UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI
INGEGNERIA MECCANICA,
ENERGETICA E GESTIONALE

UNIVERSITY OF CALABRIA
Department of Mechanical
Energy and Management Engineering

Ph.D. in
Science and Engineering of Environment,
Construction and Energy
XXXI cycle

*Ph.D. Thesis*

# Models and enabling IoT technologies for cooperative energy brokerage in smart−grid

Luigi Scarcello

UNIVERSITÀ
DELLA CALABRIA

UNIVERSITY OF CALABRIA
Department of Mechanical
Energy and Management Engineering

Ph.D. in
Science and Engineering of Environment,
Construction and Energy
XXXI cycle

*Ph.D. Thesis*

# Models and enabling IoT technologies for cooperative energy brokerage in smart-grid

Luigi Scarcello

Coordinator:
Prof. Salvatore Critelli

Supervisors:
Prof. Daniele Menniti

Prof. Anna Pinnarelli

Prof. Nicola Sorrentino

DIMEG

DIMEG - Department of Mechanical, Energy and Management Engineering
November 2018

Settore Scientifico Disciplinare:
ING-IND/33 - Sistemi elettrici per l'energia

To my family

The work has been supported by the research project:
“Sistemi Domotici per il Servizio di Brokeraggio Energetico Cooperativo ”
PON03PE_00050_2

Ministero dell’ Istruzione, dell’ Università e della Ricerca (MIUR)
Programma Operativo Nazionale “Ricerca e Competitività”
ASSE I “Sostegno ai mutamenti strutturali”
AZIONI I.3.1 “Distretti ad alta tecnologia”

# Acknowledgements

I would like to thank professors Daniele Menniti, Nicola Sorrentino and Anna Pinnarelli for their professionalism and dedication with which they supervised my research work.

I acknowledge my colleagues Luca Mendicino, Michele Motta, Giuseppe Barone, Alessandro Burgio, Stefano Mendicino, Pasquale Vizza, Michele Mercuri and Giovanni Brusco for their nearness and friendship during my Ph.D. activity.

I would like to thank the researchers of the CNR-ICAR group Carlo Mastroianni and Andrea Giordano for sharing their experiences and work skills.

Finally, I would like to thank my parents who with their affection have always sustained me in all the important situations of my life.

# Abstract

The strong decentralization of energy production, especially from non-programmable renewable sources (nPRS), obtained with the rising and interconnection of small plants, has placed the end user at the centre of the whole energy system management. Nowadays, the end user has taken the role of a "prosumer", being at the same time producer and consumer of thermal and electrical energy. While this new bivalent role has clear advantages (on-site production, lower transport losses, reduced dependence on fossil fuels, etc.), the distributed generation from nPRS causes additional injections of energy into the grid, which can bring to stability and safety problems for the operations of the grid itself. As consequence, the end-user needs to be involved in the management of the grid adopting appropriate strategies in order to maintain the balance between generation and consumption of energy, and avoid spikes of energy demand or excessive injections of energy produced but not consumed. The best strategy is to join in energy communities able to coordinate local energy flows and favouring a better use of energy. Moreover, end-users have to adopt new IoT technologies and the grid have to become a smart-grid.

This Ph.D. thesis develops some cooperative energy brokerage models based on decentralized scheme proposed in the LAboratory of Electrical Systems for Energies and Renewable sources (LASEER), headed by Prof. D. Menniti, of the Department of Mechanical, Energy and Management (DIMEG) of the University of Calabria. In the proposed models, the end-user takes a fundamental role: he can autonomously make decisions based on thermal and electrical energy requirements and collaborate in energy balancing operations of the energy community and of the national electrical grid. In according to this decentralized approach, a new price based-time of use Demand Response program has been designed. The Demand Response program is determined by solving, in a day ahead strategy, a mixed integer linear optimization problem, called "prosumer problem". In this context, end-user dwellings need to be purposely equipped with home automation systems and micro-grid devices, appropriately designed to act the planned energy management strategy.

The effectiveness and the feasibility of the proposed work have been assessed through a testbed performed in an academic experimental demonstrator sited in the University of Calabria, where the proposed model have been implemented. Moreover, different prototype versions of home automation and micro-grids devices have been realized during the development and the work carried out in the MIUR project *"Sistemi Domotici per il servizio di brokeraggio energetico cooperativo"*.

Specific contributions of this thesis are in the following areas:

- implementing an unified management model of both thermal and electrical energy needs in a price based Demand Response program;
- providing an option for end-users to participate in the National Electricity Market through demand side bidding and to manage their electricity usage;
- designing home automation systems and micro-grid devices able to monitor, control and collect data on exchanges of electrical energy flows;
- customizing cooperative energy brokerage model for supporting the management of Energy Districts;
- experimenting the energy management strategy in the academic experimental demonstrator;
- designing smart meter for end-user able to measure energy flows exchange as well as to give a view of real-time energy consumption;
- collecting representative data about end-user habits to perform statistical analysis and define load forecasting services;
- evaluating cost and quantifying the global energy demand to sensitize to more conscious consumption of energy.

The experience in developing demand response models has been shared inside Marie Skłodowska-Curie project *"Research and Innovation Staff Exchange"*, with the project partner Exergy Ltd company.

# Riassunto

La forte decentralizzazione dei sistemi di produzione di energia, in particolare da fonti rinnovabili non programmabili (nPRS), ottenuta con l'aumento e l'interconnessione di piccoli impianti, ha posto l'utente finale al centro dell'intera gestione del sistema energetico.
Oggigiorno, l'utente finale ha assunto il ruolo di "prosumer", essendo allo stesso tempo produttore e consumatore di energia termica ed elettrica. Mentre questo nuovo ruolo bivalente presenta chiari vantaggi (produzione in loco, minori perdite di trasporto, ridotta dipendenza dai combustibili fossili, ecc.), la generazione distribuita da nPRS ha provocato ulteriori iniezioni di energia nella rete, che hanno causato problemi di stabilità e sicurezza per la rete stessa. Di conseguenza, l'utente finale deve essere coinvolto nella gestione della rete adottando strategie appropriate al fine di mantenere l'equilibrio tra generazione e consumo di energia ed evitare picchi di domanda o eccessive iniezioni di energia in rete. La migliore soluzione è quella di fondare comunità energetiche nelle quali è possibile coordinare localmente i flussi energetici, e favorire un migliore utilizzo dell'energia. A tal fine, agli utenti finali è richiesto di adottare nuove tecnologie IoT e nuovi sistemi di smart-grid.

Questo tesi di dottorato propone nuovi sistemi cooperativi di brokeraggio energetico basati sui modelli e sulle architetture sviluppate nel LAboratorio di Sistemi Elettrici per le Energie e fonti Rinnovabili (LASEER), diretto dal Prof. D. Menniti, del Dipartimento di Meccanica, Energetica e Gestione (DIMEG) dell'Università della Calabria. Nei modelli proposti, l'utente finale assume un ruolo fondamentale: può autonomamente definire e gestire i propri fabbisogni di energia termica ed elettrica e collaborare alle operazioni di bilanciamento energetico della comunità alla quale appartiene. Sull base di questo modello decentralizzato, è stato progettato un nuovo programma di risposta alla domanda (demand response) appartenente alla categoria price based-time of use. Il programma di demand response è determinato risolvendo, in una strategia previsionale, un problema misto di ottimizzazione lineare intera, chiamato "problema prosumer".

In questo contesto, le abitazioni degli utenti coinvolti nel programma di demand response, sono essere appositamente equipaggiate con sistemi domotici e dispositivi di smart–grid, opportunamente progettati per attuare la strategia di gestione energetica pianificata.

L'efficacia e la fattibilità del lavoro proposto sono state valutate attraverso dei test di prova eseguiti in un dimostratore sperimentale situato nell'Università della Calabria, in cui il programma di demand response proposto è stato implementato. Inoltre, diverse versioni prototipali di dispositivi domotici e micro–grid sono state realizzate durante lo sviluppo e il lavoro svolto nell'ambito del progetto MIUR "*Sistemi Domotici per il servizio di brokeraggio energetico cooperativo*".

Contributi specifici di questa tesi sono relativi delle seguenti aree:

- implementazione di un modello di gestione unificato dei fabbisogni di energia termica ed elettrica in un programma di demand response price based–time of use;
- realizzazione di dispositivo IoT che garantisca agli utenti la partecipazione al programma di demand response per gestire il loro consumo di energia elettrici e termica;
- progettazione di un sistemi domotici e dispositivi di micro–grid in grado di monitorare, controllare e raccogliere dati sugli scambi di flussi di energia elettrica;
- castomizzazione del modello di brokeraggio cooperativo dell'energia per supportare la gestione dei distretti energetici;
- sperimentare la strategia di gestione dell'energia nel dimostratore sperimentale accademico situato nell'Università della Calabria;
- progettazione di uno smart meter per l'utente domestici in grado di misurare lo scambio di energia e fornire una visione del consumo energetico in tempo reale;
- raccolta dati di consumo e produzione ed elaborazione statistica a support dei servizi di previsione del carico;
- valutare i costi e quantificare la domanda globale di energia per sensibilizzare l’ utente verso un consumo energetico più consapevole.

L'esperienza nello sviluppo di modelli di risposta alla domanda è stata condivisa all'interno del progetto Marie Skłodowska–Curie " *Research and Innovation Staff Exchange* ", con la società partner del progetto Exergy Ltd.

# Contents

# Nomenclature

## *A. Sets*

| | |
|---|---|
| $H$ | set of the hours of a day |
| $A$ | set of schedulable loads |
| $B$ | set of non−schedulable loads |
| $T$ | set of thermal loads |
| $H^*$ | set of surplus hours |

## *B. Variables*

| | |
|---|---|
| $E^h_{dis}$ | energy drawn from the electrical storage at hour $h \in H$ [kWh] |
| $E^h_{cha}$ | accumulated energy of the electrical storage at hour $h \in H$ [kWh] |
| $E^h_{STOt}$ | energy exchanged by the thermal storage system at hour $h \in H$ [kWh] |
| $E^h_{CHP}$ | electrical energy produced by the micro−CHP at hour $h \in H$ [kWh] |
| $E^h_{imp}$ | electrical energy imported from the grid at hour $h \in H$ [kWh] |
| $E^h_{exp}$ | electrical energy exported to the grid at hour $h \in H$ [kWh] |
| $E^h_{NG}$ | thermal energy produced by the gas boiler at hour $h \in H$ [kWh] |
| $E^h_{HP}$ | electrical energy consumed by the heat pump at hour $h \in H$ [kWh] |
| $y^h_a$ | status of the schedulable load $a \in A$ at hour $h \in H$ [1=ON; 0=OFF] |
| $z^h_a$ | 1 if the schedulable load $a \in A$ is activated at hour $h \in H$, 0 elsewhere |
| $E^h_{req}$ | amount of energy surplus requested at hour $h \in \mathrm{H}$ [kWh] |

### C. Constants

| | |
|---|---|
| $c^h$ | cost to import an electrical $kWh$ from the grid at hour $h \in H$ [€] |
| $p^h$ | price to export an electrical $kWh$ to the grid at hour $h \in H$ [€] |
| $c^h_{out}$ | cost to import an electrical $kWh$ for a prosumer outside the energy district at hour $h \in H$ [€] |
| $p^h_{out}$ | price to export an electrical $kWh$ for a prosumer outside the energy district to the grid at hour $h \in H$ [€] |
| $c^h_s$ | cost to import an electrical $kWh$ of surplus energy at hour $h \in H$ [€] |
| $C_{kWht\_CHP}$ | cost to generate a thermal $kWh$ from micro-CHP [€] |
| $C_{kWht\_NG}$ | cost to generate a thermal $kWh$ from the gas boiler [€] |
| $\alpha_a, \beta_a$ | start and end time range defined by the end-user for scheduling the load $a \in A$ [h] |
| $\theta_a$ | duration of the working time of the schedulable load $a \in A$ [h] |
| $E_a$ | rated power of the load $a \in A$ [kWh] |
| $x^h_b$ | consumption forecast for non-schedulable load $b \in B$ at hour $h \in H$ [kWh] |
| $x^h_t$ | consumption forecast for thermal load $t \in T$ at hour $h \in H$ [kWh] |
| $E^h_{PV}$ | energy production forecast for PV plant at hour $h \in H$ [kWh] |
| $E^h_{tSOL}$ | thermal energy production forecast for solar panel at hour $h \in H$ [kWh] |
| $E_{CHP}$ | maximum hourly electrical energy production for the micro-CHP [kWh] |
| $F_{CHP}$ | co-generation factor of the micro-CHP |
| $E_{HP}$ | maximum hourly thermal energy production for the heat pump [kWh] |
| $COP$ | Coefficient Of Performance of the heat pump |
| $E_{NG}$ | maximum hourly thermal energy production for the gas boiler [kWh] |
| $E^{max}_{grid}$ | maximum hourly electrical energy that can be imported from the grid [kWh] |
| $\eta_{cha}$, $\eta_{dis}$ | charging and discharging efficiency factors of the electrical storage |
| $SOC_{max}$ | maximum percentage of the state of charge of the electrical storage |
| $SOC_{min}$ | minimum percentage of the state of charge of the electrical storage |
| $E^{max}_{cha}$ | maximum hourly charging energy of the electrical storage [kWh] |

| | |
|---|---|
| $E^{max}_{dis}$ | minimum hourly charging energy of the electrical storage [kWh] |
| $C_{max}$ | maximum capacity of the electrical storage [kWh] |
| $E^{*}_{STOel}$ | residual energy of the day before stored in the electrical storage [kWh] |
| $T^{max}_{STOt}$ | maximum admissible temperature for the thermal storage [° C] |
| $T^{min}_{STOt}$ | minimum admissible temperature for the thermal storage [° C] |
| $\Delta T^{max}_{STOt}$ | maximum admissible hourly temperature variation for the thermal storage [° C] |
| $\rho$, $V$, $Cp$ | fluid density, volume and specific heat of the heat transfer fluid of the thermal storage system [kg/m$^3$, m$^3$, kWh/Kg° C] |
| $E^{h}_{expFS}$ | electrical energy exported into the grid in the first stage at hour $h \in H$ [kWh] |
| $E^{h}_{acc}$ | amount of energy surplus requested and accepted at hour $h \in H$ [kWh] |

# Glossary of Terms

| | |
|---|---|
| *DR* | demand response |
| *DSR* | demand side response |
| *DSM* | demand side management |
| *RES* | renewable energy sources |
| *EMS* | energy management system |
| *nPRS* | non-programmable renewable sources |
| *PV* | photovoltaic plant |
| *HP* | heat pump |
| *CHP* | combined generator |
| *DSM* | demand side management |
| *EV* | electrical vehicle |
| *DSO* | distribution system operator |
| *TSO* | transmission system operator |
| *HEMS* | home energy management systems |
| *AMR* | advanced meter reading |
| *AMI* | advanced metering infrastructure |
| *MEMS* | micro-grid energy management system |
| *SCADA* | supervisory control and data acquisition |
| *GUI* | graphic user interface |
| *CT* | current transformers |

| | |
|---|---|
| *MVC* | model−view−controller |
| *DBMS* | database management system |
| *BMS* | battery management system |
| *RTU* | remote terminal unit |

# 1 State-of-the-Art

The strong decentralization of energy production, especially from non-programmable renewable sources (nPRS), obtained with the utilization and interconnection of small plants, has placed the end-user at the centre of the energy system management. The end user has taken the role of a “prosumer”, being at the same time producer and consumer of thermal and electrical energy. While this new bivalent role has clear advantages, such as on-site production, lower transport losses, reduced dependence on fossil fuels, etc., the distributed generation from nPRS causes additional injections of energy into the grid, which can bring to stability and safety problems for the operations of the grid. Consequently, the end-user is often encouraged to participate in Demand Response (DR) programs and to adopt appropriate strategies in order to maintain the balance between generation and consumption of energy and avoid peaks of energy demand or excessive injections of energy produced but not consumed. To cope with these issues, the end-user needs to be involved in the management of smart grids.

Smart grid refers to an intelligent electricity generation, transmission, and delivery system enhanced with communication facilities and information technologies. Smart grid is expected to have a higher efficiency and reliability and can relieve economic and environment issues caused by the traditional fossil-fuelled power generation. Efficient DSR programs and flexible exploitation of renewable energy are two fundamental features of the smart grid. The transition from the traditional fossil-fuelled power generation to the decarbonized power generation based on renewable resources (e.g., solar, wind, and geothermal resources) has been employed to cope with the rapid energy demand growth. In today’s electric power grid, we often observe substantial hourly variations in the wholesale electricity price, and the spikes usually happen during peak hours due to the high generation costs. However, nowadays, almost all end-users are charged some at-rate retail electricity price, which does not reflect the actual wholesale price.

With the at-rate pricing, users often consume a large amount of electricity during peak hours, such as the time between late afternoon and bedtime for residential users. This leads to a large fluctuation of electricity consumption between peak and off-peak hours. The high peak-hour demand not only induces high cost to the retailers due to the high wholesale prices, but also has a negative impact on the reliability of the power grid.

Nowadays, the smart grids are the centrepiece of a future with more low-carbon and intermittent energy sources, more storage and more energy traded across borders. According to this vision, prosumers will play a vital role in the future smart grid: they will know how much power they are generating and using, switch off appliances at peak times and manage demand by themselves with the aid of automated controllers and energy aggregators. In order to increase the penetration of renewables, legal incentives have been set in place so that System Operators prioritise renewables over other forms of generation. This means that renewables, whose generation is intermittent as it depends on weather, become baseload providers. At times of peak demand, increasing the output of fossil fuel generators may not be enough, making electricity prices more volatile. Electricity price spikes occur frequently when demand is very high because there is extremely high price volatility due to the higher volume risks. In such circumstances, electricity prices in wholesale markets could fluctuate from less than 0.40 **€**/kWh to as much as 0.25 /kWh on several days of the year. In essence, peak energy demand and intermittence in generation have significant implications for system balancing, utilities pricing and future grid development. Issues of time and timing have not featured strongly in energy research and energy policy analysis as both have predominantly focused on estimating and reducing total average annual demand per capita at both the individual household and system levels. Traditionally, balancing demand and supply occurred via expansion of capacity base to deal with aggregate increases in energy demand. More recently, higher awareness over the greenhouse effects of fossil fuel generation implied that concerns regarding demand-supply matching cannot justify grid expansion. As result, balancing energy supply and demand is becoming an increasingly complex challenge. A solution can be reached through the adoption of DSR programs.

The DSR is defined as a program of actions, aimed at changes in habits of end-use customers in consuming energy [1]; these changes are mainly driven by price signals and discounted rates that discourage the use of electricity during peak hours and allow savings on end-user' s bills [2]. The easiest way to induce a customer to change his habits in using electricity in order to balancing energy supply and demand, is to schedule its loads; the bigger the savings in the bill achieved through loads scheduling, the higher the participation of the customer in a DSR program. Beyond the goals of obtaining economic and energy savings, DRS programs is helpful under emergency circumstances: DSR lowers the risks of rolling blackouts by allowing suppliers and grid operators to reduce stress on the grid by having businesses lower their electricity demand.

## 1.1 Demand Side Management: Definition and Classification

In certain spaces DSR (or Demand Response, also known as DR) and Demand Side Management (also known as DSM) are used interchangeably. Like other sources, it is make the distinction and it has seen DSR as a particular form of Demand Side Management focusing on load shifting aspects, rather than aggregate conservation effects.

Demand Side Management has a long history, which dates back to over forty years ago. The oil crises triggered attempts to reduce growing demand for electricity, increasing dependency on oil imports and negative environmental impacts. In the US, laws which required utilities to purchase power from nonutility generators at posted prices equivalent to the cost of power that the utility would otherwise generate and to offer on-site energy audits to residential customers can be seen as the regulatory forerunners of Demand Side Management. The high costs of producing electricity in the late 1970s meant that several utilities started developing Demand Side Management programmes with a view to limit such costs. In the early 1980s, load control programmes appeared on the scene as a way to reduce electricity demand at times of peak energy demand, when the marginal cost of generation is at its highest level. The cost context of that historical period, combined with the regulatory framework, compelled utilities to actively manage customer loads. Later, the cost context and the incentives regime changed, hence dissuading utilities from exercising Demand Side Management.

As with anything to do with economics in energy markets, Demand Side Management (and to some extent DSR) is concerned with the basic economic issue of allocating scarce resources in the economy. This ranges from the microeconomic concerns of energy supply and demand and the macroeconomic concerns of investment, financing and economic linkages with the rest of the energy market. At the same time, the issues facing the energy industry change, and the role of Demand Side Management evolves accordingly.

In the 2010s, the increase of renewables has had a huge impact on conventional generators, which now run their plants for fewer hours in the year and for less money. Surges of renewables onto the grid have at times pushed the electricity price in some countries close to zero and even negative price levels, for instance when congested cross-border interconnectors impede an export outlet for the power. At the same time, the impact of renewables has effectively raised operating costs for conventional power plants, which have to compensate for the peaks and troughs in the supply of wind and solar power with more frequent start-ups and shutdowns of their own. This triggers extra fuel and maintenance costs, leaving conventional generators unable to cover their fixed costs in terms of capital repayment and overheads through the sale of their electricity.

The International Energy Agency (2014), for example, estimated that in 2013 the wholesale price of electricity was about 23 per cent below what power plants needed to cover the cost of supply.
New technologies are seen as key enablers for the development of the interactive smart grid where networks will be able to communicate with appliances and consumers, leading to more efficient use of energy. In these scenarios, DSR is taking an increasingly central role, with several European countries recognising the importance of this service.

This increasing role of DSR is acknowledged, for instance, in EU policy through the Demand Connection Code. This is a network, which was set up by the European Network of Transmission System Operators for Electricity. The intention is to help to accomplish the tasks of facilitating the increase of renewable energy sources. The Code produced provisions on ways to enhance the penetration of DSR in Europe. In addition, the 2012/27/EU Energy Efficiency Directive, established that 'Network tariffs and regulations allow Energy Efficiency measures and services and with dynamic pricing give clear market signals' (Art 15.1). Also, 'network tariffs do not prevent shifting or reducing demand; not hampering participation of DSR in balancing market and ancillary services provision and encourage DSR to participate in wholesale and retail markets' (Art 15.4); 'Member States promote participation of DSR in balancing, reserve and services markets' (Art 15.8). Moreover, article 18 on Energy Services calls for Member States' support and promotion of markets for energy services. Previously, the Electricity Directive 2009/72/EC set out the main criteria for Smart Meters rollout. According to this Directive, then 80 per cent of smart meters should be rolled out by 2020. [3]

There are different ways of 'doing' DSR and different types of services, which DSR can offer. Concerning ways of doing DSR, several techniques are used to perform DSR, but they all serve the same purpose, namely reducing electricity consumption from the network supply for a period. DSR reduces the metered load of the site, enabling reduction in demand by either reducing consumption at the site, or offsetting network supply with on-site generation. Demand reduction approaches fall into two main categories, namely load shifting and load reduction. Load shifting achieves reduction in electricity demand during the request period by moving the load to a different time. This approach is often used for heating and cooling loads, which can support short curtailments without affecting the activities users are carrying out. Conversely, load reduction reduces consumption, which will not be recovered later. An example of load reduction consists of temporarily turning lights off. About categories of services DSR can offer, a typical classification involves two main types: incentive-based programmes (also known as system led programmes, emergency programmes or even stability programmes) and price-based programmes (also known as market-led programmes, economic based programmes and economic-based programmes).

Incentive–based programmes comprise interruption programmes for larger industries (e.g. Interruptible Programmes) and load shifting for residential customers and small commercial customers (direct load control programmes), which receive participation payments, usually as a bill credit or discount rate, for their participation. Direct load control programmes are typically run by utilities, which can remotely turn off their customers' equipment at short notice. Large industries participating in Interruptible Programmes are asked to reduce their load to predefined values and receive upfront incentive payments or rate discounts. Those sites, which do not interrupt or curtail loads as planned are likely to be subject to penalties, which may vary according also to bilateral agreements between the utility and the industrial user. Other incentive–based programmes involve advance notice DSR for other industrial and commercial users, which are rewarded with money for their performance, depending on the amount of load reduction during critical conditions. Examples of this type of incentive–based programmes include Emergency DSR Programmes, Demand Bidding, Capacity Market and the Ancillary Services. As part of Demand bidding programmes, consumers place bids on load reductions in the electricity wholesale market. If a bid is less than the market rice, it is accepted. The customers winning bids must reduce their loads by the amount stated in the bid. Otherwise, they will be subject to penalties. Emergency DSR programmes provide incentives for specific load reductions at the time of emergency conditions (like the blackout caused by the ship in Germany). In European electricity markets, Emergency DSR programmes are usually designed for large industrial customers. They are operated by Transmission System Operators, which require response times of seconds and compensate customers through capacity and utilisation payments. DSR in Capacity Markets consists of customers who typically receive a day–ahead notice of events and receive penalties if they do not respond to signals asking them to reduce their loads. The idea is that the participant's commitment is to provide pre–specified load reductions based on when system contingencies arise. In Europe, DSR programmes within Capacity Markets are being designed for ensuring reliability. The response time consists of hours and payment occurs via capacity and utilisation payments. Customers can also bid on load curtailment in the spot market as operating reserve under Ancillary Services. If customers' bids are accepted, they are paid the spot market price. In exchange, they will have to commit to be on stand–by.

In European electricity markets, Ancillary Services involve frequency control and reserve programmes which are operated and managed by Transmission System Operators; have typical response times, which range from seconds to 30 minutes; and have payment structures based on availability and utilisation payments. Price–based programmes tend to rely on dynamic pricing rates. This means that electricity tariffs are not flat as the rates fluctuate following the real–time cost of electricity. The main aim of price–based programmes is to smooth peak demand.

High prices are imposed at peak times, whereas low prices correspond to off−peak periods (e.g. night−time and weekends). Price−based programmes comprise Time of Use tariffs, Critical Peak Pricing and Real Time Pricing. Time of Use tariffs make use of blocks of time. There are typically two during weekdays, i.e. peak and off−peak, hence the alternative name of Dual Tariffs. The tariff during peak periods is normally higher than the rate during off−peak periods, although the presence of renewables can actually reverse this. The way Time of Use tariffs are designed is to tentatively reflect the average cost of electricity during different periods. Critical Peak Pricing consists of tariffs where prices are based on critical peaks hours on event days. These may be advertised by the utility a day in advance, but there are also examples of hour−ahead notices. Critical Peak Pricing can be combined with Time of Use tariffs or normal flat rates. Under Real Time Pricing, customers are charged hourly or half−hourly fluctuating prices based on the real cost of electricity in the wholesale market. [3]

The real−time electricity price control has been proved effective in provisioning efficient DSM. Consequently, as a remedy of the problem to have an electricity consumption evenly spread across different hours of the day, researchers have proposed new time−based pricing schemes for utility companies, such as peak−load pricing (PLP), time− f−use pricing (TOUP), critical peak pricing (CPP), and real−time pricing (RTP). A common characteristic of these schemes is that they charge an end−user based on not just how much electricity is consumed but also when it is consumed. For example, PLP incentivizes users to shift the electricity consumption away from peak times, by charging users based on the peak load. TOUP typically has higher peak prices during peak hours and lower off−peak prices for the remaining hours of the day. CPP requires higher electricity prices during periods of high−energy use called CPP events, and offers lower prices during all other hours. Although TOUP and CPP encourage cost−sensitive end users to adjust their demand and make consumption scheduling decisions according to fixed time−differentiated electricity pricing, they cannot provide additional incentives to reduce demand in the real−time fashion even when the system is most stressed. Owing to the potential shortcomings of PLP, TOUP, and CPP, researchers have introduced several RTP schemes, which dynamically adjust the prices based on the load instead of using fixed time−differentiated prices, and hence can be more effective in terms of changing users’ consumption behaviours [4].

Automated Demand Controllers are other forms of centralised DSR where human intervention on electricity loads is combined with, if not displaced by, technological and automatic forms of control. Automated Demand Controllers comprise a wide family of technologies consisting of two−way metering systems to shift electric loads, switch on and off appliances and postpone itemised consumption. Because either the entire or, more frequently, parts of load profiles are pre−set or remotely controlled, peak demand can be mitigated through planning and algorithmic programming.

This means that, prior to the application of Automated Demand Controllers; an accurate understanding of the temporalities and components of the load profiles is needed. A particular advantage of Automated Demand Controllers comes from their integration with low−carbon electricity sources such as renewable systems.

The combination of micro−scale renewables with in situ demand controllers can bring about economic and environmental benefits in terms of improved demand supply matching, maintaining or improving thermal comfort, reduced operating costs and lower carbon emissions. Before detailing the characteristics of the controllers, which were, used for this analysis, it is worth reflecting a priori on some of the differences between Automated Demand Controllers and other DSR technologies and programmes. First, DSR programmes generally work upon the condition that either the demand side can respond to price signals at peak times or other enablers allow load shifts, i.e. variations in supply frequency. The limited elasticity of the demand curve for electricity suggests that ways to encourage consumers' participation in load shifting through feedback alone or economic advantage may need to be integrated with other solutions. Whilst manual DSR solutions rely on signals to induce consumers to either shift or reduce demand, Automated Demand Controllers consist of intelligent algorithms which control specific loads (e.g. electric radiators, air conditioning, lights or an appliance). Potentially this could be a less intrusive alternative to consumer−driven load shifting. Instead of having consumers running around switching devices off, Automated Demand Controllers result in automated load control being implemented as long as the service each load is providing is within upper and lower limits of acceptability. If, on the other hand, there is no code of acceptability between the user and the Automated Demand Controller provider, this might indeed turn into a more intrusive solution to peak demand shifting than other DSR alternatives. The upper and lower limits of acceptability can be re−defined each time depending on the type of load. Levels of radiance for lighting and temperature ranges for heating services and air conditioning are examples of what is acceptable, which ultimately relates either to conventional understanding of comfort and needs, or to individuals setting their own parameters. Both Automated Demand Controllers and manual DSR solutions inevitably rely on a high level of trust between the end−user and the service provider. When operated by energy aggregators, DSR functions due to the presence of two layers of contracts: (i) between the Transmission System Operator and the aggregator (also known as contracted loads), and (ii) between the aggregator and end−users.

In instances of vertical bundling, i.e. when the Transmission System Operator is also an energy supplier, contracted loads consist of a relief to the system, but there is also the risk of aggregators' overshooting, for example, delivering more load reduction than prescribed by the contract, hence limiting the profits for the energy company.

Concerning the end-users, if these do not respond in a timely manner, then aggregators may run out of shiftable loads and eventually incur penalties from the Transmission System Operator for not complying with their contractual obligations. The type of delegation process, which end-users experience through Automated Demand Controllers, requires a high degree of trust in the systems, which operate them.

Whilst it might be widely accepted that some level of automation could be in place for instance for lighting, cooling and heating services, highly discretionary loads are of an entirely different nature and, by definition, difficult to pre-schedule through an algorithm. Social practices related to highly volatile activities (e.g. charging batteries for plug-in devices or switching on kettles) are not appropriate candidates for Automated Demand Controllers, whereas highly predictable and routine-embedded social practices are better candidates. For the same reason the workplace is a more attractive test bed than the household. In this chapter simulations and trials will be based on office spaces where activities related to electricity consumption follow routines and the timing of energy demand is associated with the repetitive rhythm of practices. Indeed, the simultaneous combination of both manual and automated forms of DSR is possible [3].

## 1.2 Smart Metering Programs

Smart meters have been deployed around the globe during the past decade. In this period, the numbers of smart meters installed in the UK, the US, and China reached 2.9 million [5], 70 million [6] [7], and 96 million, respectively by the end of 2016. Smart meters, together with the communication network and data management system, constitute the advanced metering infrastructure (AMI), which plays a vital role in DSM and power delivery systems by recording the load profiles and facilitating bi-directional information flow [8]. The widespread popularity of smart meters enables an immense amount of fine-grained electricity consumption data to be collected. Billing is no longer the only function of smart meters. High-resolution data from smart meters provide rich information on the electricity consumption behaviours and lifestyles of the consumers. Meanwhile, the deregulation of the power industry, particularly on the delivery side, is continuously moving forward in many countries worldwide. Increasingly more participators, including retailers, consumers, and aggregators, are involved in making the retail market more prosperous, active, and competitive [9]. How to employ massive smart meter data to promote and enhance the efficiency and sustainability of the demand side has become an important topic worldwide [10].

