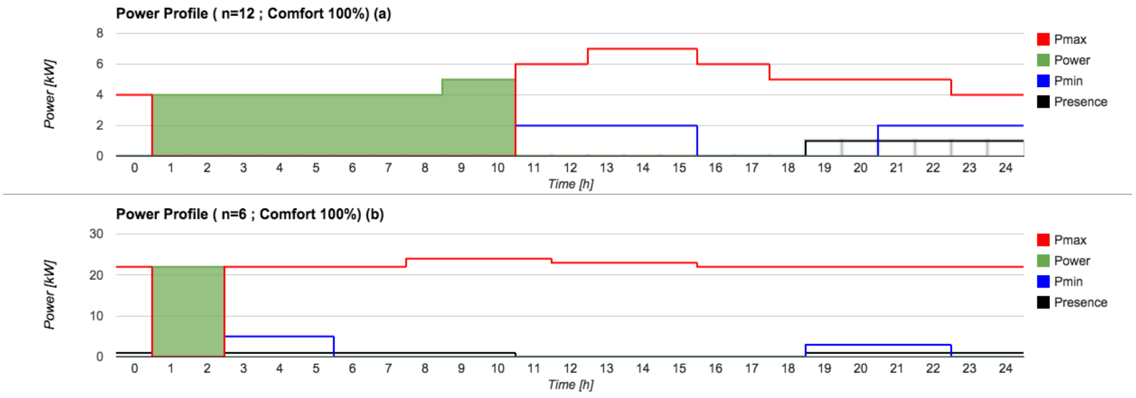


Figure 6.12: Power Profiles for a complete charge of the same car in (a) domestic case, (b) institute case

Chapter 7

OWS Test Suite

In this chapter we present the OWS Test Suite, a Java GUI software which has been implemented to simplify and speed up the testing phase of the Optimization Web Service (OWS). As first point we will analyze the amount of data needed to perform an optimization. After that we will enlist the functional and graphical user interface (GUI) requirements needed to manage such data in an easy and efficient way. Finally we will present some tests results.

7.1 Amount of data

Let's consider the worst case (24h divided in 96 timeslots of 15 minutes). We want to evaluate the data amount required to start an optimization instance for it. As shown in fig. 7.1 in the worst case the input data reaches approximately 1000 values. The same picture shows the amount of output data (approximately 1200 values).

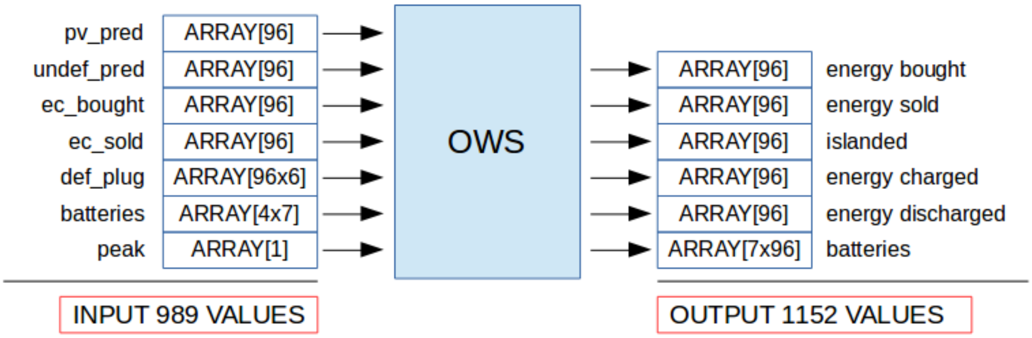


Figure 7.1: OWS amount of data for the worst case optimization instance

This first analysis encouraged us to find a graphical tool for testing purpose.

7.2 Requirements

We are looking for a tool which should provide the following functional requirements:

1. scan USER INPUT
2. convert USER INPUT into a JSON OBJECT
3. perform a HTTPS POST REQUEST passing the JSON OBJECT
4. get RESPONSE JSON OBJECT
5. print RESPONSE JSON OBJECT to USER OUTPUT

Since we have to manage high data volumes, we specify some additional GUI requirements:

1. the user should be able to insert data in a fast way, just moving the mouse and clicking around
2. the user should be able to visualize data through charts and graphs

After a web search no available software was founded which satisfied all the requirements. The second try was to integrate LibreOfficeCalc with macros which add some functionalities to spreadsheet. Technical issues have been encountered regarding HTTPS POST REQUEST. In any case by this way the GUI requirement (1) would not be covered. So we concluded that the best thing to do would be to design and implement the tool from scratch.