A premise to smart meters is that traditionally people have been unaware of their energy consumption because utility bills provide too little information, too long after the consumption to influence decisions regarding the timing of energy demand. In several places by law it is only required that traditional meter reading takes place on an annual or semi-annual basis. As a result, most of the bills received by customers consist of estimates, making it even more difficult to derive any useful information from them. The analogy to 'a supermarket with no price labels' is often used to describe such lack of information by the demand side. Smart meters do not per se deliver any change in energy demand either in absolute energy conservation or in load shifting. However, smart meters generate information (also known as direct feedback) which is otherwise not available to end-users. When combined with human intervention, smart meters have been shown to trigger some level of change in energy demand. The effectiveness of smart meters in modifying electricity consumption depends heavily on the type and medium of the feedback. Feedback can be provided indirectly, through measures such as more detailed, frequent and accurate billing. Feedback can also be provided directly through a web portal, through directly reading the meter, or through a dedicated display device [3].

Based on previous considerations, it is clear that the main benefits of smart meters reside in Smart Meter Programs that the utility chooses to implement. Indeed, the goal of Smart Metering Programs is to change the behaviour of the consumer so that the utility can reduce costs and overhead, and improve the quality of service. Most of this systems from the concept of base load. It is cheaper to run a power plant at full capacity than it is to stop it when energy is no longer needed, and start it again when power is needed. If the power plant could run continuously and supply the needed power without interruption, that is all power generated by the generation facilities was always sold, then the utility would recognize a significant cost savings in their operation. This of course involves aggregating the end-user's energy demands and changing their behaviour in favour of requesting power on a basis that can be easily managed by an energy supervisor (aggregator). This trending will eventually allow the utility to predict how much power will be needed on a daily basis. The utility accomplishes this through various programs designed to change consumer behaviour, such as:

- demand response;
- load profiling;
- automated load control;
- customer outage detection;
- customer voltage measurements and power quality;
- distributed generation monitoring and management;
- remote connect/disconnect;
- real-time meter reading and programming.

There are numerous possibilities with regard to programs that can be implemented as a result of smart meters. Various scenarios exist that can be applied to this concept, and smart meters can be used to accomplish a never-ending stream of goals. The implementation of smart meters then represents business value associated with the Smart Grid.

The utility company controls and aggregates information from meters. This allows the utility to profile load usage based on consumption levels reported by each meter. The goal of this would be to align consumption with the base load output from their generating facilities. If consumption stays consistent with the base load, then no action is needed and the utility would simply monitor power quality to make sure that nothing unusual occurs. If power quality ever indicated a disturbance, then the utility could initiate its outage management processes to predict and respond to failure before it begins. One control that a utility would be able to use in such an event would be automatic load control. This would be true if the system detected the need for more load based on the detection of low power quality. Auto load control would also be used under conditions where the utility wants to automatically ensure that consumers are only using the energy from base load output. To adjust power, the feature on auto load control might disconnect some circuits or use access into the home area network to reduce power consumption. If DG were available, the load could be adjusted by taking in energy from the consumers themselves, if they were signed up to introduce power into the grid. The point of this exercise is to ensure that there is a balanced load and that the utility only has to run base load power [11].

Smart Metering Programs has witnessed considerable developments of data analytics in the processes of generation, transmission, equipment, and consumption. Increasingly more projects on smart meter data analytics have also been established. Apart from academic research, data analytics has already been used in industry. The data analytics application areas include energy forecasting, smart meter analytics, asset management/analytics, grid operation, customer segmentation, energy trading, credit and collection, call centre analytics, and energy efficiency and demand response program engagement and marketing. Meanwhile, the privilege of smart meters and deregulation of the demand side are accelerating the birth of many start-ups. These start-ups attempt to collect and analyse smart meter data and provide insights and value-added services for consumers and retailers to make profits.

For retailers, at least four businesses related to smart meter data analytics need to be conducted to increase the competitiveness in the retail market.

1) load forecasting, which is the basis of decision making for the optimization of electricity purchasing in different markets to maximize profits;
2) price design to attract more consumers;
3) providing good service to consumers, which can be implemented by consumer segmentation and characterization;

4) abnormal detection to have a cleaner dataset for further analysis and decrease potential loss from electricity theft.

For consumers, individual load forecasting, which is the input of future home energy management systems (HEMS) [12], can be conducted to reduce their electricity bill. In the future peer–to–peer market, individual load forecasting can also contribute to the implementation of transitive energy between consumers [13] [14]. For aggregators, they deputize a group of consumers for demand response or energy efficiency in the ancillary market. Aggregation level load forecasting and demand response potential evaluation techniques are developing. For DSO, smart meter data can be applied to distribution network topology identification, optimal distribution system energy management, outage management, and so forth. For data service providers, they need to collect smart meter data and then analyse these massive data and provide valuable information for retailers and consumers to maximize profits or minimize cost. Providing data services including data management, data analytics is an important business model when increasingly more data are collected and to be processed.

To support the businesses of retailers, consumers, aggregators, DSO, and data service providers, following the three stages of analytics, namely, descriptive, predictive and prescriptive analytics, the main applications of smart meter data analytics are classified into load analysis, load forecasting, load managements, and so forth. The main machine learning techniques used for smart meter data analytics include time series, dimensionality reduction, clustering, classification, outlier detection, deep learning, low–rank matrix, compressed sensing, online learning, and so on. [10]

## 1.3 Literature

The existing literature on Demand Side Management for end–users is wide and heterogeneous. According to the definition of DR program in [15], the end–users that join a DR program, modify their electricity consumption pattern in terms of timing, level of instantaneous demand, or total electricity consumption [16] [17], in order to reduce their peak demand, save money and have a more eco–friendly standard of life [18], [19], [20].

Advancements regarding the generation of decentralized renewable energy call for further active integration of energy consumers and prosumers into the energy system. Centralized and complex top–down energy systems are currently being substituted by distributed generation that is located close to consumers [21].

Prosumers are typically residential households self-producing energy from renewable sources such as solar and wind. Currently, locally produced energy can be used for self-consumption, exported to the grid, or stored in energy storage systems. In comparison to traditional energy producers, individual "prosumers are excluded from the wholesale energy market due to their perceived inefficiency and unreliability" [22].

Moreover, the management of energy and the involved technologies are much more complex and need for dynamic optimization of the energy exchanges among the prosumers and the grid [23], [24], [25].

To face these issues, the European Commission has published the Clean Energy Package: the objective is to offer clean energy to all Europeans through a proposal of an Internal Market for Electricity with a revised electricity regulation. The concept of "Local energy community" is defined in Article 16 [26], and it is considered as an efficient way to manage energy at the community level.

Market participants can profit from (possibly) advantageous local market prices and prosumers can generate additional revenue by selling their energy directly to individual consumers [27].

The present work applies the concept of "local market" to a set of individual prosumers that constitute a district and interact with the distribution network through the intermediation of a district manager entity, referred to as "aggregator". The efficient management and operation of a district is enabled also by the exploitation of recent advancements in information and communication technologies [28].

In the literature, three types of innovative market models are identified [29]: peer-to-peer models, prosumer-to grid models, and organized prosumer groups. Peer-to-peer markets involve decentralized, autonomous and flexible peer-to-peer networks that emerge in a bottom-up fashion. Inspired by the sharing economy concept, a peer-to-peer platform allows electricity producers and consumers to bid and directly sell and buy electricity and other services, without any central authority [29], [30], [31].

Prosumer-to-grid markets involve brokerage systems for prosumers that are directly connected to a local micro-grid that, in turn, can operate in connection to the main grid or autonomously in an "island" mode. Organized prosumer groups are community-based and sit between peer-to-peer and prosumer to-grid models, in terms of structure and scale: they are more organized than peer-to-peer networks but less structured than prosumer-to-grid models. This option allows communities of prosumers, possibly corresponding to city neighbourhoods or buildings, to manage their energy needs more efficiently and dynamically, by better taking into account local needs and available resources.

Local market rules have recently received attention and investigation in the literature: in [32] a peer–to–peer market design is introduced, which relies on “random and anonymous pairwise meetings” between buyers and sellers.

A more centralized approach exploits the use of auction formats [33], [34]. Auctions allow the participants to manage buy and sell orders of local energy that are submitted to a (public) order book. The orders are then matched either continuously as in [33], or at discrete market closing times, as in [34], where a multi–agent based distributed software system is presented, which implements a (nearly) real–time energy market.

A usual approach to manage energy within a district is to schedule the load/production/storage profiles of prosumers in advance, i.e., one day ahead, with the objective of maximizing their profit, taking into account local available resources and user needs. This corresponds to the solution of a “prosumer problem”. Some models and solutions of a day–ahead prosumer problem are presented in [35], [36].

Due to the possible simultaneous presence of electric and thermal devices representing electric and thermal loads, heat pumps (HP), combined generators (CHP), n–PRS generators (e.g. photovoltaic plants) the problems of electric and thermal management are strictly interconnected. Some recent papers cover the topic of thermal and electrical management at the user level. The work presented in [37] aims to minimize the electric and thermal cost over one day, assessing the level of thermal comfort as the objective function of a linear optimization problem.

In [38], the goal is to keep the cost of the electricity bill below a threshold chosen by the user, considering that a lower threshold corresponds to a higher discomfort level. Starting from a diversified set of loads (flexible, non–flexible, thermal, curtailable and critical appliances), the optimization is performed through successive stages, in which the number of interruptible loads gradually increases and, therefore, the level of user dissatisfaction grows.

The work presented in [39] considers the presence of electrical and thermal loads and of electric vehicles used as storage systems. For each load, a flat profile is supposed, while production profiles of renewable sources are estimated using appropriate forecast models. All this data is passed to a two–stage optimization model that maximizes the algebraic sum of the revenues obtained with energy production and of the costs of energy purchase.

The work in [40] analyses the management of electric and thermal loads (controllable/uncontrollable and deferrable) and the management of production from controllable sources through two approaches: the first schedules the controllable loads, considering the user preferences and the energy prices; the second reallocates the loads depending on the availability of energy surplus from renewable sources.

The management is done by evaluating the end−user comfort in terms of the preferred temperatures setting and/or the start of the loads operation. In [40], the end−users manage their equipment by using local controllers connected to a single central controller, thus forming a "cooperative neighbourhood".

In [41], a local energy box independently manages the usage, the storage and the sale of energy in response to the real−time conditions of the grid, allowing the user to balance the level of comfort and minimize the electric bill.

The work presented in [42] analyses a management model of electric and thermal loads, based on the observance of some consumption limits. The control takes place in real−time and requires the active participation of the end−users, who must respond to the outcome of the optimization, by accepting or rejecting the proposed schedule.

The authors of [43] propose a demand response program for prosumers based on a management model of consumption and generation, and solve the so−called prosumer problem.

According to the classification of various types of DR programs in [17], [18] and [44], the management model in [43] is a "price−based" and "time−of−use" program that minimizes the cost of energy consumption. Prosumers are arranged in energy districts managed by a centralized coordinator, referred to as aggregator, which is in charge of the activities regarding the energy purchase and sale within the district and between the district and the energy market. The aggregator has the task of applying suitable strategies for improving the energy efficiency thus reducing the costs for all the users of the district.

# 2 New Models and Devices for Demand Response

## 2.1 Novelty and Contribution

In the last few decades, the energy sector has undergone a radical transformation due to different factors. Definitely two of them have been fundamental: the introduction and the widespread distribution of private small plants especially from non-dispatchable renewable energy sources [45] directly connected to the grid, and the liberalization of the energy market [46]. In the energy sector, new players appear: small size producers, beside the existing big ones, try to sell energy to the market, while wholesalers buy electricity from producers and resell it to the customers. At the same time, the Transmission System Operator (TSO) and the Distribution System Operator (DSO) control the physical energy flows to guarantee the grid security.

Renewable energy sources (RES) enable users to take an active role since they turn out to be both producers and consumers at the same time. A user with this characteristic is named prosumer in the current literature [29]. Therefore, there is an increasing difficulty in the management of the electric grid because the energy production coming from non-dispatchable RES may not correspond to the energy demand. In this case, the surplus of energy is injected to the grid.

The liberalization of the energy market fostered the reduction of the energy prices thanks to the competition among different operators. However, such reduction has no effect on the cost of energy for the end users, due to the mark-ups applied along the chain of intermediaries interposed between the energy provider and the end users. Each intermediary imposes its mark-up to the energy cost so the benefits of the energy market liberalization turn out to be very slight. Consequently, users are encouraged to join to interact with the energy provider directly.

The combined effect of the availability of RES and the liberalization of the energy market prompted researchers to study new forms of aggregation among users to give rise to the so-called energy districts.
Typically, the set of users that deliberately join the energy district are managed by a centralized coordinator, which manages the purchase and sale of the energy within the district and between the district and the energy market. The centralized coordinator, often referred to as aggregator, has the task of applying suitable strategies for improving the energy efficiency thus reducing the costs for all the users belonging to the district. However, the management of the massive distributed energy production from RES, especially from not-dispatchable RES, requires an increased transfer of responsibility towards the prosumers. In fact, each prosumer is in charge of purposely managing its own loads and generation systems. In this way, the aggregation of aware end-users in an energy district responds well to the indication of European Community [47], fostering the prosumer to the energy market, through local energy exchanges resulting in a considerable bill reduction [48] [49].

Starting from the above considerations, in this work new models and enabling IoT technologies for energy districts is proposed, which aims to optimize the energy exchange within the district between the prosumers with the goal of improving the energy efficiency and reducing the costs.
A new DR program envisioned at the energy district level where the aggregator dynamically determines the energy prices based on energy market conditions, is presented. The whole district is supported by a Cloud component, which is in charge of supplying high-level aggregated information to the prosumers to allow them to participate in the DR program and choose the best energy strategy. Each prosumer that belongs to this district and participates in the DR program, is equipped with an energy box, as described in [50], which manages the prosumer’ s devices, retrieves the aggregated information from the Cloud component, and elaborates and actuates a proper strategy for minimizing the energy cost. A unified prosumer problem is introduced, as an enhanced version of the prosumer problem described in [43].
The new version starts from a unified model for optimizing, at the same time, the electrical and thermal energy management of a prosumer. The objective is to optimally schedule the following prosumer equipment, such as loads, generation plants, electric and thermal storage systems, in order to minimize the cost associated with the supply of electricity and heat, while taking into account a set of user-defined energy preferences. The main enhancements introduced in this work with respect to [43] are summarized in the following.
First, the thermal component in [43] only consists of a micro-CHP whereas this work also considers the gas boiler, the heat pump and the solar panel. In addition, our unified prosumer problem also models the possibility to sell energy to the grid to maximize the revenues besides minimizing the costs. Another important enhancement refers to the modelling of the electric and thermal storages, not present in [43].

Moreover, the thermal load is determined using the algorithm reported in [51] that allows a good compromise between the computational burden and the accuracy of results in simulating the dynamic behaviour of the buildings, improving the thermal load model presented in [43]. Finally, while the optimization in [43] only concerns the electric loads, the unified prosumer problem introduced here also produces the optimal scheduling for the controllable plants and the electric and thermal storage systems. This unified model exhibits better performance, in terms of energy cost reduction, with respect to the approaches in which the electrical and thermal equipment are managed in a separate way.

Differently from [38] [39] [40] [41] [42], in which the management models try to achieve a trade-off between energy cost reduction and the user energy comfort, our approach allows to totally satisfy the user preferences. In addition, differently from [42], the proposed model allows to manage the prosumer equipment almost autonomously with a minimal involvement of end-users, who are only in charge of setting their load schedule preferences. The model takes into account various types of loads (both schedulable and non-schedulable) and different types of power generation systems (using traditional and renewable sources, programmable and non-programmable). Moreover, other additional devices are considered, i.e., the heat pump, the gas boiler and the solar panel system. Finally, both electrical and thermal storage systems are considered.

In addition, a novel two-stage approach for the energy district management is presented. The two-stage model, differently from the single-stage model described in the first part of the work, because it allows to improve the distribution of energy among the prosumers of the district and to better exploit the local availability of renewable energy. Preliminary, the National market provider determines the wholesale prices at which the district can buy/sell energy from/to the grid. Then, the district aggregator determines the local tariffs, i.e., the prices reserved to district prosumer for buying and selling energy within the district. In the two-stage model, each day the aggregator acts an auction organized in two stage, with the purpose of satisfy all the energy demands at a minimum cost. During a first stage, on the basis of these prices, the prosumers schedule their load/production profiles in order to maximize their profit, by solving an optimization problem called "prosumer problem of first stage", which takes into account local available resources and user needs. The objective of the second stage is to refine the solution by managing the frequent scenarios in which, at some specific hours, the quantity of produced energy is greater than the energy needed to satisfy the load requirements.

Without the introduction of the second stage, the energy surplus would be sold to the grid at the wholesale selling price. However, both the aggregator and the prosumers can take more benefits from redistributing the energy surplus within the district. The goal of the second stage is to perform this redistribution by solving a modified version of the prosumer problem, which takes into account the availability of prosumers to buy the energy surplus at a price that is more convenient than at the first stage. The addition of the second stage allows both the prosumers and the district as a whole to reduce the costs by a considerable amount. In this work, the two-stage approach is describe in detail and the numerical results achieved on a real testbed performed in the Energy District of the University of Calabria, Italy is present.

Other contributions of this Ph.D. thesis concern the section on home energy management system (HEMS) devices and Smart Meters development, in which a comprehensive literature review of smart meter data analytics on the demand side with the newest developments has been conducted.
Different prototype have been realized and tested in an experimental demonstrator realized during the development and the work carried out in the MIUR project *"Sistemi Domotici per il servizio di brokeraggio energetico cooperativo"* .

Follows a well-designed taxonomy for smart meter data analytics applications from the perspective of load analysis. An innovative Smart Meter prototype used in an energy district environment equipped with web application has been designed. Finally, thanks to the data collected through the smart meter prototypes made at the LaSEER laboratory, data analysis was performed in order to classify the monitored consumer.

## 2.2 Power Cloud Architecture and Domus District Models

In this section the architecture of the Energy District, named Power Cloud, is introduced. As mentioned before, the Power Cloud injects smartness into the management of an energy district to improve the global energy efficiency.

In general, an energy district comprises a number of dwellings joined together in order to optimize the exchange of energy with the grid and reduce costs. In particular, there can be dwellings equipped with only loads who import energy from the distribution grid in order to fulfil the energy requirement of their loads, i.e., consumers. Conversely, a producer has only local generation plants, which allow it to sell energy to the grid. In the frequent case in which a dwelling is both a consumer and a producer can be referred to as a prosumer. Henceforth, though, the term prosumer is used also for dwellings that are only consumers or only producers because they can be considered as "special cases" of prosumer. A storage system can be optionally hosted by a prosumer in order to accumulate energy during periods of overproduction to be able to exploit it when the energy requirements exceed the production.

All the prosumers in the district communicate with a cloud component, which is in charge of managing the whole district. The cloud component can be managed by a single data centre or, in case of very large districts, by a set of interconnected data centres [52]. In particular, in our proposal, each prosumer is equipped with an Energy Management System (EMS), named Smart Energy Aware Gateway (SEAG), in charge of managing the loads and the generation systems. The EMS is designed to cope with the heterogeneity of devices that are built by different vendors with different technologies. In addition to the EMSs, the whole district is supported by a cloud component that comprises the aggregator of the district and a service provider, which supplies high−level information to the EMSs necessary for their local optimization tasks. The EMSs introduce a local intelligence layer distributed across the district. On the other hand, the centralized cloud component is in charge of all the tasks requiring high computational resources or concerning aggregated information, for example, the forecast of the energy production of photovoltaic plants and of the overall energy consumption of the users [53]. Such tasks are typically performed through the usage of neural networks and other soft−computing applications, which are generally computationally intensive [54]. The aggregation of all the prosumers, equipped with the EMSs, together with the centralized cloud component, forms the the Power Cloud.

A schematic illustration of a Power Cloud system is shown in Fig. 1. The involved coarse−grained entities are a set of prosumers and a centralized cloud component. Each prosumer hosts the following equipment:

- a home automation system;
- a nano−grid system;
- a SEAG, which enables the interaction with the aggregator and supervises both the nano−grid and the home automation system. It is in charge of locally optimizing the energy management by considering the user preferences and interacting with the aggregator.

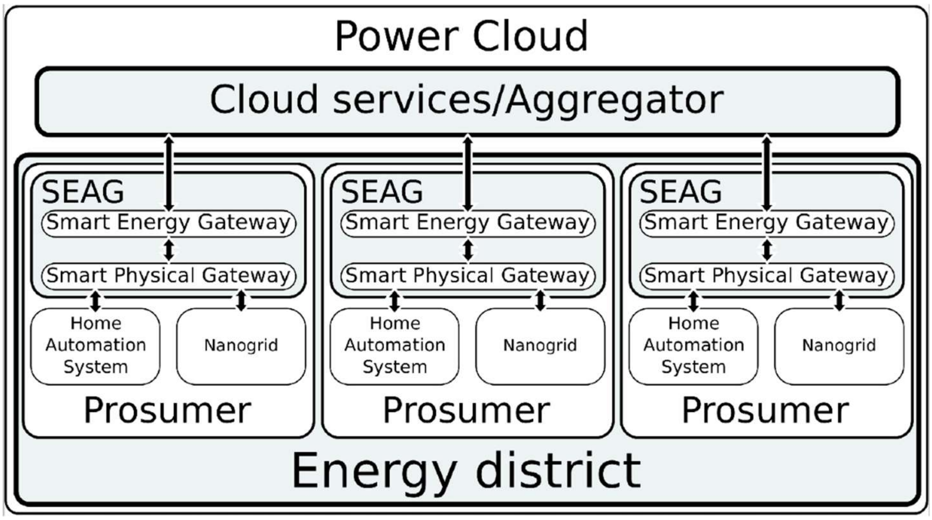


*Fig. 1 − Architecture of the Power Cloud*

The cloud component is composed of two entities: (i) the aggregator and (ii) the cloud service provider. The former is in charge of managing the energy exchanges among the prosumers and between the whole district and the main grid. The latter supplies information to the prosumers by executing a set of algorithms that require computational resources that are beyond the capabilities of a SEAG.

These algorithms supply, on a daily basis, information concerning: the hour-by-hour energy production forecasts based on the weather forecast and the physical characteristics of the generation plants; the hour-by-hour prices of the electric power determined by the conditions of the energy market. In particular, the outcomes of the electricity market define the prices, hour-by-hour, for exchanging energy with the grid: PZ, the zone prices, i.e. the selling prices, and PN, the single national prices, i.e. the buying costs.

The cloud service provider determines the buying/selling prices for the energy exchanges within the district based on PZ and PN in such a way that the buying cost is lower than PN and the selling price is higher than PZ. In order to elaborate a proper working plan for the nano-grid and the home automation system, this information is computed every day for the following day and is taken into account by the prosumers, through their SEAGs, which optimizes the energy consumption and reduces costs. In particular, each SEAG solves the so-called prosumer problem: for this issue it takes the energy production forecasts performed by the cloud component and the electrical power prices as input.

This data are used to compute the optimal schedule to:

(i) the activation/deactivation of the electrical loads;
(ii) the use of the thermal/electrical storage systems;
(iii) the amount of energy imported/exported from/to the grid.

The prosumer problem is modelled as a linear programming problem and solved with the C-Plex tool [50]. Afterwards, the SEAG communicates its resulting power profile, i.e., the energy imported/exported from/to the grid, to the aggregator, which in turn computes the aggregated power profile of the whole district. Given that the purpose of the above described plan (the output of the prosumer problem) is to respond to the needs of the dwellings inhabitants, the prosumer problem takes also into account a set of user preferences which are supplied by means of a Graphical User Interface (GUI) exposed by the SEAG (see section 5.2.2). As better described in the section 4, the above operations correspond to the so-called first stage.

In a second stage, starting from the first stage aggregated power profile, the aggregator identifies the hours of the day in which there is a surplus of produced energy and try to reallocate it within the district. Its goal through a series of auction procedures is achieved. Afterwards, the aggregator re-computes the aggregated power profile of the whole district.

### 2.2.1 The Aggregator

Aggregating the Demand Response (DR) is approved as an effective solution to improve the participation of consumers to wholesale electricity markets.
DR aggregator can negotiate the amount of collected DR of their customers with transmission system operator, distributors, and retailers in Demand Response market, in addition to participate in the energy market [55].
In the current literature, the aggregators is defined as new entity in the modern electricity market that act as mediators / brokers between users and the utility operator. Aggregators possess the technology to perform DR and are responsible for the installation of the communication and control devices (i.e. smart meters) at end-user premises. Since each aggregator represents a significant amount of total demand in the DR market, it can negotiate on behalf of the home users with the operator more efficiently [56].

In this work, an energy district framework has been proposed to optimize the participation of a DR aggregator in day-ahead energy market. The objective of each aggregator is to maximize its own net profit, namely the income received from the operator minus the compensation it provides to home users.
In this regard, the DR aggregator optimizes its participation schedule and offering/bidding strategy in the mentioned markets according to behaviour of the customers joining its energy district. In other world, the aggregators is in charge of globally optimizing the energy management of the whole energy district by providing DR services able to supervise and to manage the total energy demand and the energy exchanges among the prosumers and between the whole district and the distribution grid. In order to supervise to whole district, the aggregator makes use of home energy management systems (HEMS) installed inside the prosumer dwellings, with which communicate through a graphic interface, described in section 5.2.

### 2.2.2 The Cloud Services

The Aggregator supplies cloud services to the prosumers by executing a set of algorithms requiring computational resources that are beyond the capabilities of the local EMSs. In particular, these algorithms provide, on a daily basis, information concerning:

- the hour-by-hour energy production and consumption forecasts based on the weather forecast, the physical characteristics and the historical data of the generation plants

- the electrical and thermal loads (the thermal loads are established in order to guarantee the user−defined temperature set points [53]);
- the hour−by−hour energy prices determined on the basis of the conditions of the energy market;
- energy surplus information.

This information is computed by the Aggregator every day for the following day and is sent at a predetermined hour to all the prosumers of the district. The EMS of each prosumer use this information to elaborate a proper working plan for the nano−grid and the home automation system, which optimizes the energy consumption and reduces the costs. In particular, each energy box solves the so−called unified prosumer problem taking as input: the energy production forecasts, the energy prices and the thermal load consumption forecasts.

### 2.2.3 The Daily Workflow

The daily activities of a prosumer joining the energy district can be subdivided at a coarse−grain level into two stages. Moreover, it is possible to identify six phases, as outlined in the Fig. 2 by the horizontal black dashed lines.

Since the purpose of the scheduling is to respond to the needs of the dwellings users, in the first phase, the unified prosumer problem takes into account a set of user preferences that are supplied by means of a Graphical Prosumer Interface (GPI) exposed by the EMS and better described in the paragraph 5.2.2. In particular, the dwelling users can set their preferences about the power profile of the loads for the following day and the desired thermal preferences. This operation must be concluded before a predetermined hour, after which all the Energy Management Systems (SEAGs) start the second phase. In addition, the SEAG sends the thermal preferences, i.e., the desired set points of temperature, to the Cloud service provider which uses the preferences to compute the thermal load forecast.

In the second phase, the Cloud service provider computes the production forecast of non−controllable power plants and determines the energy prices for importing/exporting electric energy. All this information is then sent to the SEAGs. At this point, the SEAGs have all the information required to runs the unified prosumer problem and stores the results in a local database. In the third phase, each of them communicates its hourly imported/exported energy profile to the aggregator. This concludes the first stage, as well as the third phase, since the aggregator is now able to compute the aggregated power profile for the whole district.

The aggregator, based on the global profile of the energy produced and consumed inside the district, establishes the hours at which an energy surplus is available and tries to reallocate this energy back to the prosumers.

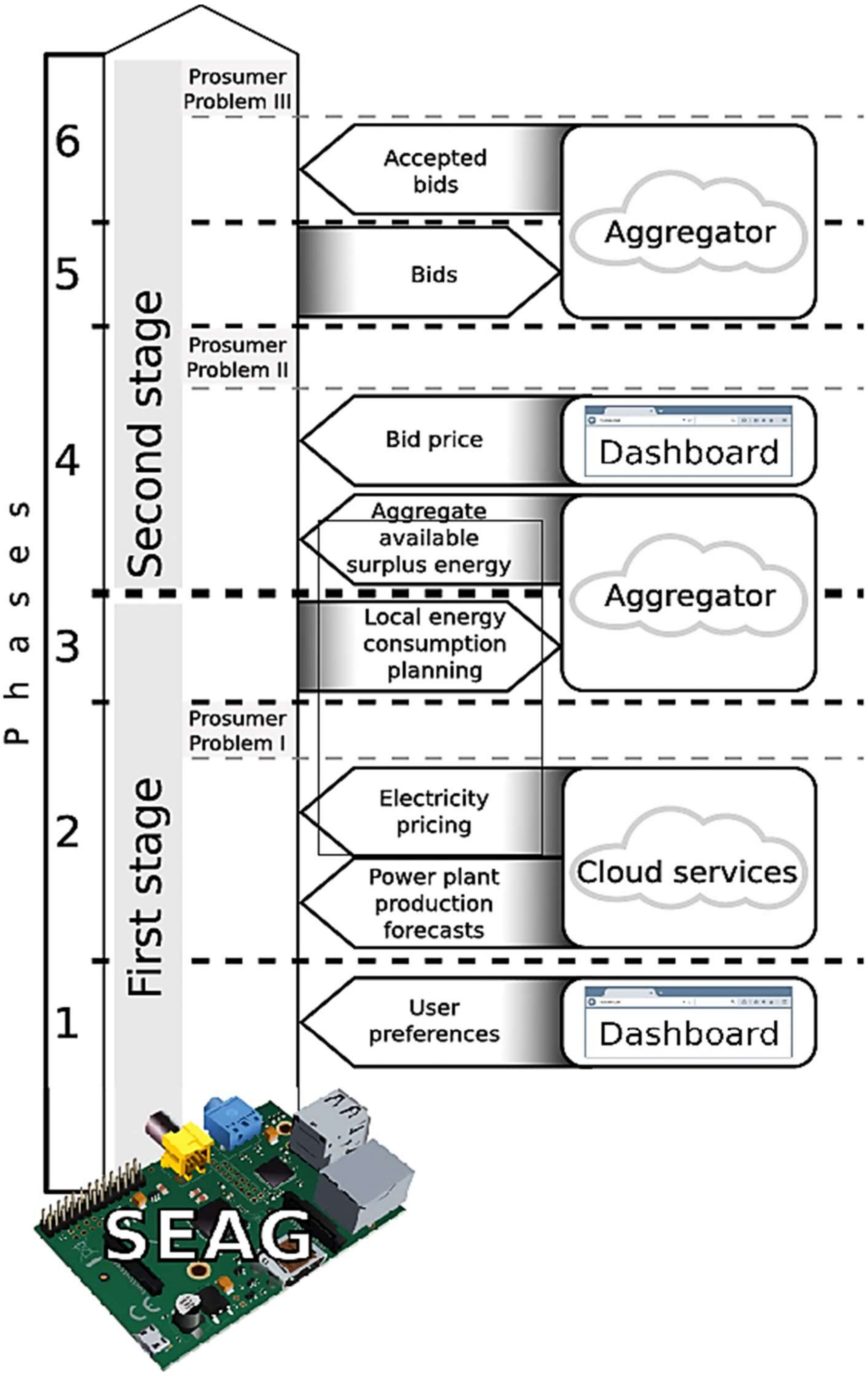


*Fig. 2 – Daily workflow*

The optimal case should be the one in which the district is energy self-sufficient. In such a case, ideally, the aggregated profile is zero for every hour, meaning that the total amount of energy produced by the prosumers within the district corresponds to the demand of energy, and there is no need to exchange energy with the distribution grid.

However, it usually happens that the aggregated profile is negative for some hours (deficit) and positive for some other hours (surplus), so it would be necessary to exchange energy with the grid. To cope with this issue, during the second stage, the aggregator tries to reallocate the surplus energy by means of a series of auctions. A prosumer can assess whether it is advantageous to buy additional energy with a cost lower than before. In particular, during the fourth phase, each SEAG retrieves from the aggregator the information about the surplus hours and the corresponding base auction prices. Based on a user defined bidding strategy, each SEAG determines the bid price for each surplus hour. Afterwards, each SEAG re-executes the prosumer problem using the bid prices as buying costs for the surplus hours. The outcome of this second run of the prosumer problem corresponds to establishing whether it is convenient to buy additional energy and, if so, at which surplus hours. This concludes the fourth phase. In the fifth phase, the bids obtained from the second solution of the prosumer problem are communicated by each SEAG to the aggregator. The latter decides which of the bids to accept and which to decline based on the availability of the surplus energy and of the received bids. In the sixth and last phase, each SEAG receives information from the aggregator about the amounts of energy surplus granted to it. A third solution of the prosumer problem is then computed taking into account the hours for which the bids have been accepted and the corresponding amounts of granted energy. The information computed by the SEAG when executing the daily workflow described previously is stored in a database.

The output of the unified prosumer problem is the optimal scheduling to:

(i) the activation/deactivation of the electrical loads;
(ii) the charging/discharging of the storage systems;
(iii) the amount of energy imported/exported from/to the grid;
(iv) the operations of controllable plants (e.g. HP and micro-CHP).

On the following day, the energy box uses these results and actuates the schedules on the nano-grid and the home automation system. In particular, the actuation involves the electric loads and the controllable plants, e.g., the gas boiler, the micro-CHP and the heat pump. During the following day, there could be some mismatch between forecasts and real value of produced/absorbed energy; such mismatch may cause imbalances between the forecasted profile exchanged with the grid and the real profile.

How to reduce such mismatch is out of topic of this work, however, this issue can be tackled by a suitable real-time control such as the one reported in [57]. More information about the IT architecture of the energy district, and the adopted hardware/software solutions, is available at [28].

## 2.3 Iot Devices for a Smart Energy District

If there were a front line in Smart Grid and Smart Energy District, then smart metering would be considered the point where Smart Grid begins. The primary mission of a meter is to monitor power consumption through metrology, which measures the amount of load an entity takes in. Meters are most widely used on commercial and residential buildings. In the past, utilities would physically visit each meter on a schedule in order to read it and determine how much energy a consumer was using. They have come up with complex mechanisms to predict how much energy a consumer would use in order to be able to bill the consumer.

If the utilities deploy smart meters today, they will be able to gain more accurate meter readings and thus be able to provide bills that are more precise to their consumers. However, it may take years of planning, strategizing, and implementing such technology. In addition, there is a cost associated with the deployment of each smart meter, which is estimated at anywhere from $50 to $200 per unit.

Smart meters have existed as both advanced meter reading (AMR) and advanced metering infrastructure (AMI). AMR meters typically represent one-way communication that allows utilities to gain meter data remotely, eliminating or reducing their need to do manual meter reads. AMI, however, brings additional functionality to the utility that can even be extended into the actual consumer space. AMI meters typically represent two-way communication that allows the utility to do more than just collect meter readings remotely. The reason behind this lies in the need to provide the capability to allow a central control point to have access to and control every meter within the architecture, while at the same time ensuring that meters have the ability to report information back to the control point. Then there is the need to process this information so that it can be used in billing and other applications that make the meters "smart." These applications are used to implement DR programs that allow the utility to realize a benefit [11].

Furthermore, one of the questions that researchers focusing on behaviour, especially in disciplines like psychology and economics, have been debating on for some time is how people respond, in terms of energy demand, to smart meters.

A set of demographic and attitudinal variables may influence conservation behaviour and the level of reduction from real-time electricity consumption feedback, though there is mixed evidence as to how much and in what direction. It has been argued that higher income is correlated to higher electricity consumption and higher environmental awareness. Smart meters may have a greater effect on energy consciousness (i.e. sticking labels on at the supermarket) rather than triggering actual energy demand reductions.

Consistently, higher levels of environmental awareness have generally not been conducive to more conservation. This may be because in empirical studies, the households that sign up to or opt into the program are more environmentally aware and therefore have already lowered their discretionary electricity use. Several of these studies are designed from a psychology of behaviour perspective and they disregard issues of supply and infrastructure [3].
In the following section, different prototype of Energy Box (EB) and Smart Meters are presented. The EMSs have been realized, installed and tested in a scientific demonstrator discussed in section 6.

### 2.3.1 Energy-Box Prototypes

In the framework of the integrated community of Power Cloud, the aggregator and the customer communicate with each other very frequently; the EB is the device, which interfaces the aggregator and the customer.

Given the aforementioned, the design of an EB is a hard task and full of challenges; a first and well-known challenge is to design the EB as a useful tool for communication between the consumer and the aggregator. A further challenge is to design an EB able to interact with the home energy management system (HEMS); this is because an HEMS, in general, does not necessarily share information and data (e.g., energy consumption measurements) with third parties, and it does not necessarily accept commands (e.g., turn on/off appliances) from third parties. In a residential unit, the HEMS is the device that monitors, controls and optimizes all peripherals, storage systems, distributed generators and smart meters. The HEMS asks the smart meters for energy consumptions to build a detailed and comprehensive status of the residential unit. Such a status is useful to precisely model and estimate energy consumption of the residential unit by using, as an example, a learning-based mechanism as in [58], [59]. Therefore, the interoperability between EB and HEMS is a crucial point for implementation of a DR program in a framework of integrated community. Interoperability must be ensured regarding the communication protocols, the data format and the physical media used for communication; interoperability must also be extended to smart meters and all peripherals [60], which operate in islanded mode or in absence of a HEMS. When the same vendor produces the EB, the HEMS, the smart meters, the smart plugs and peripherals, the full interoperability is implicitly achieved; on the contrary, the management of devices produced by different vendors is much more difficult. A last challenge is to design the EB as a cost-effective tool if this technology is intended for a large number of customers, including less affluent people.

This section presents two laboratory prototypes of the proposed energy box, namely low−EB and high−EB as described in [61]. The first prototype low−EB has a limited computing capacity and an Arduino MEGA 2560 (Arduino Holding, Ivrea, Italy) performs it; the second prototype high−EB has a greater computing capacity and a Raspberry Pi3 (Raspberry Pi Foundation, Cambridge, United Kingdom) performs it. Both prototypes are mounted on a demonstration panel of a residential unit together with a real home automation system (see Fig. 3).

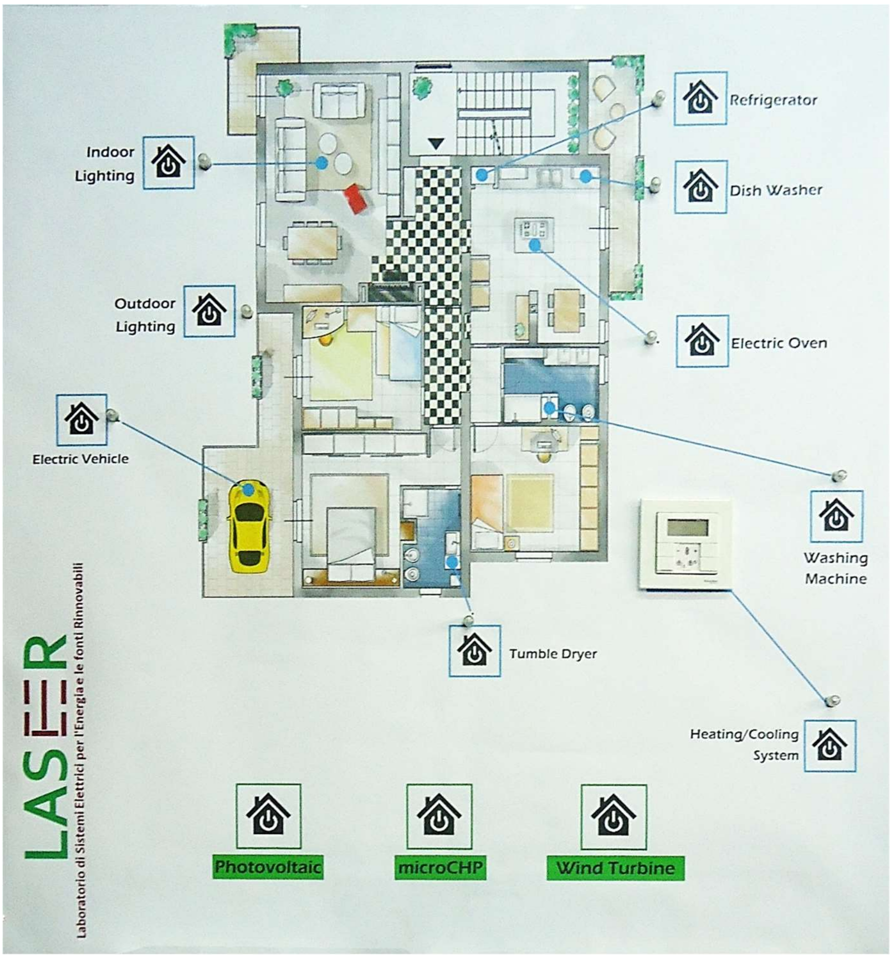


*Fig. 3 – Home automation system on the demonstrative panel*

Concerning the communication between the consumer and the aggregator, the proposed EB communicates with the aggregator’s IT platform and requires access to an application, service or system. Communication is over the Internet and based on the traditional client-server paradigm; Hyper−Text Transfer Protocol over Secure Socket Layer (HTTPS) is the communication protocol used for secure communication.

As illustrated in Fig. 4, the proposed EB connects to the aggregator, uploads the user’s preferences and requires access to the application called prosumer problem; the application responds by providing the optimal loads scheduling. Furthermore, as in Fig. 4, the EB uploads power/voltage/current measurements and it requires access to the service called monitoring and calculation; the service responds by providing reports and statistics.

Concerning the interaction with HEMS, the proposed EB overcomes the problem of interaction because it directly communicates with all peripherals of the home automation system, bypassing the HEM. In particular, the proposed EB generates the control frames to turn on/off a load or to acquire a measurement from a meter; then, the EB sends these frames to loads and meters via the physical media for the communication of the home automation system, i.e., the typical shielded–twisted pair cable.

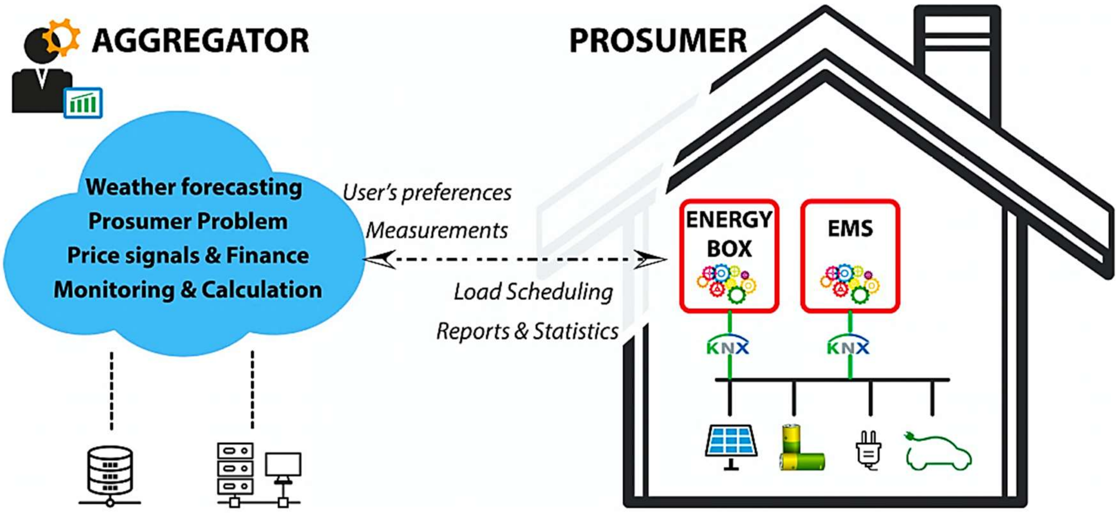


*Fig. 4 – An energy box in a cloud–based architecture for autonomous demand response*

Since the proposed EB bypasses the HEMS, two significant benefits are achieved. The first advantage is to overcome the obstacles placed by the HEMSs currently available on the market regarding the connection to devices supplied by third parties. Indeed, while HEMS are equipped with USB, RJ45 or RS482 ports for a peer–to–peer connection to EBs, a time–consuming configuration of both of these devices is usually necessary, in absence of any guarantee of obtaining a proper interaction and interoperability.

The second advantage is to provide the DR program with the diagnostic, monitoring and control functions. While very important, these functions are not performed by the HEMSs currently available on the market or they are performed with insufficient quality. As a remedy, the proposed EB can be successfully adopted because it is unchained to HEMS and the valuable functions implemented by the EB are not stifled by the limits of the HEMS itself. In particular, the proposed EB uses easy programming languages to enable the expert customer to autonomously run a DR program and implement new functions and procedures that best meet its own needs.

Concerning the management and material requirements also in terms of cost–effectiveness, the two prototypes of the proposed EB were designed and tested in the laboratory; tests were carried out in conjunction with a demonstration panel of a residential unit, equipped with a real home automation system by Schneider Electric, better described in section 6.4.

The first prototype has a limited calculation capability and a low−cost (low−EB), the second prototype has a higher cost but also a higher capacity for solving calculation problems (high−EB). The low−EB prototype communicates with the aggregator over the internet to exchange data and submit service requests; in particular, it asks and receives from the aggregator the optimum scheduling of the consumer' s loads. The low−EB prototype applies scheduling without the help of HEMS by sending the on/off commands to the peripherals of the automation system. The high−EB prototype performs the same functions as the low−EB prototype, and in addition, it is capable of calculating optimum scheduling of consumer loads.

- Energy Box: Arduino Version

This section proposes a new EB as a viable solution to the challenge of the communication between consumer and aggregator, and to the challenge of the interaction between an EB and HEMS. The prototype of the proposed energy box with a limited computing capacity is named low−EB and it mainly consists of: one liquid crystal display (LCD) with four lines and twenty characters per line, one Arduino Mega 2560, one Wi−Fi shield for Arduino, one micro SD card and one sim Tapko KNX (TAPKO Technologies GmbH, Regensburg, Germany). In Fig. 5 the low−EB is illustrated. The mission of the low−EB is exclusively to ask the aggregator for the load scheduling, i.e., the prosumer problem solution, and apply the scheduling. More precisely, the low−EB connects to the internet via a local router and synchronizes its internal clock to that provided by the National Institute of Meteorological Research. Then, the low−EB sends a request to the aggregator for the optimal scheduling of the electrical loads.

*Fig. 5 − Energy box (Arduino version)*

- Energy Box: Raspberry Pi Version

The prototype of the proposed energy box with a higher computing capacity is named high−EB and it mainly consists of a 7 inches touchscreen, one Raspberry Pi3 and sim Tapko KNX (see Fig. 6). The high−EB performs the same functions performed by the low−EB and, in addition, it is capable to self−calculate the optimal scheduling of consumer’ s loads. At this scope, the high−EB facilitates the customer in indicating their preferences, such as the interval time within the appliances must run, because the aggregator’ s GUI now locally runs on the Apache web server application installed on the Raspberry Pi3. The high−EB communicates with the aggregator and asks for services such as the hourly electricity prices and the hourly PV−wind generation forecast for the customer’ s site. The high−EB uses the customer’ s preferences, prices and forecasts to calculate the optimal loads scheduling; the high−EB hourly generates and writes control frames on the STP cable using the sim Tapko KNX in order to apply the loads scheduling.

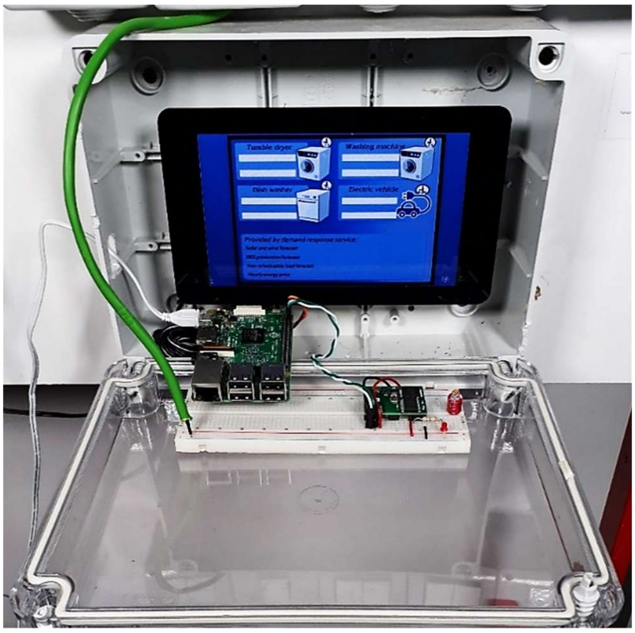


*Fig. 6 − Energy box (Raspberry Pi version)*

As well as the low−EB, every five seconds the high−EB carries out a reconnaissance on the system’ s power consumption; in particular, it invokes the smart meter for the power measurement at the point of delivery and every 15 min it sends the last 15 mean values to the aggregator.

In order to allow the high−EB to self−calculate the loads scheduling, we programmed the prosumer problem into the Raspberry Pi3 using the development environment named Eclipse for Java programming. In order to solve the prosumer problem, we used the IBM ILOG CPLEX Optimization Studio solver (CPLEX); such a solver uses the simplex method, it runs on Linux (i.e., the Raspberry Pi3 operative system) and it solves the prosumer problem within 10 - 15 s.

### 2.3.2 Smart - Meter Design

A Smart Meter is an electronic device that allows the measurement of all the quantities necessary to monitor the energy exchange through a cable electric line. The Smart Meter designed at the "Electric Systems Laboratory for Energies and Renewable Sources" is intended for using in grid−connected or stand−alone utilities, generally equipped with distributed generation systems, loads and storage systems. In particular, it allows measuring and determining the following physical quantities: voltage, current, active power, reactive power and energy exchanges. As mentioned, the Smart Meter is an electronic device consisting of a microcontroller and one or more current transformers (CT). The latter are measurement transducers physically applied to monitor all active conductors of the electrical networks in the cable. After that the Smart Meter measures the previous quantities, follows the upload of the measured data on a web server. To this end, the Smart Meter is equipped with a Wi−Fi board and an access point to the Internet. The model adopted during the upload phase is a client − server type typical of Internet networks and company information systems. In particular, the uploading phase takes place through the execution of an HTML request by the Smart Meter (client) containing the data to be sent to the web server; the web server receives the service requests from the clients and imports the data to a remote database after it has been processed accordingly. The central web server is intended to manage the traffic of information that the Smart Meters send, and to store the measurements received on a remote database. A web application, served by the web server, is used to complete the configuration process and provides information about the production / consumption status of the monitored systems / loads by graphically displaying the measured values taken from the field.
The majority of smart meters collect electricity consumption data at a frequency of every 15 minutes to each hour while this Smart Meter is able to collect information with a frequency until 5 seconds. In this way is possible to catch all the power variation and analyse with more sensitivity the power profiles.

The Smart Meter is designed to be installed at any kind of user. During procedures of configuration, it is sufficient to indicate which type the user belongs to. It is also required to indicate the type of plant and the type of connection. User can be divided into three types: producer, consumer or prosumer. While the type of plant can be divided into single−phase or three−phase. Finally, the type of connection can be grid−connected (connected to the distribution network, through POD) or stand−alone (not connected to the distribution network). In particular, a user is defined as producer if equipped with one or more distributed generation systems. There are no precise limitations regarding the size or type of systems, which can be heat engines equipped with generators, aero−generators, photovoltaic panels, small biomass power plants, with sizes from a few kW to a few MW.

Being located close to the end user, these plants are generally connected to the low voltage distribution network, by introducing the entire quantity of energy produced into the network. In some cases, it is possible to install one or more electrical energy storage systems.

A consumer is a user with one or more electrical loads. In addition, in this case, these users are generally connected to the low voltage distribution network, taking from the network the entire quantity of energy consumed. Also for this type of users, it is possible to foresee the use and therefore the monitoring of one or more electric energy storage systems.

A prosumer is a user equipped with one or more generating plants, one or more electric loads and, possibly, one or more storage systems.

Therefore, the different cable power lines that the Smart Meter can monitor refer to generation plants, loads, and accumulation systems.

For simplicity, whenever you will refer to a monitored cable power line you will avoid specifying to what type of system the line is connected (if a power plant or a load or a storage system) and you will simply talk about plant monitored.

- Technical features

The Smart Meters are therefore made-up of one or more measuring modules and one or more current transformers (CT). The measurement modules are designed to measure voltages at 230V / 50Hz, with maximum measurable values of 270V / 50Hz, so to satisfy most of the low voltage users. The CT chosen for this type of application belong to the Spark XH-SCT-T16 series.

*Table 1 - Technical features of the Smart Meter*

| | |
|---|---|
| Power supply | 230Vac (±10%) 50/60 Hz - equipped with protection fuses |
| Radio specifications | Wi-Fi 802.11b/g/n<br>Access point (AP) Station (STA), B, G, N or mixed mode |
| Memory | Data log up to five years (expandable memory) |
| Sampling | Up to 3 second |
| Status displays | 3 Led |
| Connections | Screw terminals for power connections, measurement CTs, inputs and control outputs (for extension module) |
| Current measurement | 3 channels single phase<br>Split core CT (internal Ø 15 mm max), up to 50A,<br>Accuracy ± 1% from 5% to 120% of rated current |
| Antenna | External antenna on SMA RP screw connector for data transmission via Wi-Fi |
| Outputs (optional) | Relay output (max 10A @ 230Vac)<br>Control output 0-10Vdc |
| Inputs (optional) | 2 x voltage-free alarm contact (NO) |
| Ambient parameters | Operating conditions: 0 to +50 ° C; <80% RH non-condensing<br>Storage conditions: -20 to +70 ° C; <80% RH non-condensing |
| Index of protection | IP20 |
| Dimensions (LxHxD) | 9-module DIN rail housing 160 x 110 x 60 mm |

These transducers are able to measure effective AC current values from 0A / 50Hz up to 120A / 50Hz. The CT of the selected series are designed for an easy and immediate installation around the electrical cable line to be monitored. The split-core design allows contactless current measurements through magnetic field induction, without requiring the primary wire to be taken offline and disconnected for installation. In the follow, table a list of the most important technical features.

- Installation phase

The installation of one or more Smart Meters is immediate and simple to perform. The procedure to be performed consists of a first phase of physical installation of the device on a DIN bar inside the electrical panel of the user and the assembly of the CT around the electrical cables in the cable to be monitored. In the case of a Smart Meter intended for single-phase use, it is sufficient to use a single module: 6 analogical inputs will be available, of which 1 must be used for voltage measurement of the whole electrical system of the dwelling, while the remaining 5 will be used, all or in part, for measuring the current. From one to five CT will be connected around the electrical lines in cable relative to the systems / loads / storage systems to be monitored. A graphic scheme of installation is showed in Fig. 7.

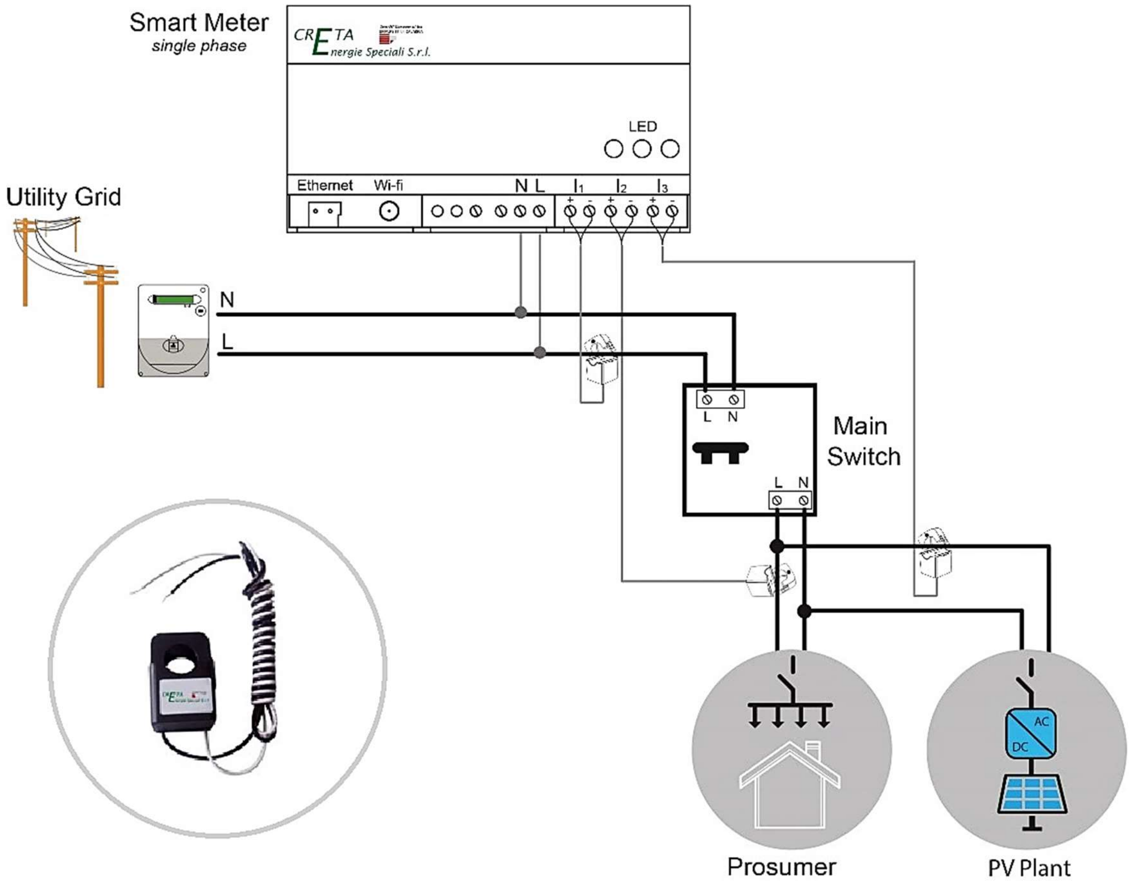


*Fig. 7 – Scheme of installation*

In the case of a Smart Meter intended for three-phase users, an additional module is required so to have up to 12 analogical inputs available, of which 3 must be used for the measurement of phase voltages (R, S, T), while the remaining 9 will be used, all or in part, to measure currents. From three to nine CTs will be connected around the electrical lines in cable relative to the systems / loads / storage systems to be monitored.

- Web Application development

A web application has been developed with the aim of supporting the installation phase; moreover, through it the user can monitor the real-time state of each appliances, loads and equipment inside the dwelling.

During the making process, the PHP Open Source Code Igniter framework is used; it is based on the Model-View-Controller (MVC) paradigm. It has been decided to use this framework being famous for its speed when compared to other PHP frameworks. The MVC approach is structured based on the three fundamental elements that make up its name:

- model (M): provides the methods to access the data necessary for the operation of the application;

- view (V): has the task of viewing the data provided by the Model and allows the interaction between users and application;

- controller (C): it is sent instructions from the user, generally mediated by the View, which modify the status of the model and the view.

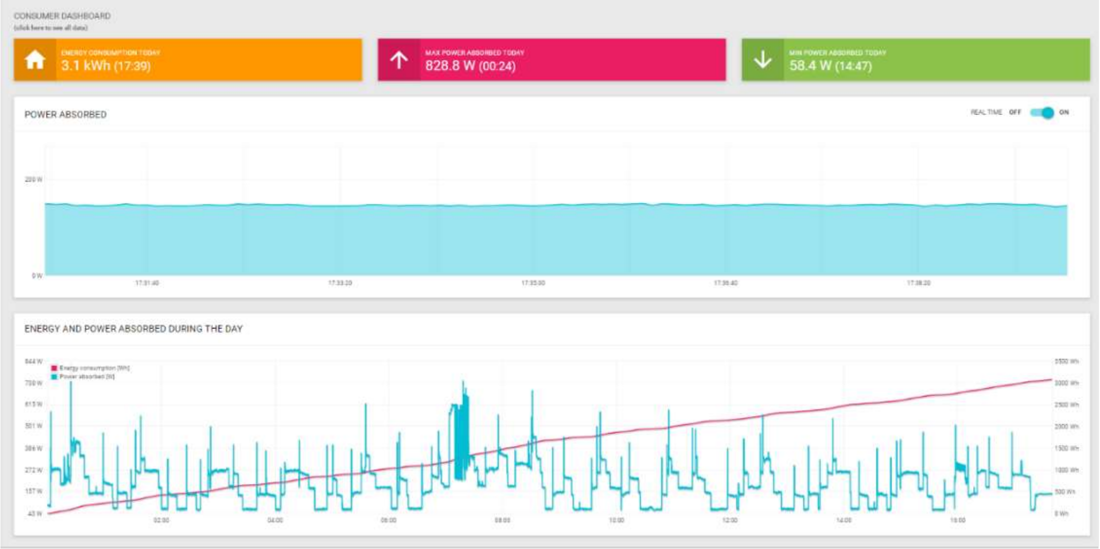
The front-end has been realized using the Bootstrap library, which contains some HTML and CSS templates for typography, forms, buttons and other interface components, as well as some JavaScript extensions. One of these is jQuery that we used for selecting, manipulating, managing events and animating DOM elements in HTML pages, as well as for implementing some AJAX features (for example, updating every 10 seconds of the graphs in real -time). A jQuery plug-in has been used to create the graphs: Flot for jQuery. Flot has been chosen because it is very simple to use, extremely graphically curated and provides various interactive features. For the representation and filtering of historical data in tabular form, the DataTables library has been used for jQuery. This adds the sorting, pagination and filtering of data to HTML tables. The following figures shows how the web application appears (see Fig. 8, Fig. 9).

- Database Structure

The web application is supported by a remote relational database based on the SQL language, in which reside information on registered users, PODs, Smart Meters, measured voltage, power and energy values. As Database Management System (DBMS) PhpMyAdmin has been used.

- Real–time monitoring

The web application allows to graphically displaying the real–time status for the monitored systems. In Fig. 8 is showed the real–time status of a consumer with only one Smart Meter used for monitoring an electrical load line. The web application provides daily values related to energy consumption reported in kWh, maximum power absorbed and minimum power absorbed reported in W. In addition, web application provides the daily trends (updated in real–time) related to the power absorbed by the load in the last 10 minutes and the power profile and energy absorbed during the day.



CONSUMER DASHBOARD
(click here to see all data)

ENERGY CONSUMPTION TODAY 3.1 kWh (17:39)

MAX POWER ABSORBED TODAY 828.8 W (00:24)

MIN POWER ABSORBED TODAY 58.4 W (14:47)

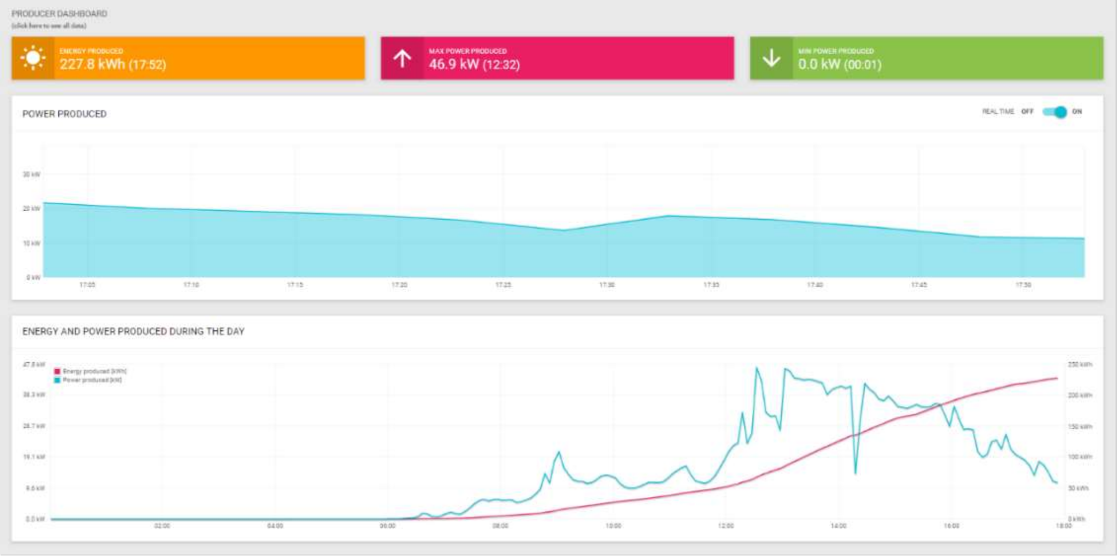
POWER ABSORBED

REAL TIME OFF ● ON

ENERGY AND POWER ABSORBED DURING THE DAY

*Fig. 8 – Web application for consumers*

The following image shows, instead, the real–time status of a producer user with only one Smart Meter for monitoring a photovoltaic generation plant. In analogy to the previous case, the web application provides daily values related to energy production and power profile.