7.3 Design

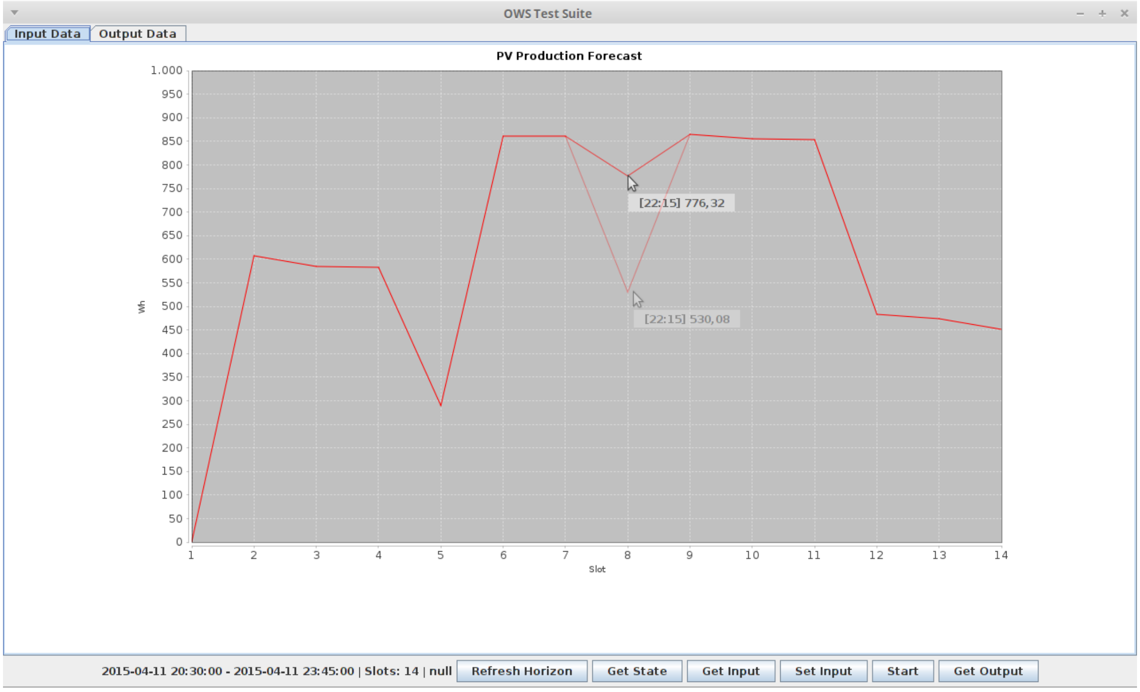
We considered our software platforms background and chose the one which better fits requirements, our knowledge and easiness of design and implementation. The chosen one is Java Platform. During the design phase we investigate about the existence of external libraries which satisfied requirements. Table 7.1 shows the requirements coverage.

Table 7.1: OWS Test Suite external libraries and requirements coverage

Project	Libraries	Requirements						
		Functional					GUI	
		1	2	3	4	5	1	2
JFreeChart [32]	jfreechart-1.0.19.jar	X					X	X
	jcommon-1.0.23.jar	X					X	X
Gson [33]	gson-2.3.1.jar		X			X		
Apache HttpComponents [34]	httpclient-4.4.1.jar			X	X			
	httpcore-4.4.1.jar			X	X			
	commons-logging-1.2.jar			X	X			

7.4 Implementation

We started the implementation with the aim of satisfying GUI requirement number 1: we created a new class object called EasyFloatChartPanel which extends ChartPanel and implements ChartMouseListener. We consider this component the most important of the entire tool because it enables the user to change data by simply selecting the desired values in a chart by using the ^{mik_i}mouse. Figure 7.2 shows how a value of a specific timeslot can be easily changed:



2015-04-11 20:30:00 - 2015-04-11 23:45:00 | Slots: 14 | null

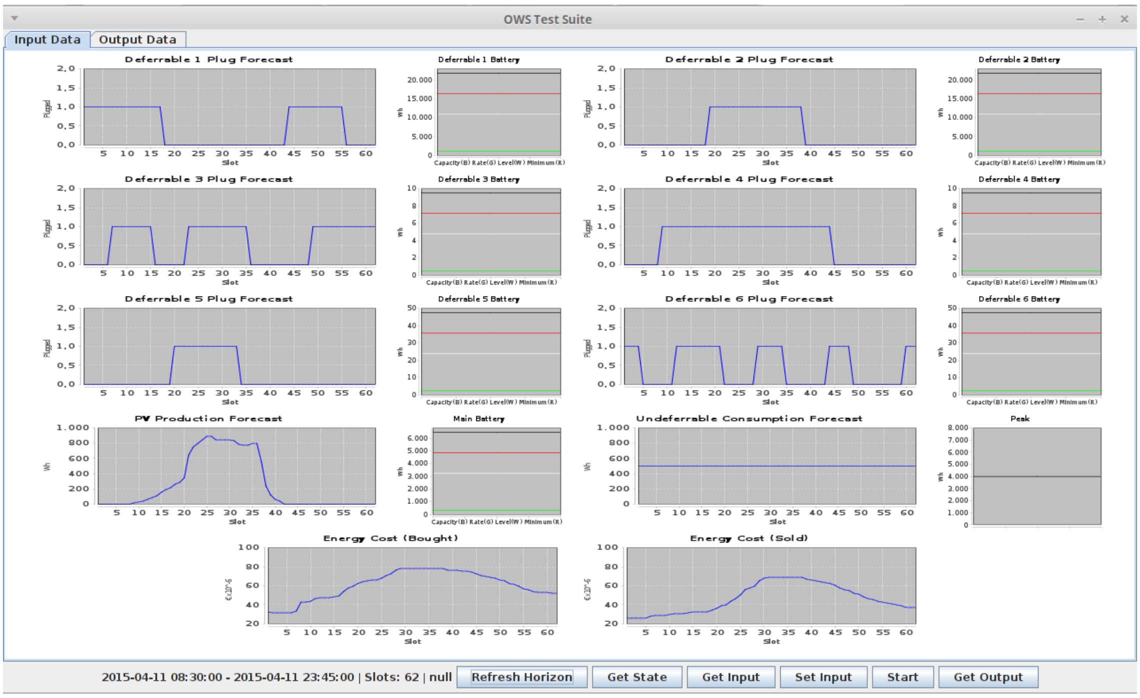
Figure 7.2:OWS Test Suite: user modifies values with a simple mouse move

Implemented components:

- Easy4ConstantsChartPanel: for managing the 4 constant values used for each battery (capacity, recharge rate, level, minimum)
- EasyConstantChartPanel: for managing a single constant value (peak)
- EasyIntegerChartPanel: for managing n integer values. n represents the number of slots
- EasyFloatChartPanel: for managing n float values. n represents the number of slots