PRODUCER DASHBOARD
(click here to see all data)

ENERGY PRODUCED 227.8 kWh (17:52)

MAX POWER PRODUCED 46.9 kW (12:32)

MIN POWER PRODUCED 0.0 kW (00:01)

POWER PRODUCED

REAL TIME OFF ● ON

ENERGY AND POWER PRODUCED DURING THE DAY

*Fig. 9 – Web Application for producers*

- Historical data and download

The web application presents a section for displaying and downloading historical power and energy data. In particular, it is possible to indicate the time interval within which the data must be contained. The data are shown in tabular form.
A filter function allows to perform cross-searches and to compute statistical calculations to obtain maximum values, minimum values and average values of power; it is also possible to obtain the cumulative daily, monthly and annual energy values. The results shown in the table can be copied, exported and downloaded in csv format, excel format and pdf format.

The historical data collected thanks to the installation of the firsts Smart Meter prototypes are of fundamental importance because through their analysis it has been possible to determine the behaviour of the monitored users, in terms of energy requirements, and thus allow them to become aware of their consumption. Moreover, knowing in real-time the values of electric power required to satisfy their own loads, it allows users to avoid situations of overload or criticality, ensuring a conscious use of the available energy resources.

# 3 Algorithms for New Price-Based DR Model

## 3.1 Introduction

Energy management plays an important role in the safe, reliable and economical operation of micro-grids. Energy management is responsible for scheduling and controlling the distributed generators, energy storage devices and controllable loads based on the operating conditions of the system.
The optimal planning of micro-grids is also crucial, which aims to obtain the best solution to system configuration (e.g. the types and capacities of the devices) according to energy demand and available distributed energy resources during the planning period, together with the specified planning objectives and system constraints. Due to the need for an economic analysis of the devices during their life cycle, the selection of proper operational strategies for micro-grids becomes an important component of optimal planning, which means that the operational strategies will greatly affect the final planning solution.

The main aim of a micro-grid energy management system (MEMS) is to achieve coordinated control and optimal operation of micro-grids, through system-level management and control. Each MEMS contains two main modules, which are supervisory control and data acquisition (SCADA) and energy management, as well as the associated hardware and software systems to support the functions of these two modules. In micro-grids, the main function of SCADA is to transmit real-time monitoring data to the database and to the energy management module, as well as to convey the generation scheduling and control instructions from the energy management module to the local control systems. In micro-grids, distributed generators are equipped with local control systems, and the SCADA system bridges the energy management module and these local control systems.

The energy management module is the core of MEMS. Based on real-time, forecasted and historical data, as well as the policy and market information, etc., the energy management module is able to produce operational scheduling for various distributed generators, energy storage devices and the controllable loads in a micro-grid. These operational schedules are sent to these local devices via the SCADA system. From the functionality point of view, the energy management modules can be divided into four parts:

1. data forecasting: forecasting demand and output of distributed generators;
2. optimal scheduling: formulating scheduling plans based on the economic, environmental and technical requirements and the micro-grid operational constraints;
3. operation control: real-time or near-real-time monitoring and adjusting the operation of the devices to maintain system voltage and frequency stability;
4. data analysis: analysis of all the real-time and historical data in order to obtain information related to system economics, stability and security.

The micro-grid scheduling strategy is mainly used to schedule the power output of distributed generators and energy storage systems. A reasonable scheduling strategy can enable the micro-grid to achieve the predetermined operation goals, such as minimum operation cost, maximum efficiency of system energy utilization and lowest carbon emissions. Micro-grid scheduling strategies can be divided into two categories: heuristic scheduling strategies [49] [50] [51] and optimization strategies [52]. Optimization strategies can be further divided into static optimization and dynamic optimization.

- Heuristic Scheduling Strategy

In theory, wind, photovoltaics (PV) and other renewable energy sources should prioritize meeting the demand. Based on this, the heuristic scheduling strategy formulates the generation priorities of different distributed generators associated with the start/stop conditions of conventional distributed generators (e.g. diesel generation units) and the charging/discharging conditions of energy storage systems. Such scheduling ensures effective operation of these devices.

- Static Optimization Strategy

Based on the availability of distributed generation and their operational cost per unit (e.g. per kWh) during a period, as well as the requirements of demand at the same period, the static optimization strategy produces the optimal dispatch values of all devices (including the distributed generators and energy storage devices) [53]. This strategy usually does not consider the correlation of the available resources among different periods, and thus the optimization is often formulated for each period independently. In order to achieve the most cost-effective operation, the availability and costs of all schedulable power sources should be considered.

For a micro−grid operating in grid−connected mode, the power from the main grid should also be considered as a schedulable source, participating in the cost comparison with other distributed energy resources.

- Dynamic Optimization Strategy

Due to the relatively low ramp rates of some distributed generators (e.g. diesel generators, micro−turbines) and the constraint of the residual capacity of energy storage systems from a previous period, only considering the available resources at the current period sometimes will not result in the optimal operation scheduling. Therefore, dynamic optimization strategies have been proposed to optimize system operation with the goal of maximizing the overall benefits for the scheduling period [54], taking into account the predictive data of multiple periods. Due to the daily cycle characteristics of demand and output of distributed generators (e.g. PV), dynamic optimization strategies are usually implemented daily to develop the solution of the so−called day−ahead dynamic economic scheduling. In order to reduce the coupling of different cycles, the residual capacities of energy storage systems are commonly required to be the same at the start and end of the scheduling cycles. In addition, the prediction is usually updated by using the recently monitored data to increase the accuracy, based on which the optimal schedules can be improved in a rolling manner [62].

Starting from the previous general framework, a novel approach for the optimal management of prosumers is introduced. As better detailed in the following section, the introduced "unified prosumer problem", has been modelled as a mixed integer linear optimization problem and solved with a Branch and Bound algorithm. The solution of the problem consists in the definition of the usage schedule of electrical and thermal appliances and of renewable−based generators, allowing each prosumer to maximize the revenues and minimize the costs while respecting the local constraints. The efficiency and novelty of the approach mainly rely on two features: the first concerns the concurrent management of electrical and thermal energy, which leads to a significant cost saving or revenue increase when compared to the approaches where the two aspects are managed separately. The second pertains to the definition of the energy district architecture, which combines the computational power of a Cloud service provider, in charge of computing aggregated information and supplying it to the prosumers, with the limited but distributed power of end−user energy boxes. The advantages have been assessed through a testbed performed under the academic/industrial Italian project PON03PE_00050_2, "Sistemi Domotici per il servizio di brokeraggio energetico cooperativo".

## 3.2 End-User' Equipment and Micro-Grid Modelling

Before describing the characteristics of thermal/electrical prosumers, we underlined that each prosumer joining the energy district hosts the following equipment:

(i) *nano-grid system*, which manages the energy exchange between the prosumer and the distribution grid, the local energy production plants and the storage systems;
(ii) *home automation system*, which manages the activation and deactivation of the electrical loads of the dwellings and the thermal devices;
(iii) *energy box*, which enables the interaction with the Cloud service provider and supervises both the nano-grid and the home automation system. It runs the so-called *unified prosumer problem* discussed in the following.

In particular, the electrical loads of the dwellings and the thermal devices controlled by the home automation system can be categorized into three main groups:

(i) *electrical and thermal loads*, e.g. lightning, appliances, etc.;
(ii) *electrical and thermal storage systems*;
(iii) *generation plants*, divided in renewable energy sources such as PV plants, solar thermal panels and biomass-based micro CHP generators and traditional energy sources such as the gas boilers, the heat pumps, and the points of delivery of the distribution grid.

In the following, the main parameters and the characteristic equations for each equipment are introduced.

### 3.2.1 Loads

- Electrical loads

The loads of a generic prosumer can be divided into $L$, the set of electrical loads and $T$, the set of thermal loads.
For the sake of simplicity, we assume that each electrical load $a \in L$ can be either turned on or turned off. A load $a$ is turned on for a given number of hours $(\theta_a)$, during which it operates at its rated power $P_a^{rat}$, while it is turned off during the rest of the day. Let us define $E_a$ as the hourly energy required by a load $a$. It can be computed as $E_a = P_a^{rat} * \Delta t$ with $\Delta t = 1h$.

The electrical loads are further divided into a set $A$ of schedulable loads and a set $B$ of non−schedulable loads. A schedulable load is a load that can be activated at any time within a user−defined time interval, whereas a non−schedulable load must be activated at a fixed hour of the day. Washing machines and dish−washings are examples of schedulable loads, while refrigerators are examples of non−schedulable loads.

- Thermal loads

Each thermal load corresponds to a room that needs to be separately conditioned in a multi−zone heating system. The Cloud service provider based on the user−defined thermal preferences (temperature set points), the weather forecast and the physical and geometrical characteristics of the envelope computes the thermal energy profile.

Thermal loads are computed exploiting the dynamic model 5R1C described in the standard EN ISO 13790 [63]. The hourly energy profile of an electrical load $a \in L$ and of a thermal load $t \in T$ at a given hour $h$ are respectively referred to as $x_a^h$ and $x_t^h$.

### 3.2.2 Storage Systems

The storage devices considered in this work refer to thermal energy storage systems and to electric energy storage systems.

- Electric storage system

The electric storage system is used to store the surplus of energy and exploit it when an energy deficit happens. During the charging/discharging phases, there is an energy loss, which is modelled by the charging/discharging efficiency factors, respectively $\eta_{cha}$ and $\eta_{dis}$. Other characteristic parameters are the maximum/minimum percentages of the state of charge, $SOC_{max}$ and $SOC_{min}$, the maximum capacity of the storage, $C_{max}$, and the maximum hourly charging/discharging amounts of energy, $E_{cha}^{max}$ and $E_{dis}^{max}$. Let me define $E_{dis}^{h}$ and $E_{cha}^{h}$ as, respectively, the drawn and the stored energy during the hour $h$. I also define $E_{STOel}^{*}$ as the residual energy stored in the systems from the day before. The constraints related to the maximum drawn and stored hourly energy can be expressed by the inequalities (1) and (2).

$$0 \leq E_{cha}^{h} \leq E_{cha}^{max} \quad \forall h \in H \tag{1}$$

$$0 \leq E_{dis}^{h} \leq E_{dis}^{max} \quad \forall h \in H \tag{2}$$

The inequalities (3) and (4) verify that the total stored energy at each hour $h \in H$ is within the minimum and maximum state of charge values.

$$E_{STOel}^{*} + \sum_{i=0}^{h} E_{cha}^{i} - \sum_{i=0}^{h} E_{dis}^{i} \geq SOC_{min} * C_{max} \quad \forall h \in H \tag{3}$$

$$E_{STOel}^{*} + \sum_{i=0}^{h} E_{cha}^{i} - \sum_{i=0}^{h} E_{dis}^{i} \leq SOC_{max} * C_{max} \quad \forall h \in H \tag{4}$$

- Thermal storage system

The thermal storage system is typically an insulated water tank that exploits the water thermal capacity in order to temporary store the surplus of thermal energy. The main parameters of the storage system are *V*, the volume of the tank, and the thermodynamic properties of the heat transfer fluid, i.e., the fluid density and the specific heat $C_p$. Other parameters of the thermal storage system are $T_{STOt}^{max}$ and $T_{STOt}^{min}$, which are respectively the maximum and the minimum admissible temperature, and $\Delta T_{STOt}^{max}$, the maximum temperature variation in an hour. Let us define $E_{STOt}^{h}$ as the energy exchanged by the storage system during the hour *h*, with the convention that $E_{STOt}^{h}$ is positive when the storage is discharged and negative when it is charged. We also define $E_{STOt}^{*}$ as the thermal energy remaining in the thermal storage system at the end of the previous day.

The inequality (5) ensures that the temperature variation does not violate the maximum allowed value, whereas the inequality (6) forces the temperature to be inside its minimum−maximum range.

$$-\rho V C_p * \Delta T_{STOt}^{max} \leq E_{STOt}^{h} \leq \rho V C_p * \Delta T_{STOt}^{max} \quad \forall h \in H \tag{5}$$

$$0 \leq \sum_{i=0}^{h} E_{STOt}^{i} + E_{STOt}^{*} \leq \rho V C_p * \left(T_{STOt}^{max} - T_{STOt}^{min}\right) \quad \forall h \in H \tag{6}$$

### 3.2.3 Generation Plants Models

- PV generation system

The PV plant is an n−PRS electric generator. The power output of a PV generation system is closely related to the solar radiation irradiated on the surface of PV arrays, the operation conditions and physical parameters of the system, etc. In this energy management model, the electrical energy produced during the hour h is referred to as $E_{PV}^{h}$.

- Solar thermal panels

The solar thermal panel is a n−PRS thermal generator typically consists in a panel that transfers primary solar energy to a thermal fluid (a water−glycol mixture) forced to flow in a closed circuit. The thermal fluid transfers the captured energy to an insulated water tank by means of a heat exchanger. We define the thermal energy produced at hour h as $E^{h}_{tSOL}$.

- Micro−CHP generator

A micro−CHP generator is a system able to produce thermal and electrical energy at the same time. This kind of system is based on different primary sources such as fossil fuels, natural gas, organic material, wood, crop residues, which are usually called biomasses. In this work, we focus on an innovative micro−CHP generator consisting of a biomass boiler on which a free piston Stirling engine and a linear generator are mounted. This micro−CHP generator is characterized by the electrical rated power Prat CHP and the thermal rated power $P^{\mathrm{rat}}_{CHPt}$ , which correspond, respectively, to the maximum electrical and thermal powers that can be generated. The ratio between electrical and thermal power is called co−generation factor, $F_{CHP}$ , and it can be computed using the rated powers, i.e., $F_{CHP} = P^{\mathrm{rat}}_{CHPt} = P^{\mathrm{rat}}_{CHP}$. The hourly maximum electrical energy, $E_{CHP}$ , can be easily derived from the rated power: $E_{CHP} = P^{\mathrm{rat}}_{CHP} * \Delta t$, with $\Delta t = 1h$. Other parameters of the combined generator are the electrical (thermal) efficiency, $\eta^{el}_{CHP}$ ($\eta^{t}_{CHP}$), obtained as the ratio between the produced electrical (thermal) power and the power supplied by biomass combustion. The latter depends on the lower heating value of the biomass, $LHV_{biomass}$, i.e., the amount of thermal energy produced per biomass unity (kg).

Finally, $E_{CHP}$ is defined as the hourly electrical produced energy at hour h. The latter amount of energy must be lower than the hourly maximum electrical energy $E_{CHP}$ , as expressed by the inequality (7).

$$0 \leq E^{h}_{CHP} \leq E_{CHP} \quad \forall h \in H \tag{7}$$

The thermal energy produced at a given hour can be derived by multiplying the co−generation factor by the produced electrical energy: $F_{CHP} * E^{h}_{CHP}$ .

- Connection to the distribution grid

The prosumer is connected to the grid by means of the so−called Point of Delivery (POD) through which it exchanges electrical energy with the other prosumers of the energy district and with the distribution grid (via the aggregator). The rated power $P_{rated}$, established with the local retailer, defines the maximum power that can be supplied by the distribution grid.

We define $E^{h}_{imp}$ and $E^{h}_{exp}$ as the imported and the exported energy at hour $h$, respectively.

The maximum amount of energy that can be imported in an hour can be computed as $E_{grid}^{max} = P_{rated} * \Delta t$ with $\Delta t = 1h$, so the imported energy at a given hour is constrained by the inequality (8):

$$E_{imp}^{h} \leq E_{grid}^{max} \quad \forall h \in H \tag{8}$$

The exported energy is inherently limited by the rated powers of the plants that are typically sized not to overflow the maximum amount of exportable power, established with the local retailer.

- Gas boiler

When there is not sufficient thermal energy supplied by the micro−grid, gas boilers can be used. A typical gas boiler converts the chemical energy stored in natural gas into thermal energy by combustion with a constant efficiency. It is characterized by the thermal rated power $P_{NG}^{rat}$, which corresponds to the maximum thermal power that can be generated. The hourly maximum thermal energy, $E_{NG}$, can be derived from the rated power: $E_{NG} = P_{NG}^{rat} * \Delta t$ with $\Delta t = 1h$. Another important parameter is the thermal efficiency, NG obtained as the ratio between the produced thermal power and the power supplied by natural gas combustion. The latter depends on the lower heating value of the gas, $LHV_{gas}$, i.e., the amount of thermal energy produced per gas unity (Nm$^3$). Finally, $E_{NG}^{h}$ is defined as the energy produced at hour $h$. The latter energy must be lower than the hourly maximum energy $E_{NG}$, as expressed by the inequality (9):

$$0 \leq E_{NG}^{h} \leq E_{NG} \quad \forall h \in H \tag{9}$$

- Heat pump (HP)

A HP transfers thermal energy from the outside to the inside and vice versa, consuming electrical energy. The ratio between the thermal rated power $P_{HPt}^{rat}$, i.e., the maximum power that can be produced, and the electrical rated power $P_{HP}^{rat}$, i.e., the maximum power that can be consumed, is called Coefficient Of Performance, $COP$. We define $E_{HP}^{h}$ as the electrical energy consumed at hour $h$. The maximum amount of hourly energy that can be consumed is derived from the electrical rated power: $E_{HP} = P_{HP}^{rat} * \Delta t$ with $\Delta t = 1h$, so the consumed electrical energy is constrained as specified in inequality (10):

$$E_{HP}^{h} \leq E_{HP} \quad \forall h \in H \tag{10}$$

The thermal energy produced at hour $h$ can be computed as $* E_{HP}^{h}$ .

## 3.3 The Optimal Scheduling Model

Starting from the parameters and equations/inequalities introduced in the previous section, we build a linear integer optimization problem consisting of an objective function and a set of inequality/equality constraints. The formalization of the unified prosumer problem as a linear integer optimization problem allow us to find the optimal solution by adopting the well-known Branch and Bound algorithm. The optimal solution consists in determining the values of a set of variables that minimize the costs and maximize the revenues, while respecting a set of constraints.

In the proposed model, we use an hour as temporal granularity, i.e., the power consumed by the loads as well as the power produced by the plants or exchanged with the storage systems is assumed to be constant within each hour $h$ of the day [35].

### 3.3.1 Input: Day-Ahead Information

As mentioned before, each day, at a predetermined hour, the prosumer the production forecast of the renewable plants and the values of thermal load that fulfil the thermal preferences of the users. In particular, the cost, hour-by-hour, of a kWh imported/exported from/to the grid, $c^h/p^h$, is computed taking into account the trend of the electrical market prices.

A Cloud service provider taking into account the weather forecast elaborates the day-ahead production forecasts. In particular, the production forecasts concern the hour-by-hour energy production of the PV and the solar panels, defined respectively as $E_{PV}^h$ and $E_{tSOL}^h$. The Cloud service provider taking into account the user-defined temperature set points, the weather forecast and the thermodynamic characteristics of the dwellings also computes the values of the thermal loads.

The solution of the unified prosumer problem aims to optimize the operation of the prosumer equipment by taking into account the user preferences about the scheduling of the loads. As described previous section, the set $L$ of electrical loads is divided into two subsets: the set of schedulable loads $A$ and the set of non-schedulable loads $B$. These sets change dynamically and need to be defined by the user in order to plan which appliances will be activated in the next day, and at which hours. The user can also set the working time of non-schedulable loads by providing the daily energy profile in terms of hour-by-hour energy consumption $x_a^h$ for each load $a \in B$.

In practice, $x_a^h$ is set to be zero for each hour $h \in H$ except for the hours in which the appliance is scheduled to be switched on (in these hours the energy consumption is equal to the hourly energy required $E_a$). For schedulable loads, the user must define, for each $a \in A$, the duration in hours of the working time $\theta_a$ and the range of hours $[\alpha_a; \beta_a]$ to which the working time must belong. In addition, the user can define the temperature set points that are used by the Cloud service provider to compute the thermal loads. These preferences and user data need to be managed both with an administrative and with a technical approach to ensure privacy. User data, specifically the thermodynamic characteristics of each dwelling, is protected by an ad-hoc agreement signed by the user and the district administrator. This agreement specifies that such information cannot be shared with the other users or with external entities, and can only be used by the Cloud service provider for the technical purposes of the district, e.g., obtain the thermal load forecast, which is needed to solve the prosumer problem.

From a technical point of view, it is necessary to protect the private data in two ways: (i) the transmission of the data to the district database must be secure; (ii) access to data must be denied to non-authorized users and services. A specialist, possibly in presence of the dwelling inhabitant, fills up a document with all the needed thermodynamic characteristics regarding the dwelling. Then, the specialist uploads the data on the district database. The data upload procedure is done through the database client using the access privileges assigned to the specialist. Once uploaded and stored in the database, the data – unless it is successively updated, using a similar procedure – will only be used by the load forecast service, while it will not be accessed by any other user or service.

### 3.3.2 Output: Scheduling and Daily Energy Cost

The solution of the unified prosumer problem aims to optimize the operation of the prosumer equipment by taking into account the user preferences about the scheduling of the loads. In particular, the optimization model supplies in output information about the daily scheduling for the controllable loads and generation plants included the point of connection with the grid.

The daily energy cost incurred by a prosumer is related to the quantity of primary energy sources utilized by the controllable generation plants, i.e., the biomass of the micro-CHP generator, the natural gas used in the gas boiler and the energy imported from the distribution grid. The cost of a kilogram of biomass is denoted as $c_{kgbiomass}$ .

The cost of a thermal kWh produced by the micro-CHP generator can be computed as:

$$C_{kWht\_CHP} = c_{kgbiomass} * \frac{1}{F_{CHP} * \eta_{CHP}^{el} * LHV_{biomass}} \tag{11}$$

An analogous computation applies to the gas boiler: the cost of a Nm$^3$ of natural gas is denoted as $c_{Nm^3}$ gas and the cost of a thermal kWh produced by the gas boiler is:

$$C_{kWht\_NG} = c_{Nm^3} * \frac{1}{\eta_{NG} * LHV_{gas}} \tag{12}$$

The cost of an electrical kWh imported from the grid varies with the hour $h$ and is denoted as $c^h$. The prosumer can also export electrical energy to the grid. In this case, the energy is sold at a given hourly price $p^h$. For the sake of simplicity, we do not consider any installation or maintenance cost related to the plants and, as a consequence, there are no costs for the energy produced by the PV plant and by the solar panels.

### 3.3.3 Variables and Constrains

In the following, we first identify the variables of the optimization problem, then we detail the constraints and the objective function. The variables are:

1) the hour-by-hour amounts of energy introduced in the previous section, which are related to the controllable plants (i.e., the distribution grid, the electrical and thermal storage systems, the micro-CHP generator, the gas boiler and the HP);
2) a set of auxiliary variables used to model the activation/ deactivation of the loads;
3) a set of variables used to model the hourly surplus of thermal energy, as will be clarified in the following.

The first set comprises the following variables, defined $\forall h \in H$ of the next day:

- $E_{dis}^h$, the energy drawn from the electrical storage;
- $E_{cha}^h$, the accumulated energy of the electrical storage;
- $E_{STOt}^h$, the energy exchanged by the thermal storage system;
- $E_{CHP}^h$, the electrical energy produced by the combined generator;
- $E_{imp}^h$, the electrical energy imported from the grid;
- $E_{exp}^h$, the electrical energy exported to the grid;
- $E_{NG}^h$, the thermal energy produced by the gas boiler;
- $E_{HP}^h$, the electrical energy consumed by the heat pump.

The auxiliary variables used to model the activation/ deactivation of the loads, defined $\forall h \in H$ of the next day and $\forall a \in A$, are the following:

- $y_a^h$, has value 0 if the load $a$ is scheduled to be inactive at the hour $h$, and has value 1 if the load $a$ is scheduled to be active at the hour $h$;
- $z_a^h$, has value 1 at the hour $h$ in which the load $a$ is scheduled to be switched on, passing from the inactive state to the active state, and has value 0 at all the other hours.

Starting from these variables, we can model the activation / deactivation of the loads taking into account the user preferences detailed in chapter 3.3.1. The equations (13) and (14) force the activation of a load $a$ to occur at a single hour $h \in [\alpha_a, \beta_a - \theta_a + 1]$. The upper bound of the latter interval is set to $\beta_a - \theta_a + 1$, instead of $\beta_a$, to ensure that the working time of the load $a$ ends before $\beta_a$.

$$\sum_{h=\alpha_a}^{\beta_a - \theta_a + 1} z_a^h = 1 \quad \forall a \in A \tag{13}$$

$$z_a^h = 0 \quad \forall h \in H \setminus [\alpha_a, \beta_a - \theta_a + 1] \quad \forall a \in A \tag{14}$$

The equation (15) ensures that the load $a$ is activated exactly for $\theta_a$ hours inside the $[\alpha_a, \beta_a]$ preference interval. In the case of the $y_a^h$ variables, differently from the $z_a^h$ variables, there is no need to set the variables to *zero* outside the user preference interval. Indeed, the optimization process excludes this possibility because it would lead to a sub−optimal solution: the activation of the load outside the user preference interval would increase the costs.

$$\sum_{h=\alpha_a}^{\beta_a} y_a^h = \theta_a \quad \forall a \in A \tag{15}$$

The set of inequalities (16) forces the load $a$ to operate during its working time without interruptions. Indeed, for all $h$ where $z_a^h$ is *one*, the $y_a^h, y_a^{h+1}, \ldots, y_a^{h+\theta_a-1}$ variables can assume values greater or equal to *1*. On the other hand, the equation (15) forces the same variables to assume values lesser or equal to *one*.

Consequently, the $y_a^h$ variables are equal to *one* for each hour $h \in [h_a^*, h_a^* + \theta_a - 1]$ where $h_a^*$ is the activation hour of the load $a$, i.e. the hour in which $z_a^h = 1$. Similarly, the equation (15), combined with the inequality (16), also ensures that the $y_a^h$ variables are equal to *zero* outside the $[h_a^*, h_a^* + \theta_a - 1]$ interval.

$$y_a^h \geq z_a^h, \ y_a^{h+1} \geq z_a^h, \ldots, \ y_a^{h+\theta_a-1} \geq z_a^h \quad \forall h \in [\alpha_a, \beta_a], \ \ \forall a \in A \tag{16}$$

All the introduced energy variables must satisfy the electrical and thermal energy balancing. In particular, equation (17) models the electrical energy balancing, whereas equation (18) models the thermal energy balancing.

$$E_{imp}^{h} + \eta_{dis} * E_{dis}^{h} + E_{CHP}^{h} - E_{exp}^{h} - \frac{1}{\eta_{cha}} * E_{cha}^{h} - E_{HP}^{h} - \sum_{a \in A} y_a^h * E_a = \sum_{b \in B} x_b^h - E_{PV}^{h} \quad \forall h \in H \tag{17}$$

$$E_{HP}^{h} * COP + E_{CHP}^{h} * F_{CHP} + E_{NG}^{h} + E_{STO_t}^{h} - X_{diss}^{h} = \sum_{t \in T} x_t^h - E_{SOL_t}^{h} \quad \forall h \in H \tag{18}$$

In equation (18) we have introduced the third set of variables, used to model the hourly surplus of thermal energy, i.e., the variables $X_{diss}^{h}$. More specifically, they are used to model the amount of produced thermal energy that exceeds the thermal loads, which is consumed by a purposely-adopted dissipation system. There is no need to introduce similar variables for the electrical part because the electrical energy that exceeds the prosumer requirements can always be injected into the grid. The other constraints of the model are the inequalities introduced in the previous sections that are referred to the equipment, i.e., the inequalities (1)-(10).

To give a simplify description of the thermal and electrical energy exchanges, in the following image is shown a scheme of the energy flows and the interaction between thermal and electrical parts.

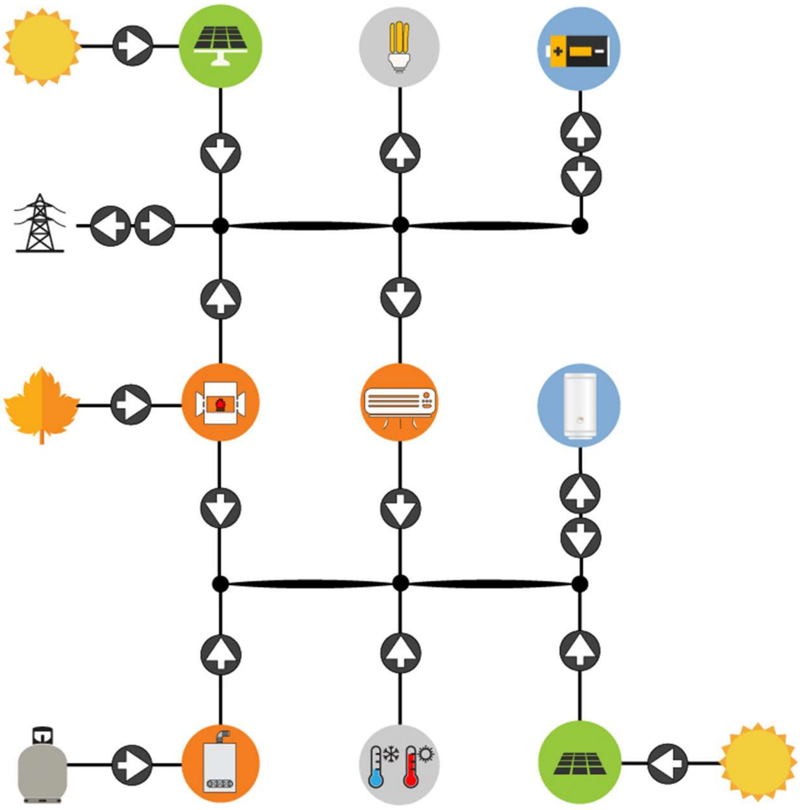


*Fig. 10 – Thermal and electrical balance scheme*

### 3.3.4 The objective Function

The daily energy cost for the prosumer is used as the objective function to minimize, see formula (19). The function is expressed as the sum of:

- the daily costs related to the micro−CHP (positive term);
- the gas boiler (positive term);
- the electrical energy imported from the grid (positive term);
- the revenues obtained by selling energy to the grid (negative term).

$$min \sum_{h \in H} (C_{kWht_{CHP}} * F_{CHP} * E_{CHP}^{h} + C_{kWht_{NG}} * E_{NG}^{h} + c^{h} * E_{imp}^{h} - p^{h} * E_{exp}^{h}) \tag{19}$$

The total number of variables is $11 * |H| = 264$, where $|H| = 24$ is the cardinality of $H$. The number of constraints is:

$$14 * |H| + 2 * |A| + \sum_{a \in A} (\theta_a * (\beta_a - \alpha_a) + |H| + \alpha_a + \theta_a - \beta_a - 1) \tag{20}$$

where $|A|$ is the cardinality of $A$, i.e., the number of schedulable loads. For example, considering a number of schedulable loads equal to five, an average working time $\theta$ equal to 3 hours and an average user preference interval $(\beta - \alpha)$ equal to 10, the number of resulting constraints is 576.

In order to find a correct solution for the unified prosumer problem, it is necessary to impose the $z_a^h$ variables as binary, so the whole optimization problem can be classified as a mixed integer linear programming problem. In a mixed integer linear programming problem, some variables are constrained to be integer (or binary) and some others are not.

This kind of problem can be solved with the Branch and Bound technique, in particular we exploited the implementation provided by the CPLEX Library [51]. CPLEX allows to stop the execution of the algorithm after a predetermined number of iterations or execution time, and provide a sub−optimal solution if the optimal one has not been found. However, in our scenario, given the limited size of the problem, we did not set any limit to the execution because the algorithm is able to achieve the optimal solution in a few seconds.

## 3.4 Case Studies

In this Section, we evaluate the effectiveness of the presented unified model. In particular, we compare the annual costs / revenues supported by a prosumer, in two cases: *CASE I* considers the separated electrical and thermal management, also referred to as non−unified model in the following; *CASE II* considers the unified electrical / thermal management. The optimization model is solved by using the Java language and the CPLEX library. The optimal solution of the model is computed in a time interval between *1* and *3* seconds on an ASUS Intel I7 computer equipped with 16GB RAM and Windows 10. The results are evaluated on three prosumers, equipped with identical electrical equipment and different thermal generation plants. Each prosumer owns a dwelling with a size of about $100\,m^2$, which hosts four people and is located in the municipality of Rende, Italy.

Table 2 reports the user preferences, about the schedulable loads, considered for the experiments. In Table 3, the production plants and the storage systems of each prosumer are reported with their main technical characteristics. The dwellings need a daily amount of electrical energy of about $10\,kWh$, for each day of the year. The daily thermal energy requirement depends on the season: it is about $20.0\,kWh$ in spring and autumn (assuming a set point temperature $T$ equal to $23\,°C$), about $8.7\,kWh$ in summer ($T = 25\,°C$) and about $42.0\,kWh$ in winter ($T = 20\,°C$).

*Table 2 − User setting for the schedulable loads*

| Schedulable loads | Rated Power [W] | $\boldsymbol{\theta}$ | $\boldsymbol{\alpha}$ | $\boldsymbol{\beta}$ |
|---|---|---|---|---|
| Washing machine | 1500 | 2 | 11 | 18 |
| Tumble dryer | 1200 | 1 | 16 | 22 |
| Dish washer | 1900 | 3 | 9 | 19 |
| Electric vehicle | 200 | 3 | 9 | 19 |

*Table 3 − Plants of the prosumers*

| Plants | Prosumer 1 | Prosumer 2 | Prosumer 3 |
|---|---|---|---|
| PV (peak power) | $6\,kW$ | $6\,kW$ | $6\,kW$ |
| Connection to the grid (rated power) | $6\,kW$ | $6\,kW$ | $6\,kW$ |
| Electric storage system (capacity) | $6\,kWh$ | $6\,kWh$ | $6\,kWh$ |
| Solar panel (area) | $4\,m^2$ | $4\,m^2$ | $4\,m^2$ |
| Heat pump (rated power) | $10\,kW_t$ | − | − |
| Natural gas boiler (rated power) | − | $25\,kW_t$ | − |
| Micro−CHP (rated powers) | − | − | $2\,kW_e$ and $6\,kW_t$ |
| Thermal storage system (volume) | $250\,l$ | $250\,l$ | $250\,l$ |

Table 4 reports the daily revenues and costs experienced by the three prosumers in the different seasons, when the electrical and thermal management are separated (*CASE I*). More specifically, the table reports the cost of the electrical energy imported from the grid, the revenue obtained by selling the electrical energy to the grid, the cost of the natural gas, the cost of the biomasses and finally the overall daily revenue (a positive value corresponds to a revenue while a negative value corresponds to a cost).

*Table 4 – CASE I: daily revenues and costs of a prosumer*

| | | Electric energy cost [€] | Electric energy revenue [€] | Natural gas cost [€] | Biomasses cost [€] | Daily revenue/cost [€] |
|---|---|---|---|---|---|---|
| Prosumer 1 | Spring/Autumn | 1.000 | 1.441 | – | – | 0.441 |
| | Summer | 0.288 | 1.474 | – | – | 1.186 |
| | Winter | 1.335 | 0.419 | – | – | −0.916 |
| Prosumer 2 | Spring/Autumn | 0.287 | 1.411 | 0.793 | – | 0.331 |
| | Summer | 0.287 | 1.474 | 0.011 | – | 1.176 |
| | Winter | 0.351 | 0.723 | 2.746 | – | −2.374 |
| Prosumer 3 | Spring/Autumn | 0.287 | 1.577 | – | 0.987 | 0.303 |
| | Summer | 0.287 | 1.476 | – | 0.014 | 1.175 |
| | Winter | 0.351 | 1.281 | – | 3.417 | −2.487 |

*Table 5 – CASE II: daily revenues and costs of a prosumer*

| | | Electric energy cost [€] | Electric energy revenue [€] | Natural gas cost [€] | Biomasses cost [€] | Daily revenue/cost [€] |
|---|---|---|---|---|---|---|
| Prosumer 1 | Spring/Autumn | 0.309 | 1.441 | – | – | 1.102 |
| | Summer | 0.287 | 1.474 | – | – | 1.187 |
| | Winter | 0.864 | 0.723 | – | – | −0.141 |
| Prosumer 2 | Spring/Autumn | 0.287 | 1.411 | 0.566 | – | 0.558 |
| | Summer | 0.287 | 1.474 | 0.000 | – | 1.187 |
| | Winter | 0.351 | 0.723 | 2.745 | – | −2.373 |
| Prosumer 3 | Spring/Autumn | 0.287 | 1.542 | – | 0.704 | 0.551 |
| | Summer | 0.287 | 1.474 | – | 0.000 | 1.187 |
| | Winter | 0.263 | 1.247 | – | 3.417 | −2.433 |

*Table 6 - Comparison between CASE I and CASE II*

| | | Daily improvement [%] | CASE I Annual revenue [€] | CASE II Annual revenue [€] | Annual improvement [%] |
|---|---|---|---|---|---|
| Prosumer 1 | Spring/Autumn | 149.90 | 103.68 | 295.50 | 182.00 |
| | Summer | 0.00 | | | |
| | Winter | −84.60 | | | |
| Prosumer 2 | Spring/Autumn | 68.60 | −48.24 | −6.30 | −86.90 |
| | Summer | 0.90 | | | |
| | Winter | 0.00 | | | |
| Prosumer 3 | Spring/Autumn | 81.80 | −63.54 | −12.54 | −79.60 |
| | Summer | 1.00 | | | |
| | Winter | −2.20 | | | |

The electrical equipment usage is scheduled by solving the prosumer problem in which only the electrical part is considered. The scheduling for the thermal part is obtained by considering that the thermal load of a prosumer is fulfilled by the solar panel and by the controllable thermal plant owned by the prosumer. Table 5 shows the results obtained when the unified electrical/thermal model is adopted (*CASE II*). In this case, *Prosumer 1* registers an annual revenue of 295.50 **€**, *Prosumer 2* presents an annual cost of 6.30 **€**, and *Prosumer 3* has an annual cost of 12.54 **€**. In Table 6, the results of the prosumer management in CASE II and I are summarized. In particular, the table shows the additional revenues or cost savings obtained with the unified model with respect to those associated with the non-unified model. We can notice that the unified model offers a significant advantage for *Prosumer 1*, especially in spring/autumn and in winter. Indeed, this prosumer can obtain a reduction of the electrical energy cost and an increase of the electrical energy, as can be seen by comparing the data reported in Table 4 and in Table 5. In general, Table 6 shows that, when using the unified model, all the prosumers experience an economic improvement, especially in spring/autumn when the limited thermal load is mainly supplied by the generation from n-PRS plants. Indeed, the unified model allows to face an excess of production from n-PRS plants with respect to the energy demand and to store this excess into the storage systems. The unified model schedules the charge/discharge of storage systems depending on the energy load and generation, and determines when it is convenient to inject/absorb electrical energy into/from the grid. It is worth to underline that the HP maximizes the interaction between thermal and electric management because it acts as an electrical load and thermal generator at the same time. More specifically, the HP allows using cheap electric energy, e.g., energy produced by the PV plant or low-price energy imported from the grid, to produce the thermal energy.

The PV production profile is obtained from the forecasting services implemented in the Cloud Service Provider, as described in [37]. The electricity price is taken from the Italian day-ahead market. Fig. 11 and Fig. 12 show, respectively, the electrical equipment scheduling and the thermal equipment scheduling of *Prosumer 1* in a typical spring/autumn day. Fig. 11 also shows the hourly energy costs, i.e., the selling price and the purchasing price, and the PV profile retrieved from the Cloud service provider. In the figure, the "*distribution grid*" indicates the exchange profile between the nano-grid of *Prosumer 1* and the grid: negative values represent an absorption (purchase) of energy, while positive values represent an injection (sale) of energy.

Several interesting considerations can be taken from Fig. 11, as described in the following. At 4:00, an absorption of energy from the grid completely recharges the electric storage system, because the purchasing price is minimum. At 8:00, the energy produced from the PV plant and the stored energy are partially injected into the grid due to the high selling price.

The electric storage system remains at the minimum SOC level until 12:00, because the PV production is sufficient to supply the schedulable and non-schedulable loads and the energy surplus is injected into the grid. The electric storage system is recharged from the PV plant from 12:00 to 14:00, because the value of the selling price is at a local minimum, so the management model decides to store energy and sell it later, in a more convenient time, specifically starting from 19:00.

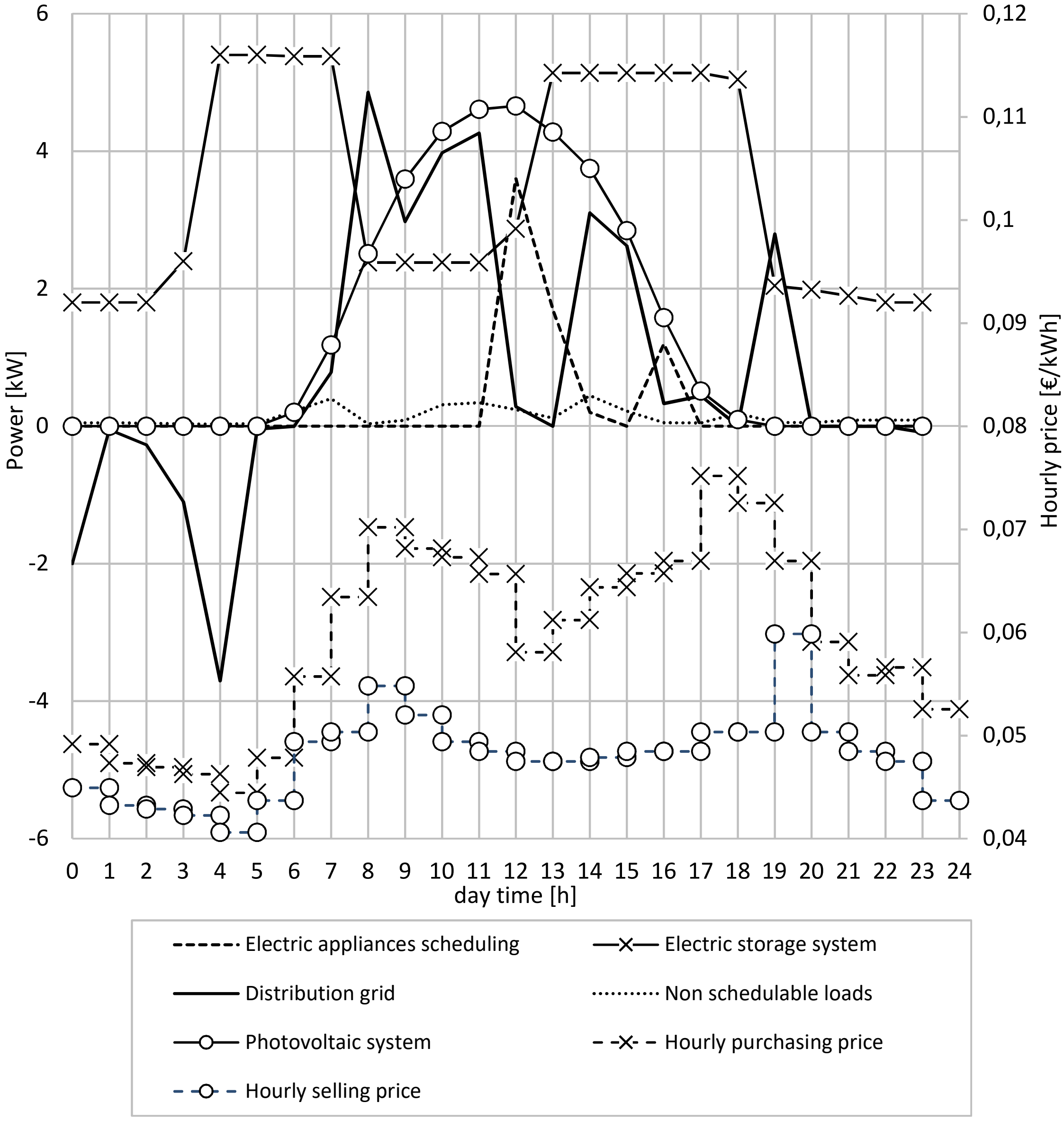


*Fig. 11 – Electrical scheduling for Prosumer 1 in a spring/autumn day*

Fig. 12 shows that, starting at 8:00, the HP and the thermal storage system supply the required thermal load. More specifically, from 8:00 to 9:00, the HP exploits the energy provided by the PV plant and the electric storage system. At 10:00, the thermal storage system is completely discharged and the thermal load is supplied from the thermal solar system. From 11:00 to 14:00, the production from the thermal solar system that is not required by the thermal load is stored into the thermal storage system.

As a conclusion, it is interesting to assess the results of the unified prosumer problem when varying the user preferences. As an example, we executed the prosumer problem with different values of the temperature set point desired by the Prosumer 1 in a typical winter day. We recall that the results shown in Table 4, Table 5 and Table 6 were obtained with a set point temperature equal to $20\,°C$. We assumed that the user can decide to change the temperature in a range between $19\,°C$ and $21\,°C$. In Fig. 13, we show the main thermal values and the costs related to the entire day, for the different values of the temperature set point. Specifically, we can see that the thermal load increases with the desired temperature. Since the energy guaranteed by the solar system is constant, the heat pump supplies the additional energy. The figure also shows that the daily cost increases with the desired temperature. In particular, we can see that the daily cost increases from about $0.14\,€$ to about $0.25\,€$ when the prosumer increases the temperature set point from $20\,°C$ to $21\,°C$, while it decreases to about $0.07\,€$ when the temperature set point is decreased to $19\,°C$.

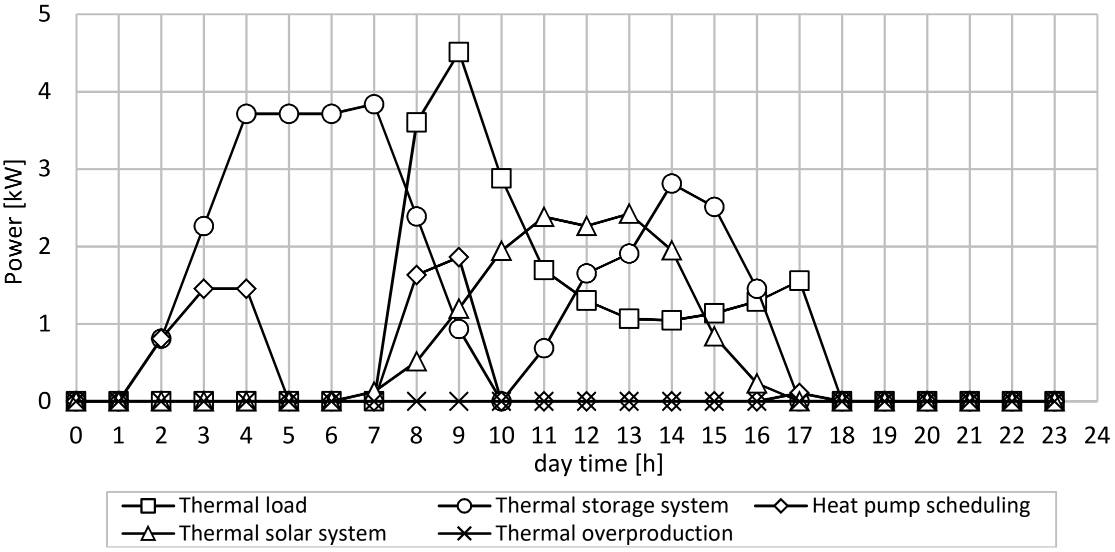


*Fig. 12 – Thermal scheduling for Prosumer 1 in a spring/autumn day*

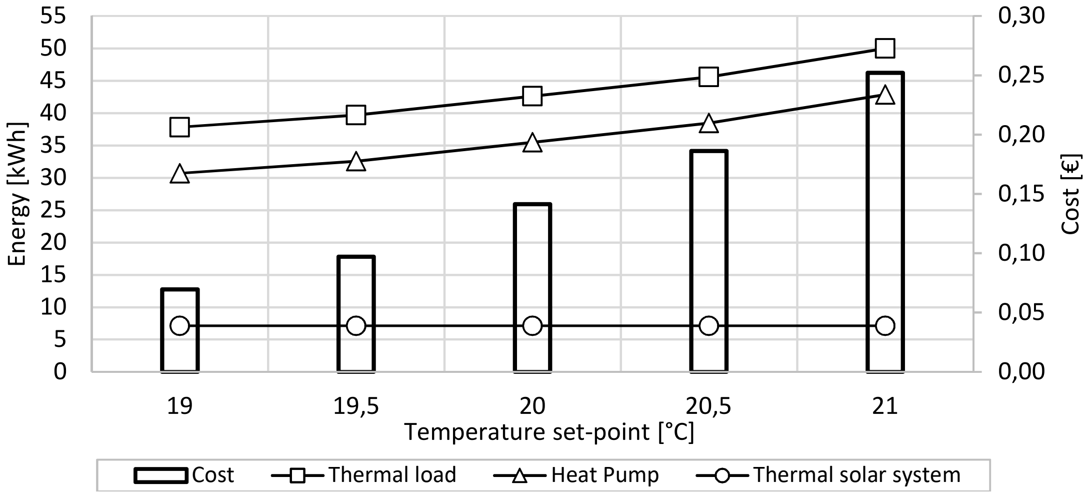


*Fig. 13 – Daily cost and thermal balance for a typical winter day, for Prosumer 1, varying the temperature set point*

# 4 Two–Stage Approach for Energy Districts

## 4.1 Introduction

The recent advancements regarding the decentralization of renewable energy production, the new technologies involved in the management of smart grids, and the opening of National energy markets, enriched with the use of demand–response strategies, have led to a notable increase of industrial and research efforts aiming at improving the management of local energy markets. A local energy market is defined as an aggregation of energy producers, consumers and prosumers that are located in a restricted area and see an interest in joining together to form a so–called "energy district".

In the literature, there are a number of approaches for the design and management of districts with the objective of meeting the local demand and availability of renewable energy production. In this Ph.D. thesis, a new two–stage optimization approach has been presented: the aim is to minimize the costs and/or maximize the revenues deriving from the provision and the sale of energy, both for single prosumers and for the district as a whole.

The main novelty with respect to the state–of–the–art is the introduction in the optimization process of a second stage that, starting from the energy exchanges determined in the first stage, re–distributes to the prosumers the surplus energy, i.e., the energy produced locally that exceeds the demand of the prosumers. The first stage optimizes the energy flows and computes the global energy profile when considering the prosumer needs, the energy prices and the energy production forecast. At the second stage, the aggregator identifies the surplus hours, i.e., the hours at which the produced energy exceeds the overall demand of prosumers, and puts on sale the surplus energy at a more convenient price, to redistribute this energy within the district.

The two–stage approach benefits have been assessed in a real–life testbed: a set of experiments was carried out at the campus of the University of Calabria.

The results have confirmed that the refinement of the solution, achieved at the second stage, allows reducing the energy exchanges between the district and the grid and leads to cost savings both for the single prosumers and for the energy district as a whole. Indeed, the two−stage approach improves the matching between the energy produced locally and the prosumers’ demand, and contributes to the self−sustainability of the local market and to its ability to reward the market operation costs.

### 4.1.1 Architecture and daily activities

The following section resumes the architecture of an energy district and describes the daily activity inside the energy district. As reported in Fig. 14, each prosumer joining an energy district need to host the following equipment:

- a **home automation system**, which manages the activation and deactivation of the electrical loads and the management of the thermal devices (e.g., solar panel, heat pump, gas boiler and thermal storage system) hosted inside the dwellings;
- **a nano−grid system**, which manages the energy exchange between the prosumer and the distribution grid, the local energy production plants and the electrical storage system;
- an **energy box**, which enables the interaction with the aggregator and supervises both the nano−grid and the home automation system. It is in charge of locally optimizing the energy management by considering the user preferences and interacting with the aggregator.

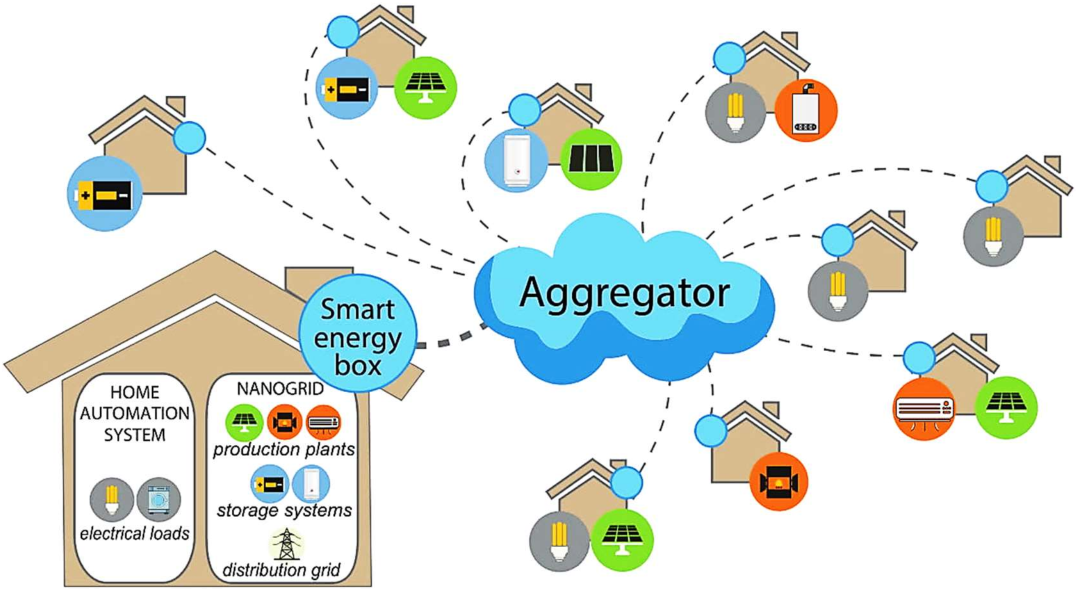


*Fig. 14 – Architecture of the energy district*

The aggregator is in charge of globally optimizing the energy management of the whole district with the goal of reducing the total cost. It supervises the energy exchanges among the prosumers, between each prosumer and the aggregator itself and between the aggregator and the distribution grid. It also interacts with all the smart energy boxes by supplying them information need to elaborate a proper working plan for the nano−grid and the home automation system. The aggregator computes this information every day for the following day. In detail, the daily activity of the aggregator to manage the district is organized as depicted in Fig. 15. First, energy production and consumption forecasts are computed by the forecast services of the Aggregator, starting from the weather forecast and the historical data of production/consumption of all the prosumers of the district.

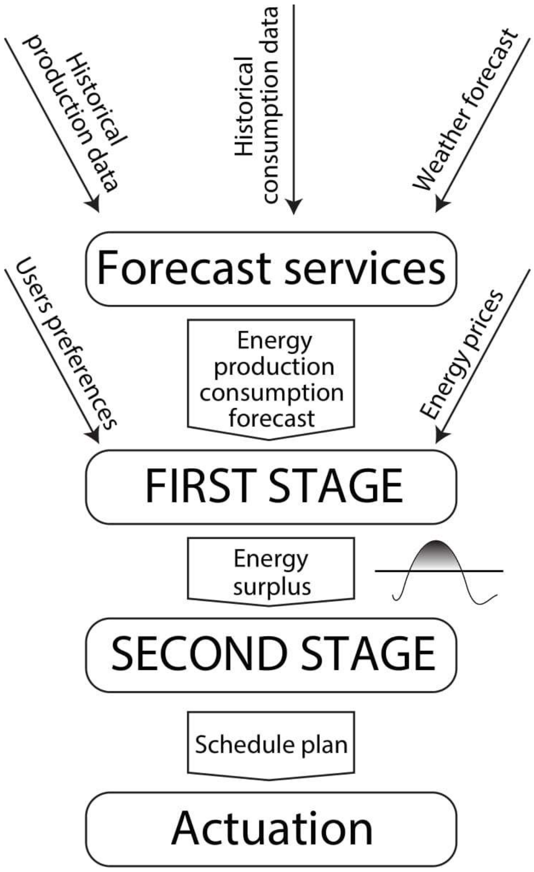


*Fig. 15 − Daily workflow*

At the first stage, each energy box takes into account the energy production / consumption forecasts, the energy prices, a set of user preferences about the electrical load scheduling and the thermal requirements. Using this information, each energy box solves the first stage prosumer problem in order to determine the optimal management of the energy flows. In particular, a prosumer problem solution consists in the optimal scheduling for determining the activation/deactivation of the electrical loads, the charging/ discharging of the electrical/thermal storage systems and the amount of energy imported/exported from/to the grid, and the operations of the controllable plants (e.g., the heat pump and the micro−CHP).

After the first stage, each energy box sends the energy exchange profile, i.e., the schedule of the energy to be imported/exported from/to the grid, to the aggregator. The latter, in turns, computes the global profile of the energy produced and consumed inside the whole district. Based on this global profile, the aggregator identifies the surplus hours, i.e., the hours at which the energy produced by the whole district exceeds the overall demand of energy. At the second stage, this energy surplus is partially reallocated to the prosumers. In particular, each energy box establishes if it has convenience or not to buy additional energy. In the Actuation phase, the nano-grid and the home automation system of each prosumer eventually actuate the schedule plan obtained in the first and second stages.

## 4.2 Prosumer Problem Models

The following section presents the optimization models for the prosumer problem, which aim to ensure optimal energy management and the economic benefits.

In detail, the prosumers obtain benefits to join an energy district for two main reasons: (i) the district, through the aggregator, can negotiate directly with the energy provider that applies wholesaler energy prices; (ii) the energy exchange inside the district and between the district and the energy provider can be locally optimized as proposed in this work. The district takes into account the daily trend of the energy market. In our scenario, the Italian energy market defines the wholesaler prices, hour-by-hour, at which the district can exchange energy with the energy provider: the zone price ($PZ^h$), i.e., the selling price, and the single national price ($PUN^h$), i.e., the buying cost. The approach presented in this work is applied to the Italian market, but is valid for all the cases in which the energy cost changes hour-by-hour, due to the free-market fluctuations, and a gap exists between the selling and purchasing price. In the case that prosumers do not join in a district, they need to negotiate with a wholesaler. As a consequence, if we call $c_{out}^h$ and $p_{out}^h$ the hourly selling price and buying cost for prosumers that operate in isolation, i.e., outside any district, it results $c_{out}^h \geq PUN^h$ and $p_{out}^h \leq PZ^h$. The aggregator is free to choose the tariffs to be applied to the prosumers of the district. In particular, the prices $c^h$ and $p^h$ are established by considering a trade-off between the prosumers and the aggregator economic advantages. Clearly, to ensure that prosumers have a benefit to join the district, it must hold that $c_{out}^h \geq c^h$ and $p_{out}^h \leq p^h$. Finally, it results:

$$c_{out}^h \geq c^h \geq PUN^h \geq PZ^h \geq p^h \geq p_{out}^h \tag{21}$$

### 4.2.1 First stage

In Fig. 16, the first stage workflow is summarized. Every day, before a predetermined hour, users set their thermal and electric preferences for the following day (label 1 in Fig. 16). Each energy box sends the thermal preferences, i.e., the desired set points of temperature, to the aggregator (label 2), which uses the preferences to compute the thermal load forecast. Moreover, the aggregator computes the production forecast of non−controllable power plants, the loads consumption forecast and the buying and selling energy prices applied to the prosumers of the district. All this information is then sent to the energy boxes if the prosumers (label 3), which solve the first stage prosumer problem (label 4) and send the resulting energy exchange profiles to the aggregator (label 5), which is now able to compute the global energy profile.

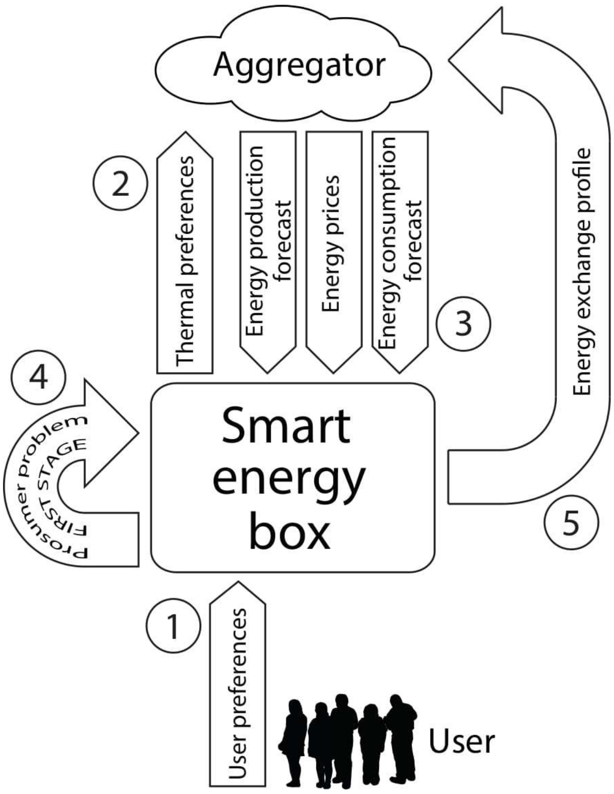


*Fig. 16 − Workflow of the first stage*

In the following, we report the objective function, the constraints and the upper and lower bounds that define the optimization model. Further details and explanation can be found in section 3.3.

1) Objective function

$$min \sum_{h \in H} (C_{kWht_{CHP}} * F_{CHP} * E^{h}_{CHP} + C_{kWht_{NG}} * E^{h}_{NG} + c^{h} * E^{h}_{imp} - p^{h} * E^{h}_{exp}) \qquad (22)$$

The function is defined to maximize the revenues and minimize the costs incurred by a prosumer.

2) Constraints

$$E_{imp}^{h} - E_{exp}^{h} + \eta_{dis} * E_{dis}^{h} - \frac{1}{\eta_{cha}} * E_{cha}^{h} + E_{CHP}^{h} - E_{HP}^{h} - \sum_{a\in A} y_a^h * E_a = \sum_{b\in B} x_b^h - E_{PV}^{h} \quad \forall h \in H \tag{23}$$

$$COP * E_{HP}^{h} + F_{CHP} * E_{CHP}^{h} + E_{NG}^{h} + E_{STO_t}^{h} - X_{diss}^{h} = \sum_{t\in T} x_t^h - E_{SOL_t}^{h} \quad \forall h \in H \tag{24}$$

Equations *(23)* and *(24)* define, respectively, the electrical and thermal energy balance.

$$\sum_{h=\alpha_a}^{\beta_a} y_a^h = \theta_a \quad \forall a \in A \tag{25}$$

$$\sum_{h=\alpha_a}^{\beta_a-\theta_a+1} z_a^h = 1 \quad \forall a \in A \tag{26}$$

$$z_a^h = 0 \quad \forall h \in H \setminus [\alpha_a, \beta_a - \theta_a + 1] \quad \forall a \in A \tag{27}$$

$$y_a^h \geq z_a^h,\ y_a^{h+1} \geq z_a^h, \ldots,\ y_a^{h+\theta_a-1} \geq z_a^h \quad \forall h \in [\alpha_a, \beta_a], \tag{28}$$

Equations (*25*), (*26*), (*27*) and inequality (*28*) define the constraints on the schedulable loads. Note that, the electrical loads are divided into schedulable loads and non−schedulable loads. A schedulable load can be active at any time within a user−defined time interval, whereas a non−schedulable load must be active at a predetermined hour of the day.

$$\sum_{i=0}^{h} E_{cha}^{i} - \sum_{i=0}^{h} E_{dis}^{i} \leq SOC_{min} * C_{max} - E_{STOel}^{*} \quad \forall h \in H \tag{29}$$

$$\sum_{i=0}^{h} E_{cha}^{i} - \sum_{i=0}^{h} E_{dis}^{i} \geq SOC_{max} * C_{max} - E_{STOel}^{*} \quad \forall h \in H \tag{30}$$

Inequalities (*29*) and (*30*) force the state of charge of the electrical storage system to be inside its admissible range.

$$\sum_{i=0}^{h} E_{STOt}^{i} \leq \rho V C_p * \left(T_{STOt}^{max} - T_{STOt}^{min}\right) - E_{STOt}^{*} \quad \forall h \in H \tag{31}$$

$$\sum_{i=0}^{h} E_{STOt}^{i} \geq -E_{STOt}^{*} \quad \forall h \in H \tag{32}$$

Inequalities *(31)* and *(32)* force the state of charge of the thermal storage system to be inside its admissible range.