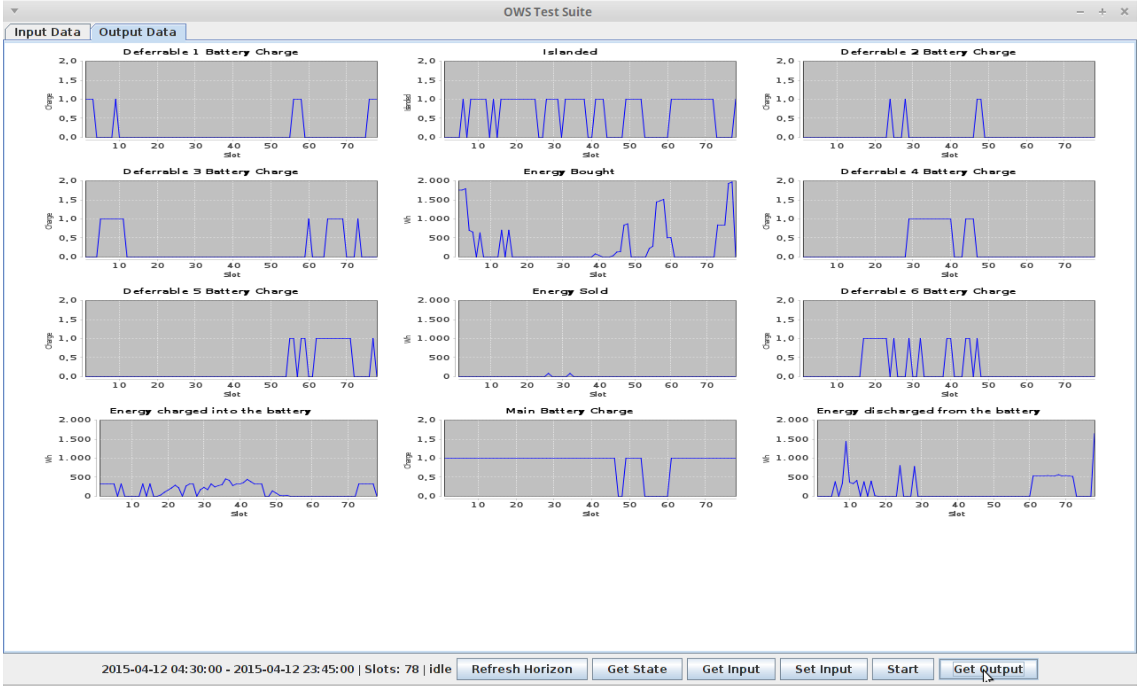
Once all components have been implemented we tried to fit all the data (input and output) in one screen but since there were approximately 2000 values to be displayed we couldn't achieve that. So we divided data in two tabs: input data and output data. Figures 7.3 and

7.4 show the OWS Test Suite GUI. Once user draws the input data he/she can submit it to the OWS using Set Input button. After that the optimization starts using the Start button and output data can be withdrawn using Get Output button.



2015-04-11 08:30:00 - 2015-04-11 23:45:00 | Slots: 62 | null

Figure 7.3: OWS Test Suite GUI: input data tab



2015-04-12 04:30:00 - 2015-04-12 23:45:00 | Slots: 78 | idle

Figure 7.4: OWS Test Suite GUI: output data tab

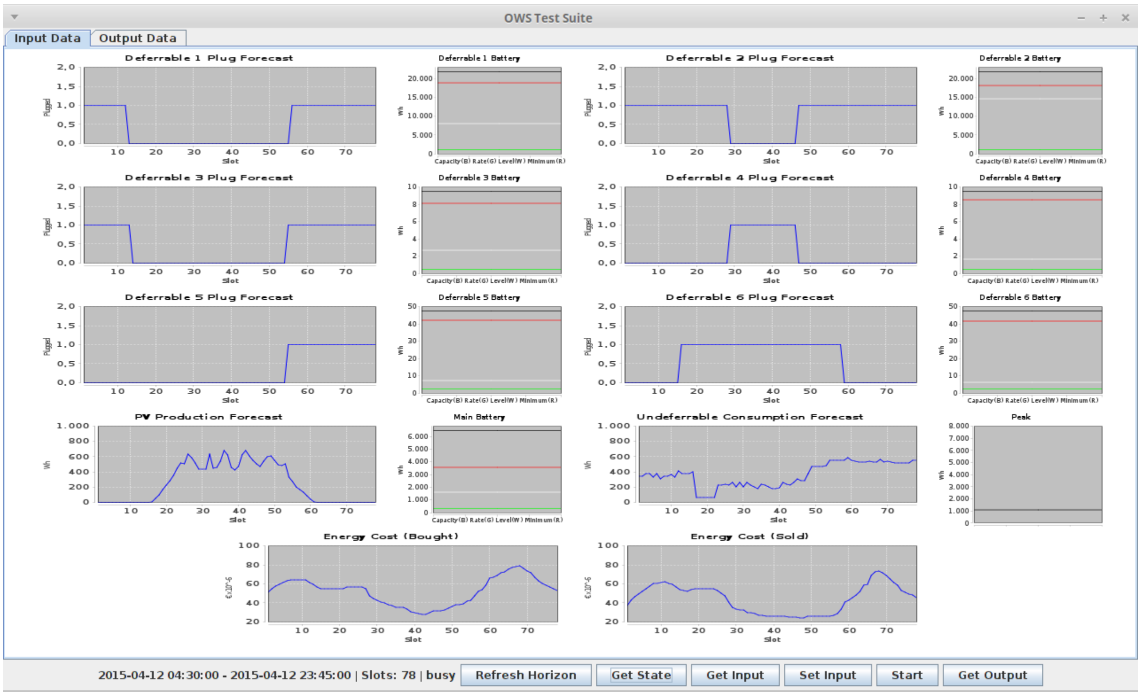
7.5 Results

Here we show the results of two tests (fig. 7.5 and fig. 7.6)