3) Upper and lower bounds

The upper and lower bounds that define the optimization model are reported in inequalities *(33)–(40)*.

$$0 \leq E_{imp}^{h} \leq E_{grid}^{max} \quad \forall h \in H \tag{33}$$

$$0 \leq E_{exp}^{h} \quad \forall h \in H \tag{34}$$

$$0 \leq E_{cha}^{h} \leq E_{cha}^{max} \quad \forall h \in H \tag{35}$$

$$0 \leq E_{dis}^{h} \leq E_{dis}^{max} \quad \forall h \in H \tag{36}$$

$$0 \leq E_{HP}^{h} \leq E_{HP} \quad \forall h \in H \tag{37}$$

$$0 \leq E_{CHP}^{h} \leq E_{CHP} \quad \forall h \in H \tag{38}$$

$$0 \leq E_{NG}^{h} \leq E_{NG} \quad \forall h \in H \tag{39}$$

$$-\rho V C_p * \Delta T_{STOt}^{max} \leq E_{STOt}^{h} \leq \rho V C_p * \Delta T_{STOt}^{max} \quad \forall h \in H \tag{40}$$

## 4.2.2 Second stage

In the second stage, the aggregator, starting from the global energy profile resulting from the first stage, identifies the surplus hours, i.e., the hours at which the energy produced by the whole district exceeds the overall demand of energy. The goal of the second stage is to reallocate partially this energy surplus to the prosumers. To this end, the aggregator puts on sale this energy surplus at a more convenient price $c_s^h$ with respect to the purchase price reserved at the first stage. The inequality *(21)* is updated by including the price $c_s^h$, as follows:

$$c_{out}^{h} \geq c^{h} \geq \{PUN^{h}, c_s^{h}\} \geq PZ^{h} \geq p^{h} \geq p_{out}^{h} \tag{41}$$

The price $c_s^h$ must be greater than $PZ^h$, i.e., the price at which the aggregator sells energy to the grid, otherwise it would be more convenient for the aggregator to sell the energy surplus to the grid rather than distributing it within the district, and there would be no benefit for the prosumers. On the other hand, there exists no particular order relationship between the values of $c_s^h$ and $PUN^h$, which is expressed by the curly brackets in expression *(41)*.

The workflow of the second stage is outlined in Fig. 17. First, the aggregator sends to all the energy boxes (label 1) information about the surplus hours and the corresponding costs. Afterwards, each prosumer solves the so-called second stage prosumer problem – request phase optimization model (label 2).

By solving this model, the prosumer establishes if it is convenient or not to buy a portion of the energy surplus. The solution can correspond to a different schedule with respect to the one determined in the first stage, because the prosumer can take into account the availability of the surplus energy, offered at a lower price. The solution includes a set of hourly−based energy surplus requests that are then sent to the aggregator (label 3). The latter, based on the surplus availability, decides which requests can be granted, totally or partially, and which must be rejected. The granting strategy privileges, for each hour, the request for the highest amount of energy. The amounts of surplus energy granted to the different prosumers are then communicated to the energy boxes (label 4). If a prosumer is granted all the surplus energy requests, the second stage is considered complete. On the other hand, if some requests are not accepted, or are accepted partially, the prosumer needs to solve the prosumer problem again, in order to refine the solution obtained at the request phase by considering the energy requests partially granted or not granted at all. Therefore, the prosumer solves the so−called second stage prosumer problem − grant phase optimization model (label 5). The main difference between the request and the grant phase is that in the request phase each energy box is free to request any amount of energy surplus that minimizes its objective function, while in the grant phase it has to consider a fixed amount of energy surplus, that is, the amount granted by the aggregator at each hour. Finally, the energy box uses the final solution to actuate the schedules on the nano−grid and on the home automation system (label 6).

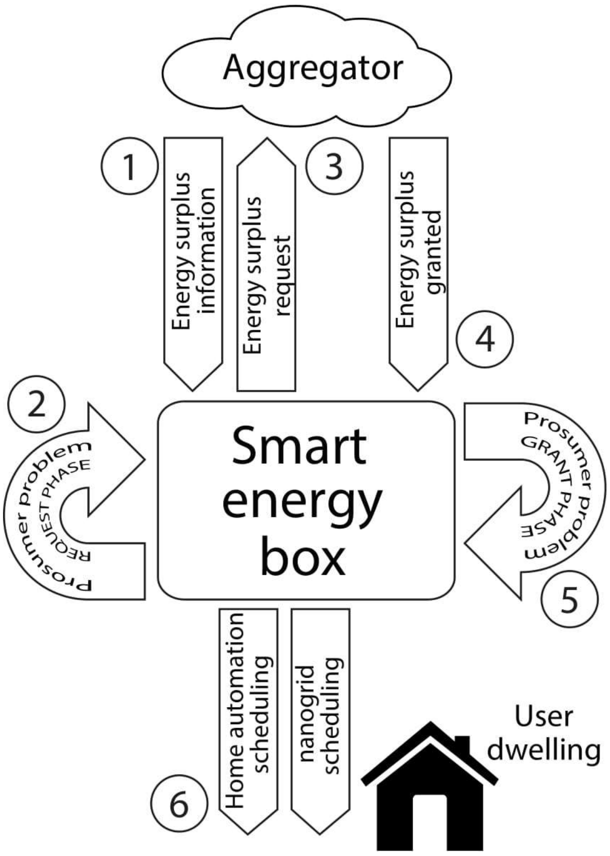


*Fig. 17 − Workflow of the second stage*

1) Request phase

The model for the request phase of the second stage uses the same variables as the first stage model plus another set of variables, $E_{req}^{h}$, which are the amounts of energy surplus that the prosumer will request. The same constraints and upper/lower bounds as the first stage model are also adopted, with the differences and the additions that are specified in the following. Preliminarily, we need to introduce $H^{*}$, the set of surplus hours. The hourly cost of the energy surplus, $c_{s}^{h}$, is a new constant introduced in the second stage, and it is established by the aggregator starting from the values of $c^{h}$ and $p^{h}$, as detailed before.

The objective function – see expression (*22*) – and the electrical balance constraint – see equation (*23*) – of the first stage model are substituted with the expression (*42*) and the equation (*43*), in which the new variables $E_{req}^{h}$ are now considered.

$$min \sum_{h \in H} (C_{kWht_{CHP}} * F_{CHP} * E_{CHP}^{h} + C_{kWht_{NG}} * E_{NG}^{h} + c^{h} * E_{imp}^{h} - p^{h} * E_{exp}^{h} + \boldsymbol{c_{s}^{h}} * \boldsymbol{E_{req}^{h}}) \tag{42}$$

$$E_{imp}^{h} - E_{exp}^{h} + \boldsymbol{E_{req}^{h}} + \eta_{dis} * E_{dis}^{h} - \frac{1}{\eta_{cha}} * E_{cha}^{h} + E_{CHP}^{h} - E_{HP}^{h} - \sum_{a \in A} y_{a}^{h} * E_{a} = \sum_{b \in B} x_{b}^{h} - E_{PV}^{h} \quad \forall h \in H \tag{43}$$

The hour−by−hour electrical energy exported to the grid as resulting from the solution of the first stage model is introduced in the request phase of the second stage model as a constant, $E_{expFS}^{h}$. Indeed, if the amount of exported energy were modified at the second stage, the surplus energy could be no longer available, thus making the execution of the second stage not consistent with the solution of the first stage. Therefore, the amount of energy exported during the surplus hours by each prosumer in the second stage must be equal to the corresponding amount of the first stage, which is guaranteed by equation *(44)*.

$$E_{exp}^{h} = E_{expFS}^{h} \quad \forall h \in H^{*} \tag{44}$$

Inequalities *(45)* and *(46)* determine the admissible range of values for $E_{req}^{h}$. In particular, inequality (*45*) substitutes the analogous inequality in the first stage model, i.e., inequality (*33*). Expression (*46*) and (*47*) specify that $E_{req}^{h}$ can be greater than 0 only in the surplus hours, while in the remaining hours it is equal to zero.

$$0 \leq E_{imp}^{h} + E_{req}^{h} \leq E_{grid}^{max} \quad \forall h \in H \tag{45}$$

$$E_{req}^{h} \geq 0 \quad \forall h \in H \tag{46}$$

$$E_{req}^{h} = 0 \quad \forall h \in H \backslash H^{*} \tag{47}$$

2) Grant phase

The model for the grant phase of the second stage uses the same variables, constants and constraints of the first stage model, with the differences specified in the following. The quantities $c_s^h$, $H^*$, $E_{expFS}^h$ have the same meaning as in the request phase. New constants $\boldsymbol{E_{acc}^h}$ are introduced, which represent the amount of energy surplus requested by the prosumer and granted by the aggregator. The objective function, the electric balance constraint and the constraint on the maximum amount of energy that can be imported from the grid are modified accordingly in expression (*48*), equation (*49*) and inequality (*50*).

$$min \sum_{h \in H} (C_{kWht_{CHP}} * F_{CHP} * E_{CHP}^h + C_{kWht_{NG}} * E_{NG}^h + c^h * E_{imp}^h - p^h * E_{exp}^h + \boldsymbol{c_s^h} * \boldsymbol{E_{acc}^h}) \tag{48}$$

$$E_{imp}^h - E_{exp}^h + \eta_{dis} * E_{dis}^h - \frac{1}{\eta_{cha}} * E_{cha}^h + E_{CHP}^h - E_{HP}^h - \sum_{a \in A} y_a^h * E_a = \sum_{b \in B} x_b^h - E_{PV}^h - \boldsymbol{E_{acc}^h} \quad \forall h \in H \tag{49}$$

$$0 \leq E_{imp}^h \leq E_{grid}^{max} - \boldsymbol{E_{acc}^h} \quad \forall h \in H \tag{50}$$

Similarly, to what said for the request phase, also in the grant phase the amount of energy exported to the grid during the surplus hours is set to be equal to the amount computed after the first stage, see equation (*51*).

$$E_{exp}^h = E_{expFS}^h \quad \forall h \in H^* \tag{51}$$

## 4.3 Experimental Results

In this section, we compare the costs/revenues achieved with the first and the second stage in order to assess the benefits of the energy surplus redistribution performed within the second stage. In addition, we compare the results with those obtained when the users exchange energy directly with a wholesaler, i.e., without joining a district.

The experimental part was carried out at the University of Calabria, Italy. In particular, the considered energy district is composed of many buildings located in the University campus, where each building is a prosumer of the district. Fig. 18 reports a view of the whole district (the black-coloured blocks are the buildings acting as prosumers in the district) while Table 7 details the user equipment. The reported experiments were conducted to determine the optimal schedule for the day October 27th, 2017.

The equipment are categorized into three main groups: (i) plants, i.e., renewable energy sources (PV plants and thermal solar systems) and traditional energy sources (gas boilers, heat pumps and points of delivery of the distribution grid); (ii) electrical and thermal loads; (iii) electrical and thermal storage systems. Table 7 also reports the rated power of each plant and the capacity of each storage system.

*Table 7 – District prosumers and corresponding equipment*

| Users | Plants (rated power) | | | | | Loads | | | Storage (capacity) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | grid [kW] | PV [kW] | gas boiler [kW] | heat pump [kW] | thermal solar system $[m^2]$ | non schedulable | schedulable | thermal | electrical [kWh] | thermal [litre] |
| Chiodo2 | 10 | 9.00 | – | 9 | – | y | y | y | 25 | 800 |
| Cubo 44B | 30 | 31.36 | 20 | – | 10 | y | y | y | 25 | – |
| Orto Botanico | – | 472.50 | – | – | – | n | n | n | – | – |
| Cubo 0B | 60 | 62.72 | – | – | – | y | y | n | – | – |
| Cubo0C–1C | 30 | 31.36 | – | – | – | y | y | n | – | – |
| Cubo12C–18B | 30 | 31.36 | – | – | – | y | n | n | – | – |
| Cubo15B | 30 | 31.36 | – | – | – | y | n | n | 25 | – |
| Cubo17B | 30 | 31.36 | – | – | – | y | n | | 50 | – |
| Cubo31B | 30 | 31.36 | – | – | – | y | n | n | 75 | – |
| Cubo41C | 20 | – | – | – | – | y | n | n | 25 | – |
| Cubo1A–2A–3A–4A–5A | 20 | – | – | – | – | y | y | n | 75 | – |
| Cubo6A–7A–8A–9A–10A | 20 | – | – | – | – | y | n | n | 75 | – |

*Fig. 18 – Map of the University of Calabria*

The national selling and buying energy prices for each hour, $PZ^h$ and $PUN^h$, were retrieved from the Italian energy market manager called "Gestore dei Mercari Energetici" (GME). Each day for the following day, it defines the wholesaler hourly prices at which the district can exchange energy with the energy provider: the zone price ($PZ^h$) and the single national price ($PUN^h$).
The prices $c_{out}^h$ and $p_{out}^h$ represent the hourly selling price and buying cost for prosumers that operate in isolation, i.e., outside any district.
The prices $c^h$, $p^h$, and $c_s^h$ were established by the aggregator of the energy district to be compliant to inequalities (*41*). $c_{out}^h$, $p_{out}^h$
Fig. 19 shows the trends of such prices (in the legend, the apex h is omitted for the sake of readability.

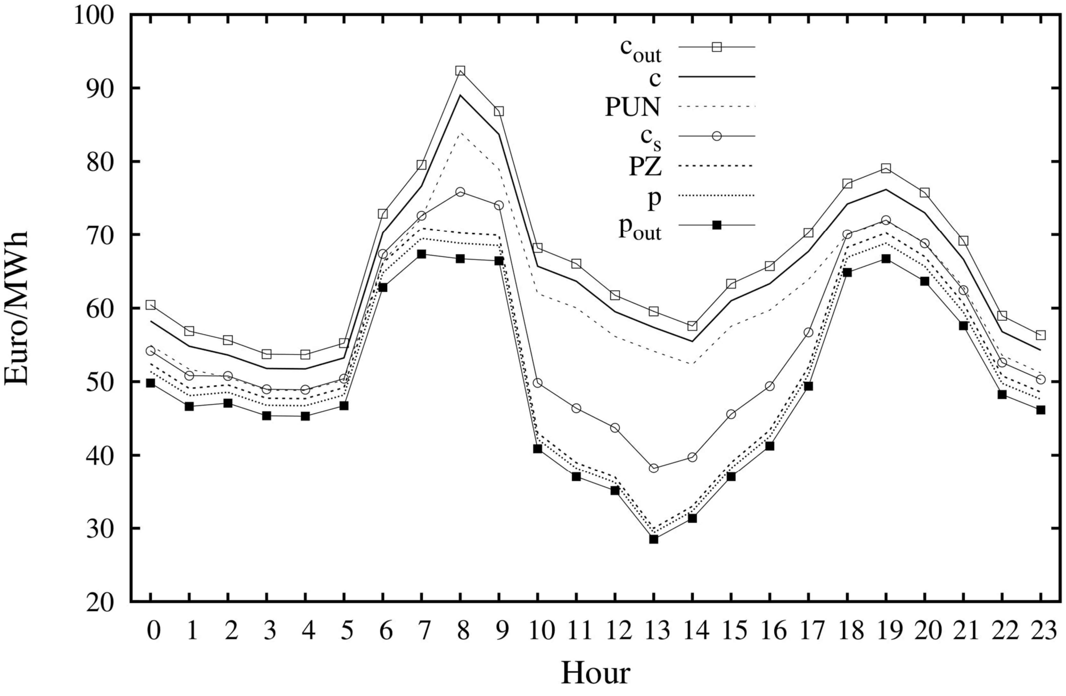


*Fig. 19 – Hourly prices on October 27th, 2017*

Before reporting the general results for the whole district, we focus the attention to a single user, the building Cubo1A, to comment how the scheduling results change after the execution of the first stage and the second stage.
In particular, Fig. 20 shows the scheduling of the energy exchanged with the grid and the energy profile of the schedulable loads (positive values indicate that energy is exported to the grid, negative values that energy is imported), while Fig. 21 reports the state of charge of the electrical storage system.

We can notice that, after the execution of the first stage, the schedulable loads are scheduled to be activated between $02{:}00$ and $05{:}00$ as the buying cost $c^h$ is at its minimum in that time interval (see Fig. 19). After the second stage, the schedulable loads are activated, instead, between $11{:}00$ and $15{:}00$, when the user Cubo1A takes advantage of the low value of $c_s^h$ and therefore buys a portion of the available surplus of energy in that time interval.

When looking at Fig. 20 and Fig. 21, it is also possible to notice interesting differences in the values of grid exchange and in the storage usage. In the first stage, a certain amount of energy is imported from the grid during the first hours of the day and stored in the storage system in order to use it later to fulfil the load demand. In the second stage, instead, a lower amount of energy is imported and stored during the first hours of the day, while a greater amount of energy is imported between 10:00 and 15:00, i.e., the surplus hours.

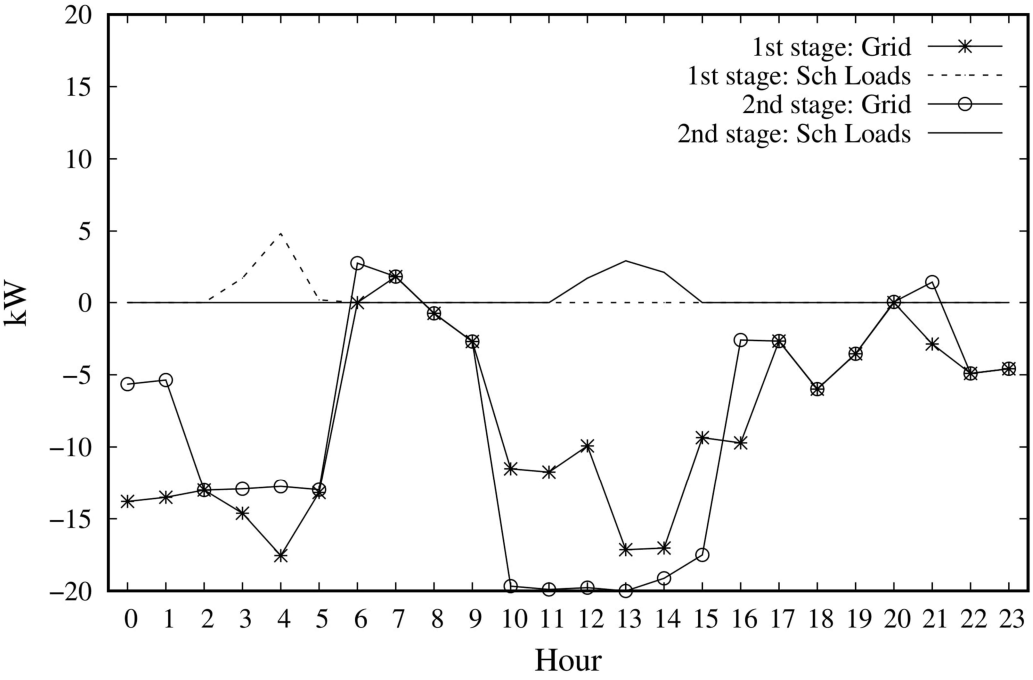


*Fig. 20 − Comparison between first and second stage for prosumer Cudo1A (grid energy exchange and schedulable loads profile)*

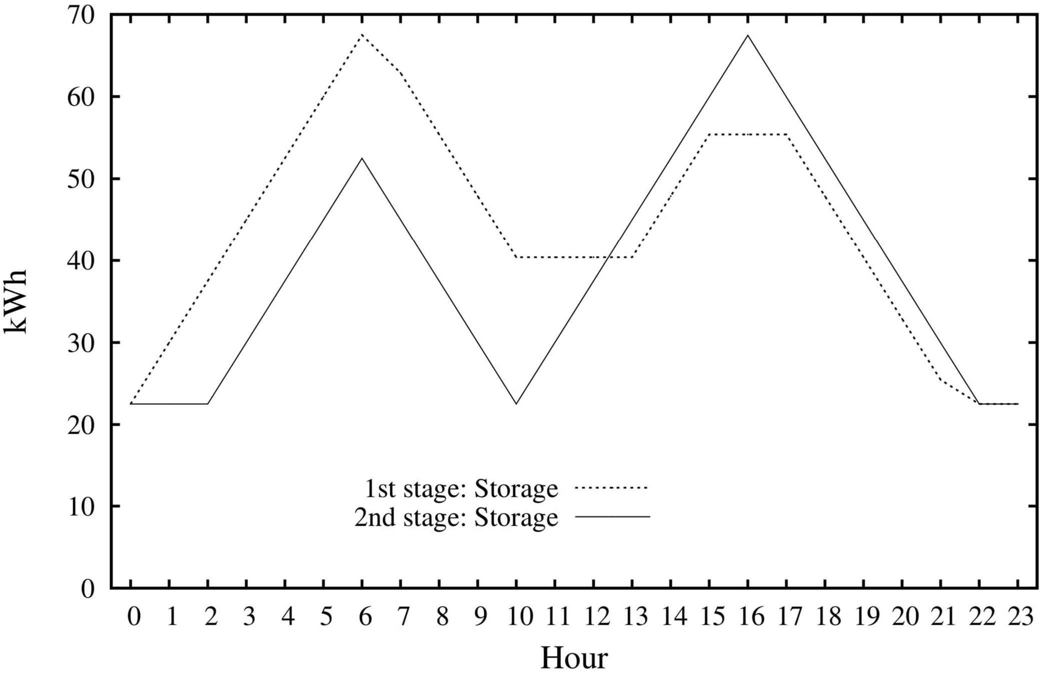


*Fig. 21 − Comparison between first and second stage for prosumer Cubo1A (state of charge of the electrical storage system)*

In Table 8, the amount of energy surplus available at the end of the first stage is shown together with the requests of surplus energy coming from the prosumers in the second stage. Since that, the overall amount of energy requested by the prosumers is lower than the available energy surplus; the aggregator can satisfy all the requests so there is no need to solve the grant phase prosumer problem.

*Table 8 – Amount of energy surplus requested and granted in the second stage*

| Surplus hours | | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| Available energy [kWh] | | 49 | 87 | 174 | 152 | 188 | 217 | 90 | 67 | 111 |
| Request for surplus [kWh] | Chiodo2 | 0 | 0 | 0 | 1.33 | 1.33 | 3.95 | 0.00 | 0.00 | 0.03 |
| | Cubo1A | 0 | 0 | 0 | 8.15 | 8.15 | 9.85 | 2.86 | 2.10 | 8.15 |
| | Cubo2A | 0 | 0 | 0 | 8.15 | 8.15 | 9.85 | 2.86 | 2.10 | 8.15 |
| | Cubo3A | 0 | 0 | 0 | 8.15 | 8.15 | 9.85 | 2.86 | 2.10 | 8.15 |
| | Cubo4A | 0 | 0 | 0 | 8.15 | 8.15 | 9.85 | 2.86 | 2.10 | 8.15 |
| | Cubo5A | 0 | 0 | 0 | 8.15 | 8.15 | 9.85 | 2.86 | 2.10 | 8.15 |
| | Cubo6A | 0 | 0 | 0 | 8.15 | 8.15 | 8.15 | 0.00 | 0.00 | 8.15 |
| | Cubo7A | 0 | 0 | 0 | 8.15 | 8.15 | 8.15 | 0.00 | 0.00 | 8.15 |
| | Cubo8A | 0 | 0 | 0 | 8.15 | 8.15 | 8.15 | 0.00 | 0.00 | 8.15 |
| | Cubo9A | 0 | 0 | 0 | 8.15 | 8.15 | 8.15 | 0.00 | 0.00 | 8.15 |
| | Cubo10A | 0 | 0 | 0 | 8.15 | 8.15 | 8.15 | 0.00 | 0.00 | 8.15 |

In the following, we focus on the performance of the whole district and compare three different scenarios:

- *out–of–district case*, in which the prosumers do not organize in a district and the strategies presented in this paper are not applicable;
- *1st stage case*, in which only the first stage is executed;
- *2nd stage case*, in which both first and second stages are executed.

In the out–of–district scenario, the optimization models introduced in the previous section cannot be applied and the prosumers behave following a simple energy strategy, which can be considered as a basic strategy for prosumers equipped with an electrical storage system (for more detail see Section **Errore. L'origine riferimento non è stata trovata.**). In particular, a prosumer fulfils the load demand by using its PV plant or its storage system, and when this is not sufficient, buys extra energy from the grid. Moreover, the energy produced by the PV plant, which exceeds the load demand, is used to charge the storage system, and is sold to the grid when the storage is full. The thermal part is managed similarly.

In Fig. 22, the hourly energy profile of the whole district is shown for the three scenarios. It is important to notice that the 2nd stage profile is smoother than the first stage profile: the reason is that the redistribution of the energy surplus among the prosumers allows reducing the energy exchanges between the district and the grid. As an example, the amount of energy imported from the grid is equal to $1573.68\,kWh/day$ for the 1st stage scenario, and it reduces to $1302.69\,kWh/day$ for the 2nd stage scenario.

The corresponding costs and revenues are reported in Fig. 23. It can be noticed that costs/revenues are related both to the trend of imported/exported energy (Fig. 22) and to the hourly prices (Fig. 19).

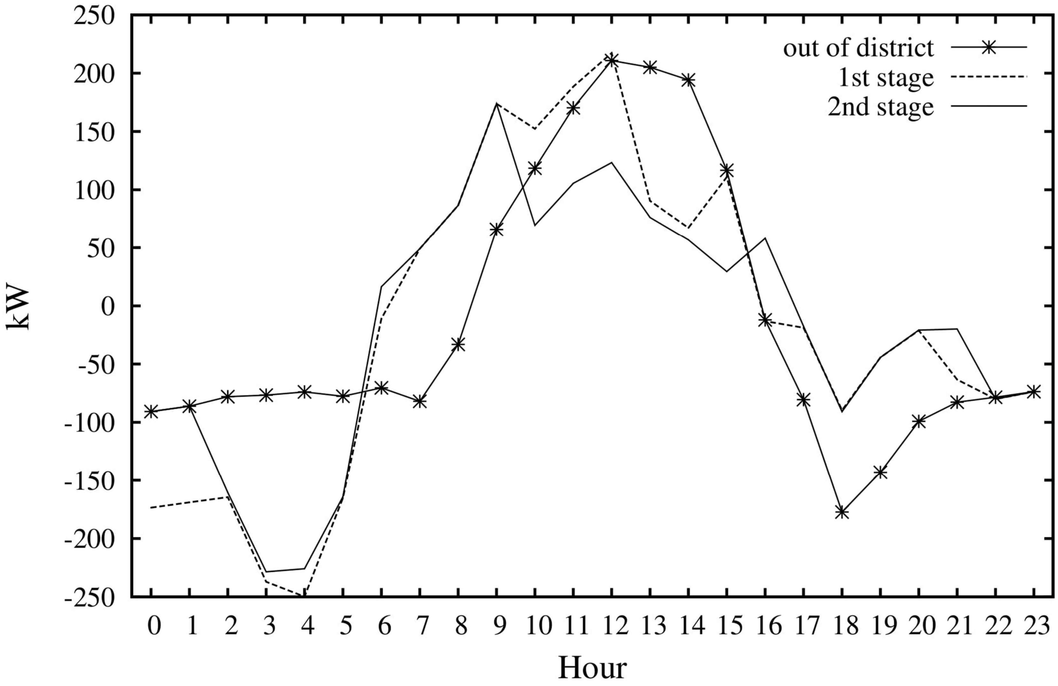


*Fig. 22 – Aggregated profile for the out-of-district, 1st stage and 2nd stage scenarios*

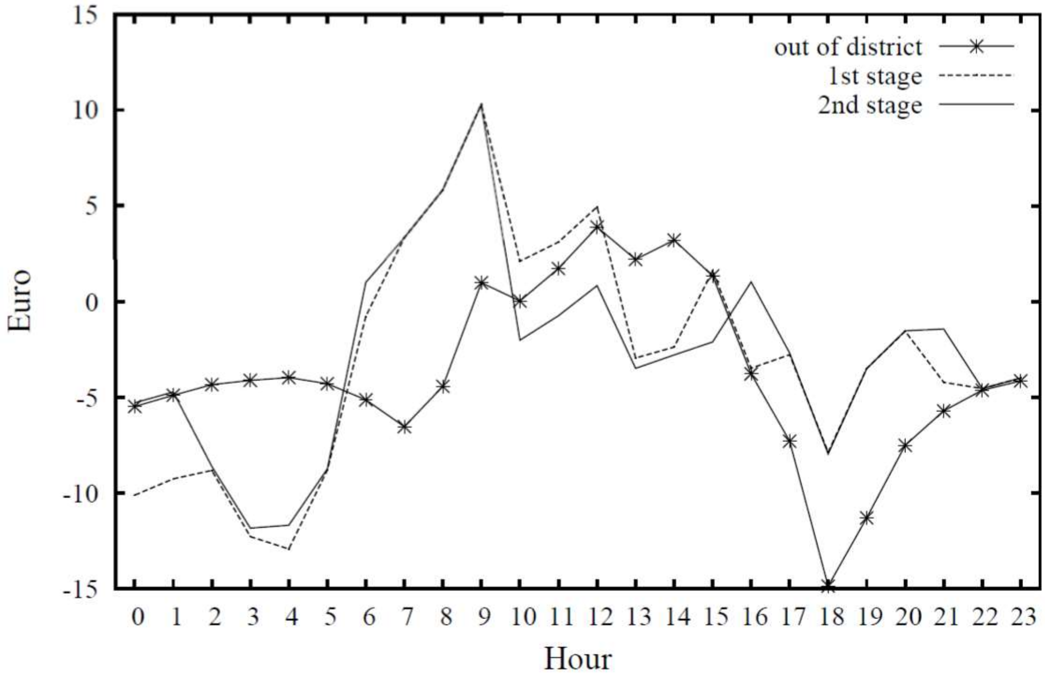


*Fig. 23 – Aggregated hourly costs (negative values) and revenues (positive values)*

In Table 9, the costs/revenues of the district are shown in detail for the three considered scenarios. In particular, the costs and revenues are reported for all the prosumers, for the aggregator and for the energy district as a whole (i.e., obtained as the sum of costs/revenues of all the prosumers and of the aggregator).

### 4.3.1 Cost-benefit for the user

The prosumer costs/revenues reported in Table 9, for the out-of-district scenario, are the algebraic sum of the costs/revenues for importing/exporting energy from/to the grid considering $c_{out}^{h}$ and $p_{out}^{h}$ as buying and selling prices. For the prosumer Cubo44b, which owns the gas boiler, the cost of the gas is also considered. For the 1st stage and 2nd stage scenarios, the cost/revenue of a prosumer is the value of the objective function of the prosumer problem model for the first and the second stage. The aggregator cost/revenue is the algebraic sum of the costs/revenues for importing/exporting energy from/to the grid, considering $PZ^{h}$ and $PUN^{h}$ as buying and selling prices, added to the costs/revenues for buying/selling energy from/to the prosumers. In particular, the price for buying energy from a prosumer is $p^{h}$ while the cost for selling energy to a prosumer is $c^{h}$, except for the energy surplus that is sold at the price $c_{s}^{h}$ . When considering the district as a whole, we can notice that the overall cost is equal to **89€** in the out-of-district scenario, while it reduces to **31.41€** in the 1st stage scenario, with a saving of about **65%**. When executing the second stage, the cost further reduces to **27.10€**, with an additional saving of about **14%**. These results witness the validity of the approach and the benefits deriving from joining the district (and exploiting the optimization models) and from the two-stage approach aimed to redistribute the surplus energy among the prosumers in a better way. Both the prosumers and the aggregator experience advantages in terms of reducing the costs and maximizing the revenues.