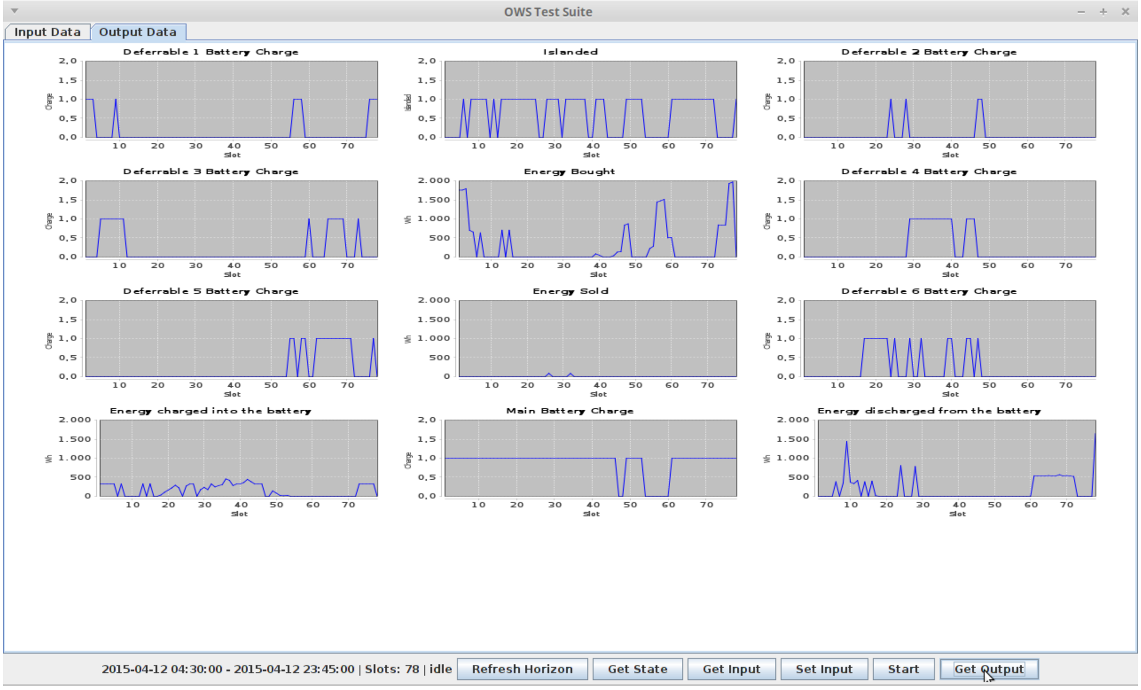
2015-04-12 04:30:00 - 2015-04-12 23:45:00 | Slots: 78 | busy

2015-04-12 04:30:00 - 2015-04-12 23:45:00 | Slots: 78 | idle

Figure 7.5: OWS Test Suite: Test 1 Clear sky



2015-04-12 04:30:00 - 2015-04-12 23:45:00 | Slots: 78 | busy



2015-04-12 04:30:00 - 2015-04-12 23:45:00 | Slots: 78 | idle

Figure 7.6: OWS Test Suite: Test 2 bad weather conditions

As can be noticed a variation of just one input profile can strongly affect different output data. For example Test 1 (fig.7.5) has a peak production around 4kW located at midday. The corresponding output figure shows that a part of that generated energy has to be sold due to an overgeneration (all the deferrable loads which require energy are served and an extra amount is available). On the other hand if the forecasted photovoltaic production is lower (for example due to bad weather conditions) no energy is sold, loads profiles are slightly shifted and more energy has to be bought from the network to satisfy what the undeferrable require

.