*Table 9 – Costs (negative values) and revenues (positive values) of the district*

| Users | Cost/Revenue [€] | | |
|---|---|---|---|
| | out-of-district | 1st stage | 2nd stage |
| Chiodo2 | −3.89 | −3.30 | −3.24 |
| Cubo44B | −6.75 | −5.98 | −5.98 |
| Orto Botanico | 45.73 | 47.17 | 47.17 |
| Cubo0B | 6.43 | 6.83 | 6.83 |
| Cubo0C-1C | 0.86 | 1.09 | 1.09 |
| Cubo12C | 1.07 | 1.31 | 1.31 |
| Cubo15B | 1.26 | 2.03 | 2.03 |
| Cubo17B | 0.02 | 1.01 | 1.01 |
| Cubo18B | 1.07 | 1.31 | 1.31 |
| Cubo31B | −2.72 | −1.82 | −1.82 |
| Cubo41C | −6.24 | −5.55 | −5.55 |
| Cubo1A-2A-3A-4A-5A | −12.87 | −11.59 | −11.20 |
| Cubo6A-7A-8A-9A-10A | −12.47 | −11.25 | −10.93 |
| All prosumers | −89.00 | −69.03 | −65.38 |
| Aggregator | 0.00 | 37.62 | 38.28 |
| Energy District (tot.) | −89.00 | −31.41 | −27.10 |

# 5 Case Study: the Domus District

In the last decade, the global electricity industry has undergone significant changes. New requirements in terms of environmental impact and energy savings have imposed major changes to the new power system, allowing the growing integration of renewable energy plants. This is why it has become increasingly difficult to maintain reliable operation and control of the system: the flow of power is no longer unidirectional.

The installation of micro-grids, capable of coordinating each other and interacting with the power system by means of decentralized operations, offers solutions to the challenges posed by this transformation. It is known that the key to increasing the operational and economic efficiency of micro-grids, especially for uses in the energy district, lies in a better participation of the customer in Demand Response programs. The aim that we have tried to achieve through the work described here, has been to develop a DR program that allows a good interaction with users and at the same time guarantees high performance to the system and the entire energy community.

In this chapter, we describe in detail the work done to achieve, according to the models previously described, a real energetic district that involved different users located on the territory of the University of Calabria.

The chapter is organized as follows: it start with an overall description of the architecture of the DOMUS energy district, made at the University of Calabria Campus based on the DR models, described in this work: the figure of the district aggregator, the services provided (forecast prices, production, consumption) and utilities involved are introduced.

Follows the description of the Graphic Aggregator Interface through which the aggregator will coordinate the prosumers' participation in the DR program and the illustration of the Graphic User Interfaces through which the users define the preferential scheduling.

Finally, the phases of participation in the DR program (1st and 2nd stage) and the implementation of the planned scheduling plan are described.

## 5.1 The Architecture

This section provides details regarding the general architecture of the Domus district, with reference to the number and type of participating users.

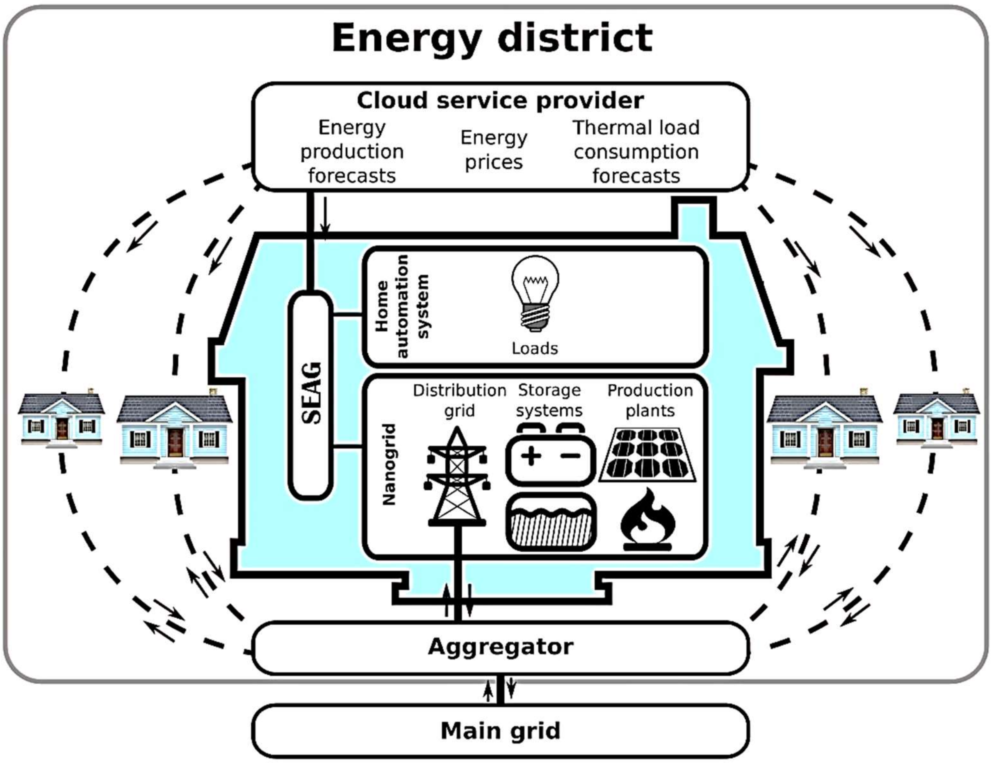


*Fig. 24 – Architecture of the Domus District*

As shown in Fig. 24 and as better explained in section 2.2, the architecture adopted in the Domus district can be organized and divided into 4 levels, which include:

- the Cloud side: Aggregator and Cloud service provider;
- the SEAG;
- the nano−Grid and Home Automation System;
- loads, generation plants and storage systems.

The Cloud side concern the set of all the services that the aggregator provides to users in order to facilitate their participation in the DR program, such as energy production forecasts, energy prices, thermal load consumption forecasts. The SEAG represents the gateway between the user and the Cloud side: through it, the user is able to virtualize their users, to define their own energy preferences and to coordinate with the rest of the energy community. Each user joining the energy district need a SEAG, which will be unique for that specific user. In addition to the functions already described, each SEAG will perform the function of HEMS, i.e., it will be able to communicate and control the nano−grid and the home automation systems, thus ensuring the implementation of the scheduling program.

In general, a home automation system allows monitoring and interaction with various parts of a dwelling with the aim of improving the quality of life of residents by automating various procedures related to the "functioning" of a home. In our case, the aim is to maximize energy efficiency by optimally turn on/off all the loads, devices and appliances connected to the electricity grid. While, the nano-grid systems combined with SEAGs are designed to control the energy flows produced by the generation plants, required by the loads and exchanged with the storage systems and the distribution grid.

The Domus district currently has about 19 users among producers, consumers and prosumer grouped into three groups: University of Calabria (UNICAL) partner, TIM partner and University of Reggio Calabria (UNIRC) partner. In particular, the University of Calabria counts 13 users.
Fig. 25 shows a complete view of the district, while in Fig. 26 the users are only for the aggregation of the University of Calabria. The images have been extrapolated from the Graphic Aggregator Interface, used by the aggregator to visualize, modify and eliminate all the characteristic data related to the users joining the energy district. More information about the Graphic Aggregator Interface is provided in the section 5.2.1.

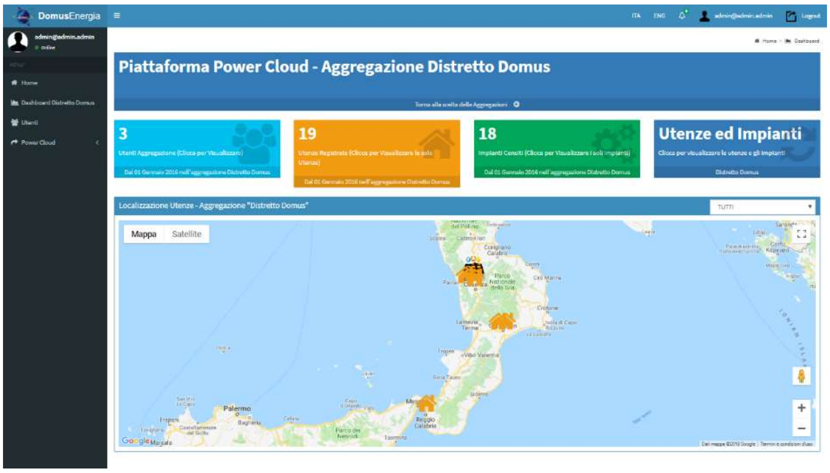
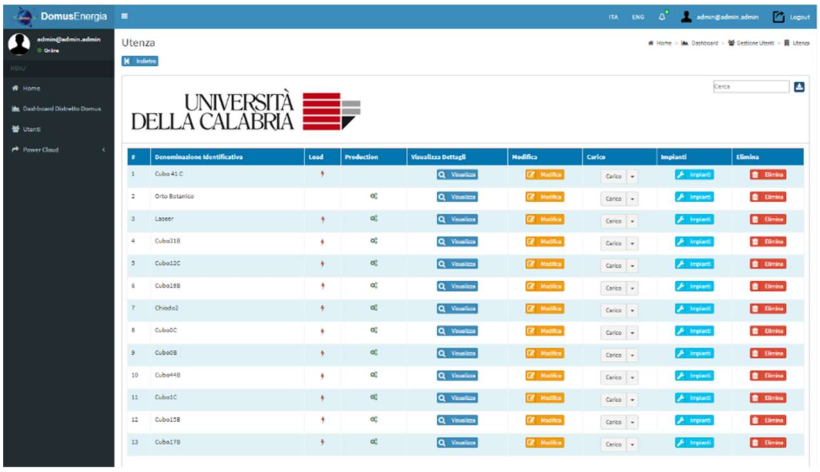


*Fig. 25 – Map of the Domus District*



| # | Denominazione Identificativa | Load | Production | Visualizza Dettagli | Modifica | Carico | Impianti | Elimina |
|---|---|---|---|---|---|---|---|---|
| 1 | Cubo 41 C | ⚡ |  | Visualizza | Modifica | Carico | Impianti | Elimina |
| 2 | Orto Botanico |  | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 3 | Laseer | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 4 | Cubo31B | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 5 | Cubo12C | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 6 | Cubo18B | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 7 | Chiodo2 | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 8 | Cubo0C | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 9 | Cubo0B | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 10 | Cubo44B | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 11 | Cubo1C | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 12 | Cubo15B | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |
| 13 | Cubo17B | ⚡ | ⚙ | Visualizza | Modifica | Carico | Impianti | Elimina |

*Fig. 26 – Domus District users (University of Calabria aggregation)*

## 5.2 The Graphic Interfaces

Two graphic interfaces offer support to the Domus District management: the first used by the aggregator to coordinate and perform the demand response program; the latter used by each end-user to define the daily thermal and electrical preferences. The Graphic Aggregator Interface and the Graphic User Interface are available typing in the address bar the following URLs, respectively:

- *http://156.54.148.101:8080/energia*
- *http://localhost:8888/DomusWeb/DomusHome.jsp*

The aggregator can access to his interface by any pc, tablet or smart-phone equipped with internet connection and using any browser, Internet Explorer, Mozilla, Chrome. While end-user can visualizes his interface through any pc, tablet or smart-phone connected in localhost.

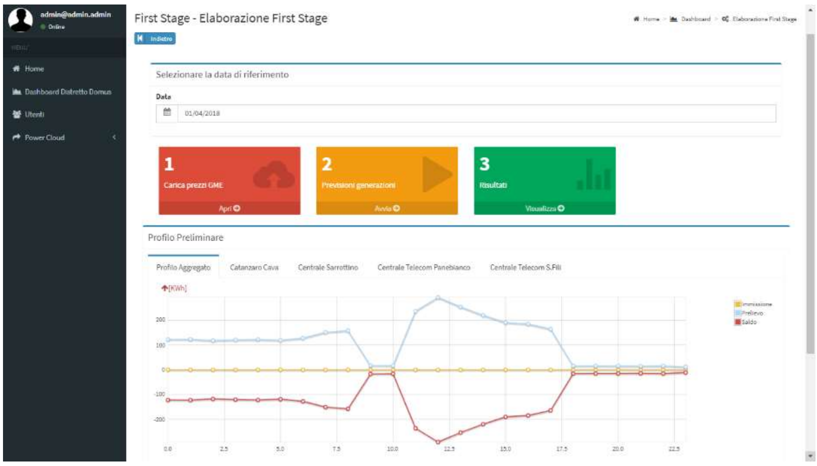
### 5.2.1 The Graphic Aggregator Interface

As already explained in Chapter 4, the demand response program takes place on two different stages.

The First Stage consists of a system for managing and optimizing the energy flows aimed at calculating the preliminary energy exchange profiles for each individual prosumers (through the resolution of the so-called prosumer problem). This structure uses a two-way communication system between the aggregator and the SEAG. In particular, through the Graphic Aggregator Interface (GAI), the aggregator execute the following operational steps (to repeat daily a day ahead for the following day):

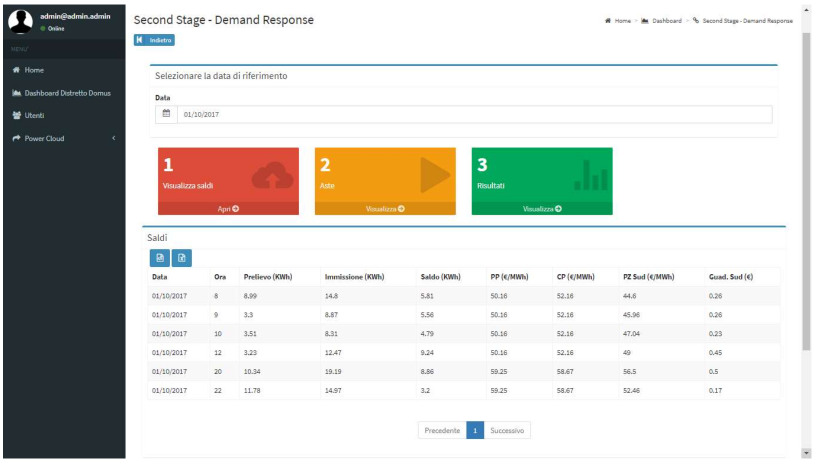
- identification of the different geographical areas present in the aggregation, necessary for the identification of zonal prices to be included in the system;
- download the currently PZ and PUN from the site of the electricity market operator;
- execution of the electrical and thermal load forecasting service for each user joining the aggregation;
- execution of the production forecast service of all the plants able to work;

- the aforementioned information is shared with the SAEGs of the users joining the aggregation, that perform the local scheduling plane (resolution of the prosumer problem);
- each SAEG computes and sends to the aggregator the preliminary load profile or the preliminary production profile and relative costs of sale and purchase of energy;
- starting from the preliminary load and production data, the aggregator calculates the aggregated profile for the whole aggregation (see Fig. 27).



Data
01/04/2018

*Fig. 27 – Dashboard to visualize the aggregate profile at the end of the 1st stage*



Data
01/10/2017

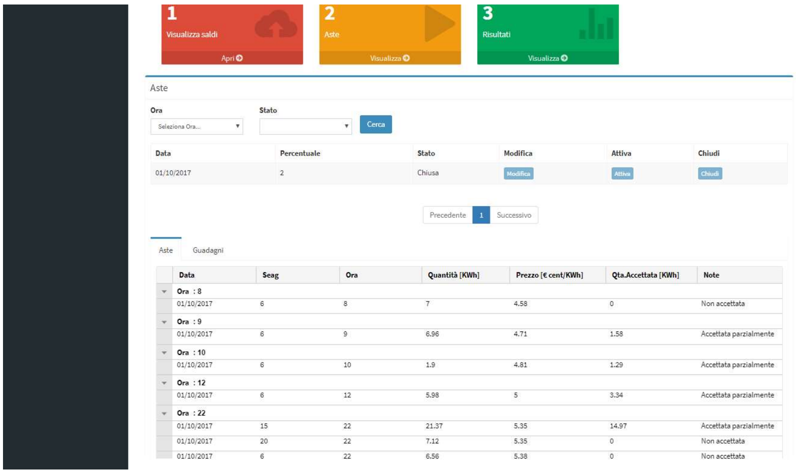
| Data | Ora | Prelievo (KWh) | Immissione (KWh) | Saldo (KWh) | PP (€/MWh) | CP (€/MWh) | PZ Sud (€/MWh) | Guad. Sud (€) |
|---|---|---|---|---|---|---|---|---|
| 01/10/2017 | 8 | 8.99 | 14.8 | 5.81 | 50.16 | 52.16 | 44.6 | 0.26 |
| 01/10/2017 | 9 | 3.3 | 8.87 | 5.56 | 50.16 | 52.16 | 45.96 | 0.26 |
| 01/10/2017 | 10 | 3.51 | 8.31 | 4.79 | 50.16 | 52.16 | 47.04 | 0.23 |
| 01/10/2017 | 12 | 3.23 | 12.47 | 9.24 | 50.16 | 52.16 | 49 | 0.45 |
| 01/10/2017 | 20 | 10.34 | 19.19 | 8.86 | 59.25 | 58.67 | 56.5 | 0.5 |
| 01/10/2017 | 22 | 11.78 | 14.97 | 3.2 | 59.25 | 58.67 | 52.46 | 0.17 |

*Fig. 28 – Dashboard to identify the amount of surplus at the end of the 1st stage*

As already mentioned, the prosumer problem of first stage identifies a sub-optimal solution of the problem, while the prosumer problem of second stage allows reaching an optimal global solution able to satisfy a global coordination between all the prosumer of the district. In particular, the second stage aims to modify, through a system of auctions, the profiles of the individual user in order to maximize the self-consumption of the whole district. By the means of the system showed in Fig. 28, the aggregator identifies the hours in which there is a surplus of energy (i.e. when the energy production exceeds the energy demand). Then, the aggregator generate an auction with the purpose to reallocate the surplus energy inside the district.

In this way, the aggregator avoid disposing the excess energy outside the district: this solution is economically disadvantageous.

Once the time slots and the percentage of the basic auction price have been defined, the aggregator activates the auction and makes it visible to the SEAG. At this stage, the aggregator receives all purchase offers. After a certain period, the aggregator finalizes the auction. After the auction is closed, the award procedure is performed. Among the various auction adjudication procedures, it was decided to implement the most profitable algorithm according to which users with a greater number of products * are preferred and with the same offer the one received temporally before the other is awarded. Furthermore, in order to redistribute all the surplus energy, the offers can be awarded either totally or partially. The dashboard used by the aggregator to perform the operations described is shown in Fig. 29.



| Data | Percentuale | Stato | Modifica | Attiva | Chiudi |
|---|---|---|---|---|---|
| 01/10/2017 | 2 | Chiusa | Modifica | Attiva | Chiudi |

| Data | Seag | Ora | Quantità [KWh] | Prezzo [€ cent/KWh] | Qta.Accettata [KWh] | Note |
|---|---|---|---|---|---|---|
| Ora : 8 | | | | | | |
| 01/10/2017 | 6 | 8 | 7 | 4.58 | 0 | Non accettata |
| Ora : 9 | | | | | | |
| 01/10/2017 | 6 | 9 | 6.96 | 4.71 | 1.58 | Accettata parzialmente |
| Ora : 10 | | | | | | |
| 01/10/2017 | 6 | 10 | 1.9 | 4.81 | 1.29 | Accettata parzialmente |
| Ora : 12 | | | | | | |
| 01/10/2017 | 6 | 12 | 5.98 | 5 | 3.34 | Accettata parzialmente |
| Ora : 22 | | | | | | |
| 01/10/2017 | 15 | 22 | 21.37 | 5.35 | 14.97 | Accettata parzialmente |
| 01/10/2017 | 20 | 22 | 7.12 | 5.35 | 0 | Non accettata |
| 01/10/2017 | 6 | 22 | 6.56 | 5.38 | 0 | Non accettata |

*Fig. 29 – Dashboard to manage the auction of the 2nd stage*

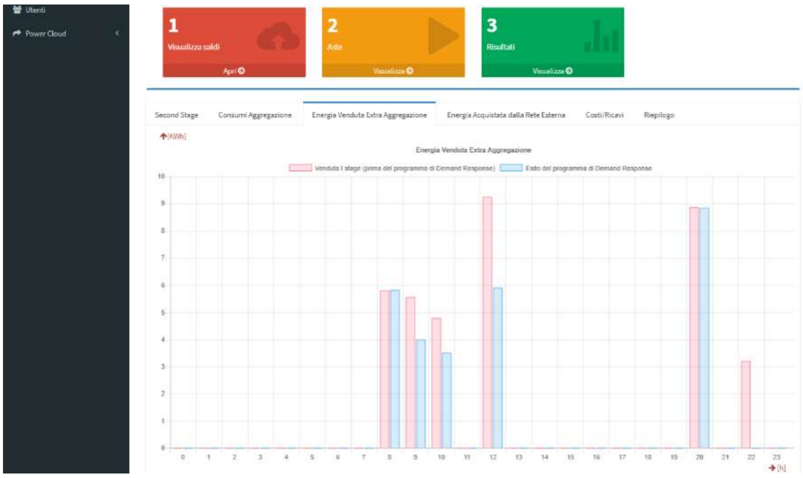


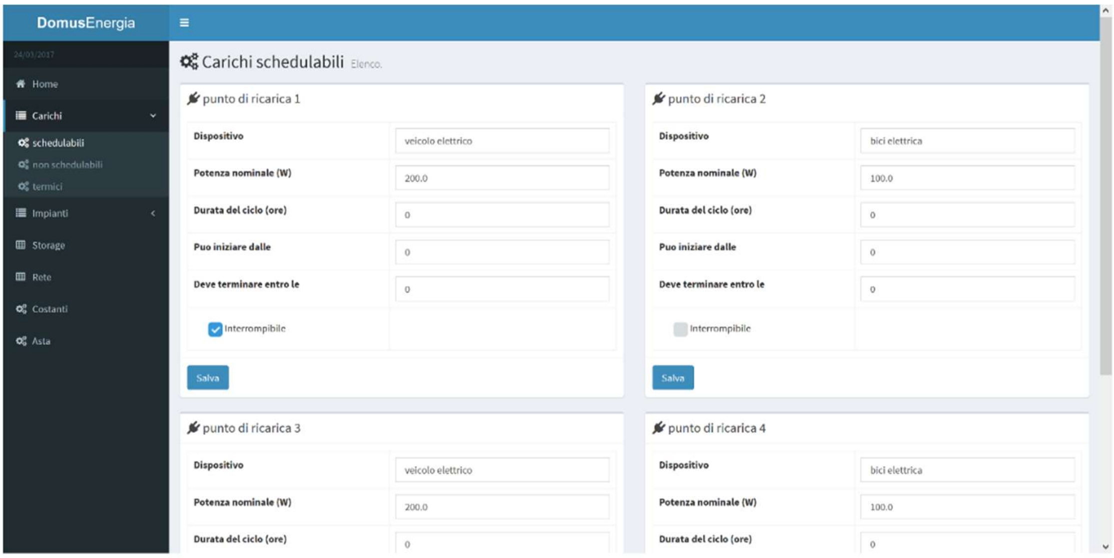
*Fig. 30 – Dashboard to evaluate the benefits at the end of the 2nd stage*

In Fig. 30 the results of the 2nd stage are shown, both in graphical and tabular format. In particular, the dashboard provides information about the amount of self–consumed daily energy within the district, it is differentiated between II stage and I.

Follow the listing of the amount of energy sold outside, the amount of energy purchased from the outside, the cost of the energy purchased in the coalition (sum of the cost valorised in the first stage more the cost of the energy purchased at the end of the 2nd stage), the cost of energy sold within the coalition, the proceeds from the 2nd stage of the whole coalition.

### 5.2.2 The Graphic User Interface

On a daily basis, the user belonging to the energy district is invited to participate in the demand response program; through the appropriate Graphical User Interface (GUI), it is able to specify its own preferences and requests regarding the loads to be scheduled and the thermal set-point to be satisfied.



punto di ricarica 1

| | |
|---|---|
| Dispositivo | veicolo elettrico |
| Potenza nominale (W) | 200.0 |
| Durata del ciclo (ore) | 0 |
| Puo iniziare dalle | 0 |
| Deve terminare entro le | 0 |

☑ Interrompibile

punto di ricarica 2

| | |
|---|---|
| Dispositivo | bici elettrica |
| Potenza nominale (W) | 100.0 |
| Durata del ciclo (ore) | 0 |
| Puo iniziare dalle | 0 |
| Deve terminare entro le | 0 |

☐ Interrompibile

punto di ricarica 3

| | |
|---|---|
| Dispositivo | veicolo elettrico |
| Potenza nominale (W) | 200.0 |
| Durata del ciclo (ore) | 0 |

punto di ricarica 4

| | |
|---|---|
| Dispositivo | bici elettrica |
| Potenza nominale (W) | 100.0 |
| Durata del ciclo (ore) | 0 |

*Fig. 31 – Graphic User Interface able to set the user preferences*

As previously described in the section 3.2.1, the energy management model optimizes the energy behaviour of the user, respecting at the same time the scheduling preferences of the electric loads. The set of electrical loads is divided into two sub-groups: the group of schedulable loads and the group of non-schedulable loads. These group vary dynamically, so the user needs to plan, a day-ahead for the next, which loads and which smart plug to use as a connection to the power system (such smart plugs need to belonging to the home automation system connected to the SEAG), by means of the GUI. In particular, the GUI is served by the SEAG, so it can be viewed through any device connected on the same LAN network as the SEAG.

For each schedulable load, the user sets the duration in hours of the work cycle and the interval in hours within which the work cycle must be contained. In addition, the user sets the temperature set point required by the cloud service provider to perform the procedure for the heat load calculation.

# 6 The Experimental Demonstrator

In this chapter, a detailed description will be provided regarding hardware, devices and smart-grid systems installed inside the experimental demonstrator located at the Chiodo2 residential centre. This demonstrator was developed as conclusion of the MIUR project PON03PE_00050_2, "*Sistemi Domotici per il servizio di brokeraggio energetico cooperativo*" in order to provide a real test bed of the methods, prototypes and demand responsive programs developed during the project.

Details about the general architecture of the user in question and its interaction with the rest of the DOMUS district is provided. Particular attention is paid to the description of the SEAG device, of the nano-Grid prototypes and of the home automation systems installed in it. Follows the description of the loads, generation plants, and storage systems.

Finally, the communication protocols adopted by HEMS prototypes for controlling the home automation systems, as well as the communication tools between SEAG and nano-Grids are described.

## 6.1 The Architecture

The experimental demonstrator is responsible for representing a typical prosumer user, equipped with thermal and electrical production plants, loads and storage systems. Such user belongs to the DOMUS energy district and takes part in the demand response program described in the previous chapters. The aim is to demonstrate that joining the energy district allows to manage in a better way the energy flow exchanged inside the habitation, and consequently allow to obtain economic benefits.

In particular, inside the experimental demonstrator are installed the following thermal and electrical devices (see Fig. 32):

- *3 nano-Grid*, which manage electrical energy flows exchanged between loads, distribution grid, local generation plants and storage systems;
- *2 home automation systems*, which manage the control of the power lines (the first) and the activation / deactivation of electrical loads (the latter);
- *1 electrical SEAG*, which enables the interaction between the aggregator and simultaneously supervises the electrical loads, the distribution network, the local generation electrical systems and the electric energy storage systems;
- *1 thermal SEAG*, which enables interaction between the aggregator and simultaneously supervises local generation thermal plants and thermal energy storage systems.

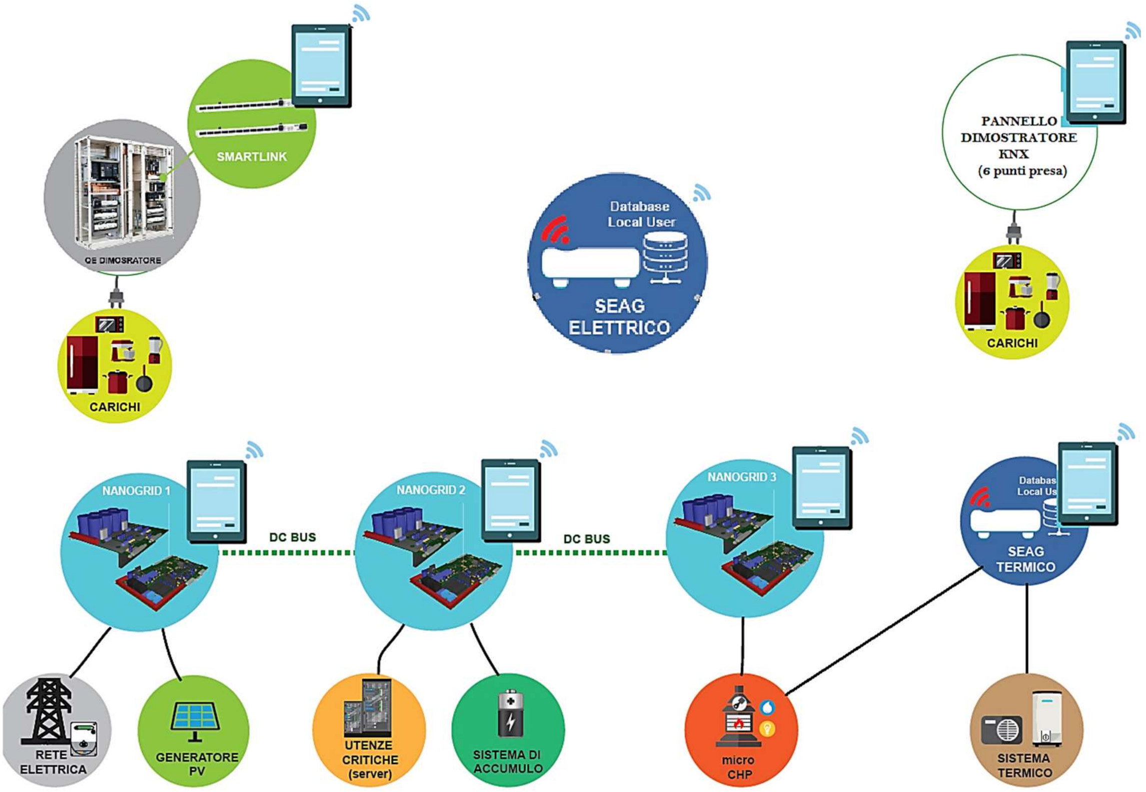


*Fig. 32 – Architecture of the experimental demonstrator*

Every day, with reference to the following day, the SAEG solves the prosumer problem and returns the optimal scheduling plans as output, such as:

- the hours of activation / deactivation for the electrical loads;
- the charging / discharging phases and the amount of energy exchanged by the electrical and thermal storage systems;
- the amount of energy withdrawn / injected from / into the network;
- the power modulation for controllable generation plants (such as heat pump and micro-CHP).

The purpose of the SEAG is to solve the prosumer problem by responding to certain preferences indicated by the prosumer user through the SEAG.

In particular, every day, before a certain time, the user of the Campus Unical demonstrator sets the electrical loads to plan and the preferential scheduling times for the following day.

Consequently, each SEAG requires the aggregator the forecasts of production for non−controllable generation plants (i.e. photovoltaic), the prices of input / withdrawal of energy to / from the grid and the forecasting of the thermal load necessary to air−condition the rooms and maintain the internal temperature equal to the desired value. At this point, the SEAG executes the resolution algorithm of the prosumer problem and it stores the results in a local database. The following day, each SEAG reads the results of the prosumer problem from its database and implements the scheduling on the corresponding devices installed inside the Campus Unical demonstrator.

Under normal operating conditions, the systems are able to satisfy the set points sent by the SEAG (obtained as result of the prosumer problem) ensuring the exact execution of the optimal scheduling profiles.

Due to the likely occurrence of critical working conditions and due to the lack of flexibility linked to the technological and operating constraints of the smart systems described above, always, it is not possible to work on the required set−point values: in this case the systems try to follow in the better than the indicated set−points.

The energy profile taken / injected from / into the network represents the operating set−point with absolute priority. This means that in any critical working condition, the system tries in every way to guarantee the satisfaction of the energy set−point taken / injected from / into the network. As a result, the management of the electrical storage systems and controllable generation plants moves away from the planned scheduling profiles.