Chapter 8

Conclusions and future work

The main purpose of this work was to design and implement a system which once installed at user’s premises could interact with loads, generators and the electrical network in order to minimize the energy bill considering the desired comfort level. This system is called Energy Management System (EMS). According to the requirements, we realized a stable and replicable architecture for the different case studies with a focus on the interaction between the EMS subsystems and the final users.

For Fortiss Smart Energy Living Lab EMS we designed and implemented a subsystem which defines the set point of loads and generators corresponding to the best energy consumption scheduling. We called this subsystem Optimization Web Service (OWS). After the requirements analysis we defined the OWS functionalities and designed the interaction and data exchange protocol between EMS and OWS. To ensure a high interoperability between the two components, JSON data exchange format coupled with the standard web technologies (HTTPS and URLs) has been chosen. After the design phase we went through the implementation on top of a LAMP (Linux, Apache, MySQL, PHP) platform. The OWS is currently up and running and the performed tests show a correct behavior. Moreover we also realized a tool which offer a graphical view of submitted input and OWS output. As future steps, we will improve the system by adding more meta-information about THE optimization process, in particular in those cases where the submitted problem is infeasible because some constraints are not respected.

With regard to the SCUOLA project we participated to the EMS architecture definition introducing a communication protocol between the Optimizer and each Profile Generator. For the latter a state machine has been realized with the purpose of ensuring a stable data transfer for the two components. Finally the Electric Vehicle Profile Generator used to schedule electric cars recharge during the day has been implemented.

The start of the test phase is scheduled for the end of May 2015. All the stakeholders will analyze the real functionalities of the installed EMS whether in the Domestic or in the Institute case till the end of September 2015. We are also thinking about adapting our OWS Test Suite to this project.

Future evolutions of the EMS for SCUOLA planned for the same period will mainly focus on the relaxation of the assumptions about the Electric Vehicle Profile Generator (EV-PG). In particular for the Institute case a simultaneous battery charge using both the sockets offered by the charging station has to be investigated. Moreover we assumed to manage just one car model (Zoe by Renault). In a more general context it could be required to coordinate more than one type of vehicle with different charging features and needs. Finally, the introduction of multiple charging stations for the same institute would be an interesting challenge for strengthening our innovative EMS.

References

[1] Kyoto Protocol to the united nations framework convention on climate change, United Nations, 1998

[2] Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009,Conference of the parties, March 2010

[3] Europe 2020: A strategy for smart, sustainable and inclusive growth, European Commission, 3 March 2010

[4] Robert Passey, Ted Spooner, Iain MacGill, Muriel Watt, KaterinaSyngellakis, The potential impacts of grid-connected distributed generation and how to address them: A review of technical and non-technical factors, Energy Policy, Volume 39, Issue 10, October 2011, Pages 6280-6290, ISSN 0301-4215,

[5] Alexander Gitis, Matthias Leuthold and Dirk Uwe Sauer, Chapter 4 - Applications and Markets for Grid-Connected Storage Systems, In Electrochemical Energy Storage for Renewable Sources and Grid Balancing, edited by Patrick T. MoseleyJürgenGarche, Elsevier, Amsterdam, 2015, Pages 33-52,

[6] FarshidShariatzadeh, ParasMandal, Anurag K. Srivastava, Demand response for sustainable energy systems: A review, application and implementation strategy, Renewable and Sustainable Energy Reviews, Volume 45, May 2015, Pages 343-350, ISSN 1364-0321

[7] Nesse, J., Morse, J., Zemba, M., and C. Riva, L. L. (2014).

[8] Nguyen, T. A. and Aiello, M. (2013). Energy intelligent buildings based on user activity: A survey. Energy and Buildings, 56(0):244–257.

[9] Zarkadis, N., Ridi, A., and Morel, N. (2014). A multisensor office-building database for experimental validation and advanced control algorithm development.

[10] Counsell, J., Gillard, A., and Littlewood, J. (2009). The atlantic college case study #150; measuring performance to evaluate building simulation and enhance student learning. In Visualisation, 2009. VIZ '09. Second International Conference in, pages 102–107.

[11] Bull, R., Stuart, G., and Everitt, D. (2012). The Gorilla in the Library: lessons in using ICT to engage building users in energy reduction. In Proc. Digital Economy 'All Hands' Conf.

[12] Guan, X., Xu, Z., and Jia, Q.-S. (2010). Energy-efficient buildings facilitated by microgrid. Smart Grid, IEEE Transactions on, 1(3):243–252.

[13] Stojanovic, N., Milenovic, D., Xu, Y., Stojanovic, L., Anicic, D., and Studer, R. (2011). An intelligent event driven approach for efficient energy consumption in

commercial buildings: Smart office use case. In Proceedings of the 5th ACM International Conference on Distributed Event-based System, DEBS ’11, pages 303–312, New York, NY, USA. ACM.

[14] Noritake, M., Hoshi, H., Hirose, K., Kita, H., Hara, R., and Yagami, M. (2013). Operation algorithm of dc microgrid for achieving local production for local consumption of renewable energy. In Telecommunications Energy Conference ’Smart Power and Efficiency’ (INTELEC), Proceedings of 2013 35th International, pages 1–6.

[15] Lu, G., De, D., and Song, W.-Z. (2010). Smartgridlab: A laboratory-based smart grid testbed. In Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on, pages 143–148.

[16] Koss, D., Bytschkow, D., Gupta, P., Schatz, B., Sellmayr, F., and Bauereiss, S. (2012). Establishing a smart grid node architecture and demonstrator in an office environment using the soa approach. In Software Engineering for the Smart Grid (SE4SG), 2012 International Workshop on, pages 8–14.

[17] Bozchalui, M., Hashmi, S., Hassen, H., Canizares, C., and Bhattacharya, K. (2012). Optimal operation of residential energy hubs in smart grids. Smart Grid, IEEE Transactions on, 3(4):1755–1766.

[18] Kriett, P. O. and Salani, M. (2012). Optimal control of a residential microgrid. Energy, 42(1):321 – 330. 8th World Energy System Conference, {WESC} 2010.

[19] Piano di azione nazionale per le energie rinnovabili dell’Italia, Ministero dello Sviluppo Economico, Italy, 30 June 2009

[20] Share of renewables in energy consumption up to 15% in the EU in 2013, Eurostat report, 10 March 2015

[21] Stefano Clò, Alessandra Cataldi, PietroZoppoli, The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices, Energy Policy, Volume 77, February 2015, Pages 79-88,

[22] Delfanti Maurizio, Smart Grids and regulation for renewable energies, personal collection of Maurizio Delfanti, Politecnico di Milano, Milano, Italy

[23] Procedura per la Riduzione della Generazione Distribuita in condizioni di emergenza del Sistema Elettrico Nazionale (RIGEDI), Terna, Italy, July 2012

[24] ISO/TC/SC 69 Electric Road Vehicles and Electric Industrial Trucks, IEC - 61851, ed 2.0, 2010

[25] ISO/TC 22/SC 3 Electrical and electronic equipment (2013). ISO 15118-1 road vehicles – vehicle to grid communication interface – Part 1: General information and use-case definition, April.

[26] Alessandro Di Giorgio, Francesco Liberati, Silvia Canale, Electric vehicles charging control in a smart grid: A model predictive control approach, Control Engineering Practice, Volume 22, January 2014, Pages 147-162

[27] Energy efficiency through the Enel smart info, ENEL, 5 April 2013

[28] AEEG (Autorità per l'Energia Elettrica il Gas ed il sistema idrico), 2014, http://www.autorita.energia.it/

[29] GME (Gestore del Mercato Elettrico), 2015, https://www.mercatoelettrico.org/

[30] EUROSTAT for EU-countries, 2012, http://ec.europa.eu/eurostat

[31] Documents & Plant schemes from the SCUOLA project stakeholders, February 2015

[32] http://www.jfree.org/jfreechart/

[33] https://code.google.com/p/google-gson/

[34] http://hc.apache.org/index.html

[35] Personal notes of Cristiana Bolchini, Politecnico di Milano, Milano, Italy

[36] A. Barbato, C. Bolchini, M. Delfanti, A. Geronazzo, E. Quintarelli, V. Olivieri, C. Rottondi, G. Verticale, G. Accetta, A. Dedè, M. Trioni. An energy management framework for optimal demand response in a Smart Campus, 2014. Submitted for pubblication