This priority choice allows to minimize, or to cancel, the imbalances caused by unforeseen injections / withdrawals of energy in / from the network. In fact, having exchange profiles with the network different from the ones defined the day−ahead, means changing the energy management of the entire district. Moving away from the forecasted optimal configuration, cause an increase in energy supply costs compared to those foreseen by the prosumer problem (optimal condition). For these purposes, the nano−Grids installed in the Campus Unical demonstrator have been equipped with a control logic able to guarantee the exchange of energy with the network at the established power values.

In particular, in order to adopt precise operating constraints the 3 nano−Grids installed at the Domus demonstrator, have been specially designed and developed at the Laboratory of Electrical Systems for Energies and Renewable Sources (LASEER). Each energy exchange operation performed by one of the 3 nano−Grids conditions the voltage values of the DC bus which represents the point of union of the 3 nano−Grids through which to withdraw or to inject energy.

In order to make the system work properly, the DC bus voltage values must remain within an allowable range. Too low voltage values can be corrected by reducing the energy draw from the DC bus and taking the amount required by the electrical storage; too high voltage values can be corrected by reducing the power input to the DC bus and entering the required amount into the electrical storage. Consequently, these operations modify the use of electrical storage with respect to the scheduling of use envisaged by the prosumer problem (optimal condition).

Further differences between the real energy exchange profiles and those foreseen by the prosumer problem are due to several factors: for example, the user could use the electric loads in a different way compared to the usage preferences indicated the day before, or the user could use controllable production facilities in a different way. Above all, there could be a variation in the power produced by renewable source plants, whose production is not controllable but entrusted to changing conditions such as weather conditions, which can be predicted with a certain percentage of reliability.

In the following, the list of the nano-Grids, home automation systems and equipment and related variables monitored by the electrical SEAG (minimum value, maximum value, unit of measure, value id):

- nano-Grid 1:
  - photovoltaic system:
    - produced active power (0, 5000, W, nG1_p_fv);
  - electrical sub-grid:
    - exchanged active power (-7000, +7000, W, nG1_p_grid).

- nano-Grid 2:
  - critical loads:
    - required active power (0 , 5000, W, nG2_load);
  - electrical storage system:
    - state of charge (0, 100, %, nG2_soc);
    - exchanged active power (-6000, +6000, W, nG2_p_batt).

- nano-Grid 3:
  - micro-CHP:
    - produced active power (0, 1000, W, nG3_p_chp_el);
    - Stirling head temperature (0, 800, °C, nG3_temp_head);
    - cooling water flow rate (0, 50, l/min, nG3_flow);
    - in-temperature cooling water (0, 100, °C, nG3_t_in);
    - out-temperature cooling water (0, 100, °C, nG3_t_out);
    - produced thermal power (0, 3000, W, nG3_p_chp_term).

- home automation system (Schneider-Electric vendor):
    - power lines:
        - POD connection (−7000, 7000, W, slink_p_grid);
        - interior lighting (0, 5000, W, int_light);
        - non-schedulable loads (0, 7000, W, slink_s_grid);
        - recharge station for electrical vehicles (0, 3000, W, s_link);

- home automation system (Konnex vendor):
    - smart plugs:
        - schedulable load 1 (0, 1000, W, pdom1);
        - schedulable load 2 (0, 1000, W, pdom2);
        - schedulable load 3 (0, 1000, W, pdom3);
        - schedulable load 4 (0, 1000, W, pdom4);
        - schedulable load 5 (0, 1000, W, pdom5);
        - schedulable load 6 (0, 1000, W, pdom6);

In particular, the electrical loads concern: internal and external lightings, personal computers, TVs, appliances, air conditioning, server stations, office stations, electrical heating systems (heat pumps) and all the passive appliances connected to electrical plugs, including the recharge station for electrical vehicles.

Follows the list of the thermal equipment and related variables monitored by the thermal SEAG (minimum value, maximum value, unit of measure, value id):

- heat pumps:
    - produced thermal power (0, 30000, W, p_hp_t).

- thermal storage system:
    - water temperature (0, 100, $°C$, t_temp);
    - water flow rate** (0, 50, l/min, t_flow);
    - in-temperature cooling water** (0, 100, $°C$, t_in);
    - out-temperature cooling water** (0, 100, $°C$, t_out);
    - exchanged thermal power (obtained from the measures**).

- thermal load:
    - local temperature (0, 100, $°C$, local_temp);
    - heating water flow rate** (0, 50, l/min, t_flow).

In particular, the thermal loads refer to the conditioning system used to heat / cool the rooms of the experimental demonstrator.

## 6.2 The Smart Energy Aware Gateway

A Smart Energy Aware Gateway (SEAG) is a system capable of intelligently managing a prosumer (in this case the equipment inside the experimental demonstrator). In particular it controls the physical devices included in the nano−Grid and in the home automation systems. In addition it is in charge of interacting with the cloud component as described in the previous sections. The SEAG is installed on a Raspberry Pi 3 single−board computer, see Fig. 33. The Raspberry Pi is a general purpose computer that represents a good solution since it is inexpensive, has a low energy consumption and a small size, which allows it to be deployed in a domestic environment, and its performances are adequate to the goal.

*Fig. 33 − Raspberry Pi 3 board*

The SEAG is composed of two layers: the Smart Energy Gateway, devoted to the communications with the cloud component, and the Smart Physical Gateway, which is in charge of interacting with the physical component, namely the nano−Grid and the home automation system. Both layers rely on a middleware, iSapiens@home, which aims to simplify the development of the required software. iSapiens@home is a platform for the development of distributed applications pertaining to domains such as those related to Cyber Physical Systems, Fog Computing, Pervasive Computing and Internet of Things. It is written in Java and highly modular, and includes various layers [65]. The core component, in particular, contains two layers that provide the essential abstractions and functionalities for building the applications: an agent layer and a virtual object layer. The agent layer is characterized by an agent server on which a set of agents execute and interact with each other. Agents are entities that pursue their goals flexibly and autonomously while interacting with each other via message passing. In multi−agent systems [66], the interaction of multiple agents can produce complex emergent behaviours that own many interesting properties such as adaptively, resilience and fault tolerance.

The virtual object layer consists of a container for the so−called virtual objects, which are software abstractions of the actual physical devices. The virtual objects hide the heterogeneity of the hardware by supplying a standardized and flexible interface for abstracting the functionalities of the physical devices. In particular, the virtual object interface generalizes the read and actuation operations that allow the applications to retrieve information and control the physical devices. The two layers, the agent and the virtual object layer, are collocated in the same computer and in the same process in order to speed up the execution and cope with real−time scenarios. Instead of transferring data to a central processing unit (the cloud component), iSapiens@home enables processes (agents) to execute locally on the computers that are directly connected to the physical devices. As a consequence, less data need to be transferred towards remote hosts and local access and computation are fostered in order to achieve good performance and scalability.
The local database of the Raspberry PI 3 has been configured with the following software components:

- *Raspbian*, the operating system based on Debian and optimized for the hardware of the Raspberry for the ARM architecture;
- *Tomcat 8.0*, is an application server that implements the specific JavaServer Pages, JSP, and Servlet, providing a software platform for running web applications developed in Java language. Tomcat is distributed under the Apache License and is written entirely in Java. It can run on any architecture on which a Java Virtual Machine is installed;
- *PostgresSQL 9.0*, is a particular object−relational database management system, which is a relational and object−oriented software for database management. In PostgreSQL, data is represented through tables and tables are managed using a high−level language called SQL, which stands for structured query language.

Inside the experimental demonstrator framework, the SEAG is designed to implement the energy management strategy that guarantees the minimum procurement cost of energy sources, used to meet the electrical and thermal energy needs of the users considered. For this purpose, the SEAG has been equipped with appropriate communication tools in order to receive the production forecasts of renewable−source systems and the prices and costs for the purchase and sale of electricity. These values are provided by the aggregator of the Domus district to which the user belongs. SEAG provides output signals for the implementation of the scheduling plan concerning the nano−Grids and the home automation systems.

Periodically, the SEAG sends aggregated power values on an hourly basis of the production of generation plants (i.e. the photovoltaic system) that will be used on the Cloud side as historical for production forecasting services. Every day the SEAG executes the prosumer problem (first and second stage). The results are stored in the database; the next day the scheduling plan is executed.

## 6.3 The Equipment

This section provides details regarding the equipment, the implementation of the SEAG and its interaction with the field part of the experimental demonstrator located at the "Chiodo2" residential complex. In particular, the SEAG represents the intermediate level that interacts between the Cloud part and the field part. For this purpose, the electrical SEAG has been implemented to allow communication and to receives / sends information with all the equipment belonging to the lowest levels.

*Fig. 34 – Experimental demonstrator equipment*

As showed in Fig. 34, the main electrical equipment and their controlled systems are mainly placed inside a single room, where three electrical switchboards are installed. In particular, the picture shows the following devices:

- the 1st nano–Grid and its control system (1 in Fig. 34);
- the 2nd nano–Grid and its control system (2 in Fig. 34);
- the 3rd nano–Grid and its control system (3 in Fig. 34);
- the micro–CHP (a pellet boiler with Stirling engine) and its control system (4 in Fig. 34);
- the home automation system containing safety actuators, switches, smart plugs and smart meters (5 in Fig. 34);
- the Fronius inverter system able to control the external photovoltaic plant and a SolarLog monitoring device (6 in Fig. 34);
- the electrical storage system and its battery management system (BMS) (7 in Fig. 34);
- a work–station with three monitors connected to the SEAG and to the control system, in order to display the graphic aggregator interface (used to simulate the aggregator), the graphic user interface (used to simulate the user) and a local control dashboard (8 in Fig. 34).

### 6.3.1 The Nano−Grids

Nano−Grid systems are conceived for managing the energy flows in a dwelling; they are especially useful when the dwelling is equipped with local renewable energy generation plants. A storage device is also usually present in this kind of architecture. The typical residential architecture of a nano−Grid is showed in Fig. 35.

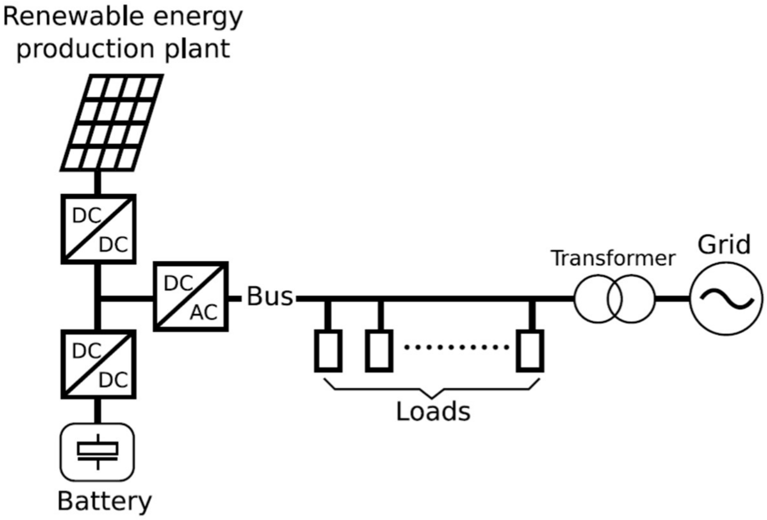


*Fig. 35 − Architecture of a nano−Grid system*

In particular, the experimental demonstrator hosts 3 nano−Grids in order to represent three residential dwellings. Each nano−Grid controls and manages the power flows exchanged between various energy plants, such as:

- electricity grid with a contractual power of 7kW;
- photovoltaic plant with nominal power of 10kWp;
- electric storage system with a capacity of 23kWh;
- micro−CHP with nominal power of 1kWe / 3kWt;
- privileged, non−schedulable and schedulable loads.

The monitoring of nano−Grid data is achieved through an intermediary microcontroller. Low−level information such as the values of current and voltage and the state of battery charge, are regularly sent by the microcontroller to the SEAG through the RS−232 serial port. In particular, the microcontroller choose is an Atmel AVR32 (AT32UC3A0512) mounted on a circuit board, such as EVK1100. The latter is a development board equipped with an SD data storage device, two serial ports, an Ethernet port, an USB port, 7 ADC channels and 8 PWM pins. Periodically, this device processes the information and stores it on an SD card. Afterwards, the information is read from the SD card and sent to the SEAG. The actuation is performed alike, i.e., the actuation commands are sent by the SEAG to the Atmel board, which in turn performs the actuation on the nano−Grid system.

The nano−Grids chosen for the application of the demonstrator have a single−phase electric power of 7 kW. Each nano−Grid is designed to perform the task of optimally managing and controlling the power flows exchanged between several equipment, where each part generates and / or absorbs electrical power. In Fig. 36 is showed the configuration for the 3 nano−Grids installed at the experimental demonstrator. As shown, the nano−Grid' s DC−BUS are connected on the same DC−LINE to share the energy sources to which they are connected.

The three nano−Grids and the relative power converters, are managed by appropriate electronic boards equipped with opt−isolated circuits for the control of power converters, and opt−isolated conditioning circuits for the acquisition of electrical measurements, as well as a microcontroller system to manage the logic of control of the converters themselves. In particular, the 1st nano−Grid (on the left) is realized with a DC/AC converter to interface with the utility grid and a DC/DC converter to interface with the photovoltaic system; the 2nd nano−Grid (in the centre) has a DC/AC converter to power electrical loads and a DC/DC inverter to interface a storage system; the 3rd nano−Grid (on the right) features a multi−converter system consisting of a DC/DC converter for storage system, a DC/AC converter for interfacing the Stirling Engine (SE) belonging to the micro−CHP and a DC/AC converter for powering a second line of electrical loads. The power converters of the nano−Grids 1st and 2nd are realized by means of two Semiteach Semitron AN−8005 inverters. Each of them allows the conversion of electrical power up to 7kVA. While, the nano−Grid 3rd uses two three−phase IRAM136−3063B inverters to implement power converters up to 1kVA. For more detail see [67].

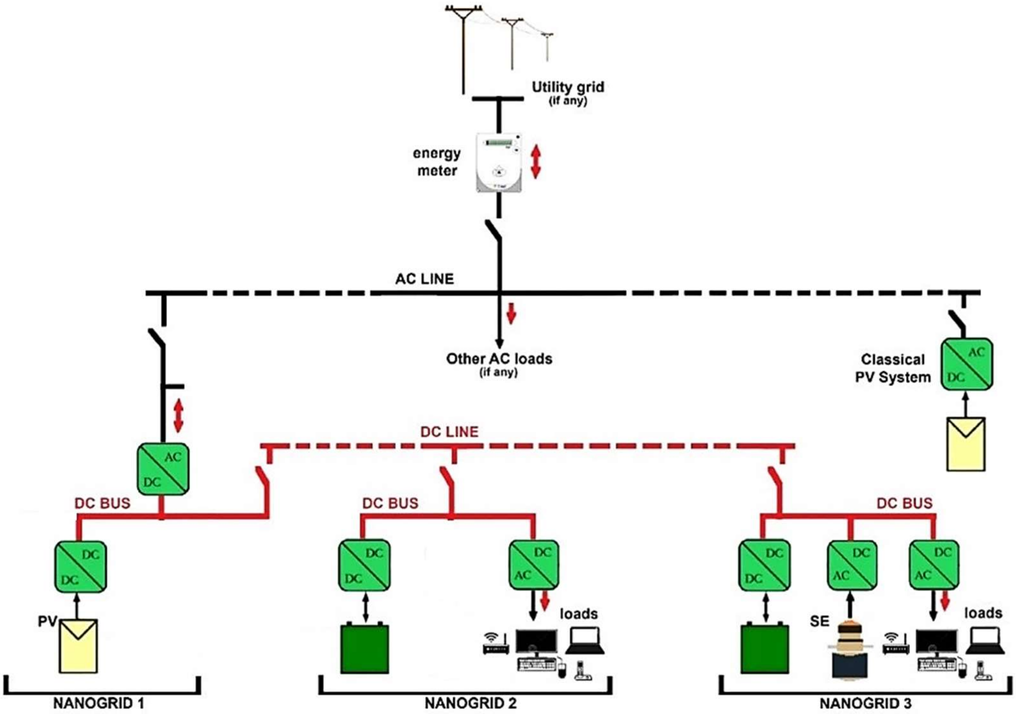


*Fig. 36 − Nano−Grids connection scheme*

### 6.3.2 The Home Automation System

The optimized load management has been achieved by installing home automation systems with centralized control. Several technologies have been devised to implement a home automation system. In particular, inside the experimental demonstrator, all electrical loads are connected downstream of two home automation systems.

- Modbus vendor

The first home automation system uses the Modbus standard to control two downstream Schneider smart-links, which are connected to energy meters and smart switches in order to manage and monitor the main power lines of the demonstrator.
Modbus standard allows communication between different devices connected to the same network. In general, it is used to connect a supervisor computer with a remote terminal unit (RTU) in supervisory control and data acquisition systems (SCADA). Two versions of the protocol are available: on serial protocol (RS485 by default, but also RS232) and on Ethernet protocol (TCP/IP).

In reference the experimental demonstrator, the Modbus system is equipped with a centralized control circuit equipped with Reflex iC60 switches, RCA iC60 switches, EM3150 energy meter and two Acti9Smartlink. The Acti9Smartlink is a smart communication module that provides instantaneous integration of data on universal Modbus protocol (see Fig. 37). Its basic management system has been enhanced through the development of a customized control software for controlling the loads related to the experimental demonstrator. In particular, this management software has been programmed to allow remote control, remote reading and status check of the connected devices; also, it allows the implementation of the scheduling plan envisaged by the energy management model, implemented on the SEAG.

*Fig. 37 – Acti9Smartlink Schneider*

Remote control of the connected devices, data collection relating to the status, energy consumption, the number of manoeuvre cycles, the operating time of the loads and many other parameters are simple and immediate, using this technology.
Moreover, the Acti9Smartlink Schneider reduces wiring errors and troubleshooting time with pre-wired Ti24 cables. The open Modbus protocol on Ethernet can collect all types of data, from digital inputs, switch status, outputs, contactors for the command, as well as meters with pulse outputs. It can also receive analog data such as temperature, humidity or light sensors.
There are two versions of the Acti9Smartlink: the first adopts the TCP / IP communication protocol, while the latter adopts the RS485 communication protocol. The modbus / TCP protocol was developed to allow the Modbus ASCII / RTU protocol to use TCP / IP based networks. The Modbus / TCP protocol incorporates Modbus messages within TCP / IP frames and sets the connections between the nodes of the network in half-duplex mode.

In particular, with reference to the RS485 communication protocol, the communication parameters of the serial port are:

- data bits: 8bit;
- baud rate: 19200 bit/s;
- parity: pair (EVEN);
- bit of stop: 1 bit.

- Konnex vendor

The latter home automation system uses the standard Konnex (KNX). Principally, this home automation system controls schedulable appliances connected to plugs, such as washing, machine, tumble dryer, dishwashers, electrical oven, and etc.
The standard KNX is one of the most popular standard developed by the KNX Association, which is open, platform-independent and approved as an European Standard (EN 50090 - EN 13321-1). KNX allows devices built by different producers to interact transparently with each other.

From a general point of view, the KNX system is a home automation system with distributed control logic, distinguished by the absence of a real control unit, instead of a system with distributed local controllers. Indeed, it consists of a series of input / output devices connected to a shared transmission means called "BUS" to which are added some system devices necessary for operation. Each device exchanges a series of information on the network containing the so-called "data points" (control and process variables), which each device must know how to interpret. A given sensor (for example, a presence detector or a manual button) generates a command at the time it is actuated and sends it as a telegram via the bus to the actuator.

Part of the research activity achieved allowed to identify various solutions able to give the above described system a centralized control and therefore an optimal optimized management of the plant itself.

In particular, the solution chosen concerned the adoption of an Energy−Box prototype (discussed in section 2.3.1). The Energy−Boxes are able to be physically connected to the KNX communication bus and the actuation on a load is managed by sending an on/off command to the Energy−Boxes that in turn triggers the transmission on the KNX bus.

By writing an exact code, the Energy−Boxes recognizes the communication protocol used by the sensors / actuators belonging to the KNX standard and therefore is able to interpret the command frames in input and output from the communication bus. This solution made it possible to overcome the constraints linked to the distributed logic belonging to the KNX standard and to extend the potential of the home automation system in question.

The home automation system installed inside the experimental demonstrator has been integrated with an Energy−Box programmed on purpose to execute the scheduling and therefore to the implementation / modulation of the loads requested. In addition, the microcontroller is able to monitor in real−time the consumption of the whole system, and to send / receive information with the electrical SEAG and the nano−Grids system.

### 6.3.3 Generation Plants: PV, micro−CHP and HP

The photovoltaic system installed at the Domus demonstrator buildings consists of a total of 36 polycrystalline modules, each of $250\,W$ of peak for a total peak power of $9\,kW$ (see Fig. 38). The production profile is monitored using a Solar−Log device communicating with the Fronius standard inverter. The installed product uses international standards in the field of monitoring and management of photovoltaic systems. It able to provide information about the instant production of the plant, also it allows access to a web portal.

*Fig. 38 − Photovoltaic plant*

In addition, the SolarLog device has an input port based on the Modbus protocol through which the device is able to communicate with the SEAG. In particular, a special software has been developed using Qt development platform [68], through which the SEAG receives all the information provided by the SolarLog. Instantaneous power values are collected with a frequency of $5\ s$, processed and sent on the Cloud platform.

The micro−CHP installed at the demonstrator site is a prototype of a pellet−based cogeneration system composed of a pellet boiler and a Stirling free−piston engine: the former generates heat, while the latter converts thermal energy into mechanical energy, and subsequently by the movement of a linear generator, in electricity.

*Fig. 39 − Micro−CHP composed of pellet boiler and Stirling engine*

In this particular application the prototype cogeneration system has two very specific functions: to integrate the production of thermal energy supplied by the main system composed of two heat pumps, and to dispense the electricity produced to the distribution network through the nano−Grid. In order to guarantee the functions listed above, the micro−CHP has been equipped with a Raspberry Pi board, with the purpose of allowing the exchange of information with the SEAG. In particular, a software has been developed using Qt development platform and installed on Raspberry. The goal of the Raspberry Pi is to ask the Stirling control unit and receives information regarding the operating status, thermal/electrical production, temperatures and flow rates.
The Raspberry Pi, equipped with internet connection, is able to communicate and transmit all the information collected to the SEAG; the latter stores sent the aggregated data to the Cloud platform.

Heat pumps are heating / cooling systems installed inside the experimental demonstrator perform high energy efficiency. The installed machines transfer energy from the outside to the inside and vice versa by absorbing a reduced quantity of electrical energy, in fact the ratio between the nominal thermal power and the nominal electric power is around 4.5. How to interface to the control system of such devices is out of topic of this work.

### 6.3.4 Electrical and Thermal Storage Systems

The electric energy storage system is used to accumulate the surplus of energy produced by the photovoltaic plant and the micro−CHP in order to make it available in the absence of production.

*Fig. 40 − Battery storage system*

The installed storage system has a capacity of approximately 23 kWh. The monitoring system that acquires information on state of charge and voltage levels is queried using the Modbus protocol. The data readings are then sent to the SEAG using the TCP / IP protocol.

The thermal energy storage system is a water tank with a volume of about 800 litres. The tank is equipped with a thermal insulator; this makes it possible to use it both in summer and in winter. How to work the control system of such device is out of topic of this work.

*Fig. 41 − Water tank used as thermal storage system*

## 6.4 Monitoring and Scheduling Plan Implementation

The general electrical panel installed at the Domus demonstrator hosts two Acti9Smartlink, the first enabled for communication in TCP / IP, the latter enabled for communication in RS485. All switches and devices downstream of the Acti9Smartlink are managed by a centralized control system. The centralized control system consists of an algorithm implemented in the Qt programming language, executed locally on a Raspberry Pi board. The implemented algorithm enables the Ethernet communication port of the Raspberry PI, allowing communication with the Ethernet communication port present on the Acti9Smartlink Ethernet. Also, the adoption of the Modbus communication protocol allows the Raspberry Pi to communicate directly with the downstream switches of the Acti9Smartlink.

The Reflex iC60 switches, RCA iC60 switches, EM3150 energy meter have been installed on the two Acti9Smartlinks in the following order:

*Table 10 – Acti9Smartlinks configuration scheme*

| Acti9Smartlink Ethernet | Acti9Smartlink RS-485 |
|---|---|
| 1: DP20 (Reflex iC60) | 1: DP30 (RCA iC60) |
| 2: DP28 (RCA iC60) | 2: DP26 (RCA iC60) |
| 3: DP32 (RCA iC60) | 3: DP25 (RCA iC60) |
| 4: DP36 (RCA iC60) | 4: DP24 (RCA iC60) |
| 5: DP37 (RCA iC60) | 5: DP23 (RCA iC60) |
| 6: DP21 (Reflex iC60) | 6: DP29 (RCA iC60) |
| 7: DP15 (RCA iC60) | 7: C15 1 (IACT24) |
| 8: void | 8: C15 2 (IACT24) |
| | 9: DP17 (Reflex iC60) |
| | 10: DP18 (Reflex iC60) |
| | 11: DP19 (Reflex iC60) |

The Schneider Energy Meters monitor the power profiles and the energy flows exchanged between the local generation plants and the distribution network; the power and energy measurements are acquired by the Raspberry Pi which, in turn, sends this information to the electrical SEAG.

The SEAG represents the intermediate level that interacts between the Cloud part and the field par. For this purpose, the SEAG has been implemented in such a way as to allow communication with all the plants belonging to the lowest levels. Indeed, the SEAG receives / sends information related to the exchanged powers (expressed in Watts) with the 1st nano-Grid, the 2nd nano-Grid, the 3rd nano-Grid, the management and control system of the micro-CHP, the domotic systems ( including actuators and enegy meters) and with the SolarLog.

Each system has been equipped with a Raspberry Pi board, opportunatly designed, through which they are able to reach and communicate with the SEAG hosting a server, constantly listening.

In Fig. 42 is shown a local control dashboard, developed in Qt, through which it is possible to have an overall scheme of the whole electric system of the experimental demonstrator and through whitch is possible to check the switches operation, as well as monitor their status. The dashboard collect the same data received to the SEAG, so to provide an overall view in real time of the whole electrical system realized in the experimental demonstrator. As previous showed in Fig. 34, a work−station with three monitors connected to the SEAG and to the control system, displayes the local control dashboard.

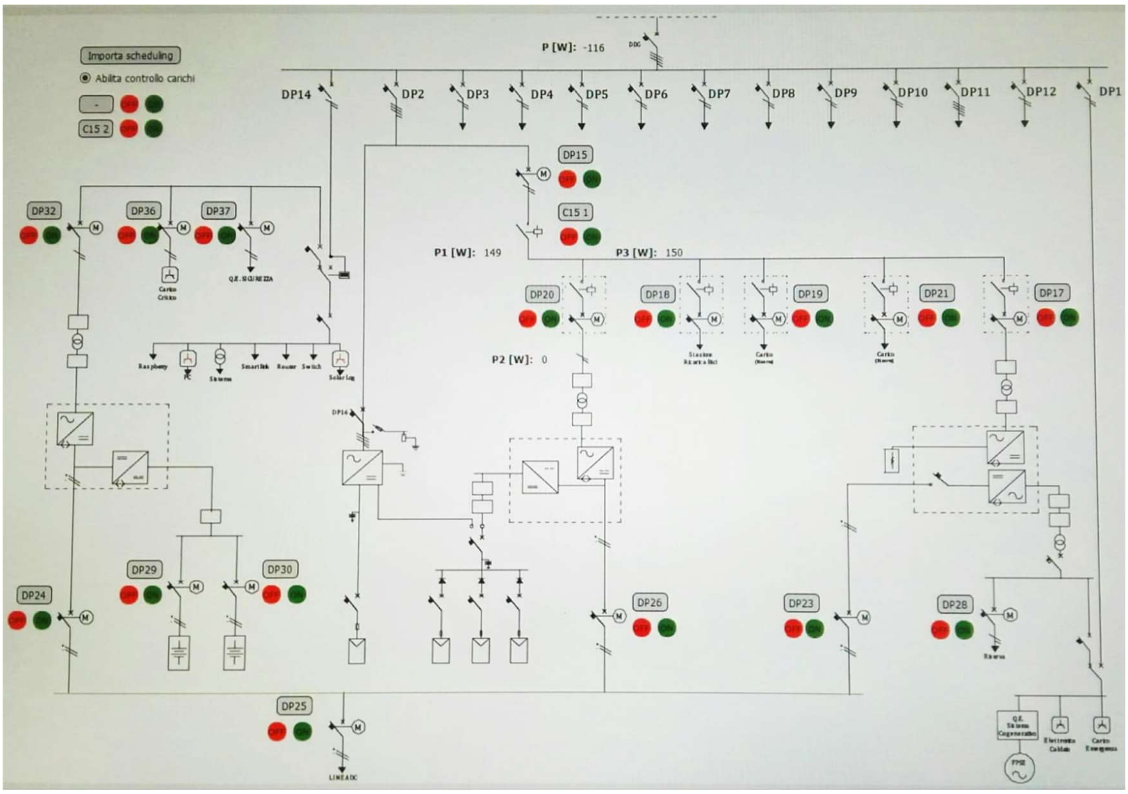
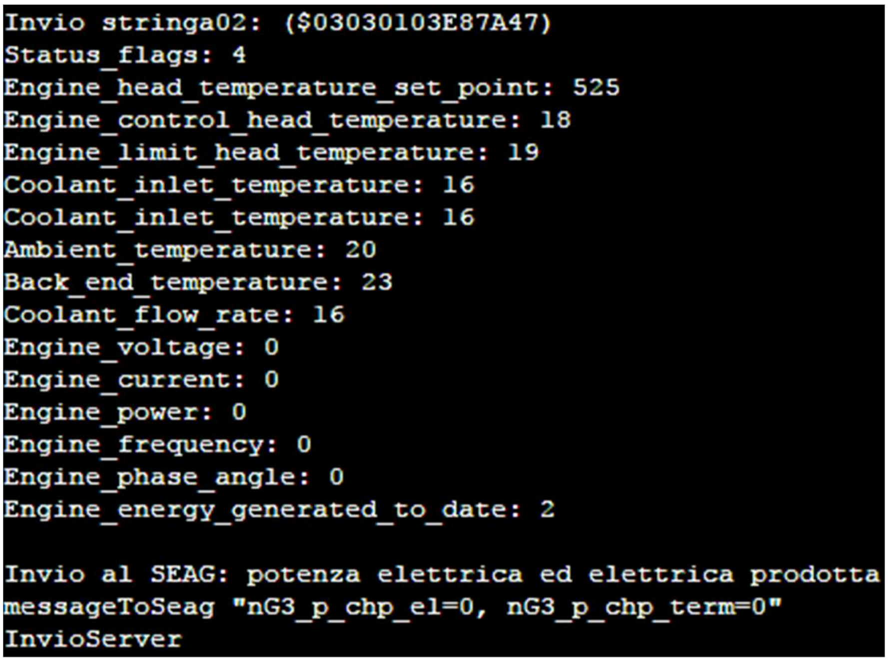


*Fig. 42 − Overall view in real time of the electrical system*

In real−time, the control dashboard supply information concerning the operating status of the switches belonging to the home automation systems. A red circle is visualized closed the symbol of each switch to indicate the off−mode, while a green circle is visualized to indicate the on−mode.
Moreover, the control dashboard allows the user to execute a direct control on the switches and to invert their operating status. Clicking on the on/off buttons, the control software send a control frame to the home automation system, whitch set the desired mode on the correspond switch.

The control dashboard, also, shows the instant values of power supplied by the energy meters and the nano−Grids, so to give an immediate estimate of the energy produced and self−consumed.

In Fig. 43 are reported the information acquired by the Raspberry designed for monitoring the Stirling engine, mounted inside the micro−CHP. The Raspberry asks to Stirling control system to upload the real time data concerning the production state (i.e. status flag, engine head temperature set point, enine control had temperature, engine limit head temperature, coolant inlet temperature, etc). Consequently, the Raspberry sent to the SEAG the produced thermal and electrical power. In this case the last values are equal to $nG3\_p\_chp\_el = 0W$ and $nG3\_p\_chp\_term = 0W$.



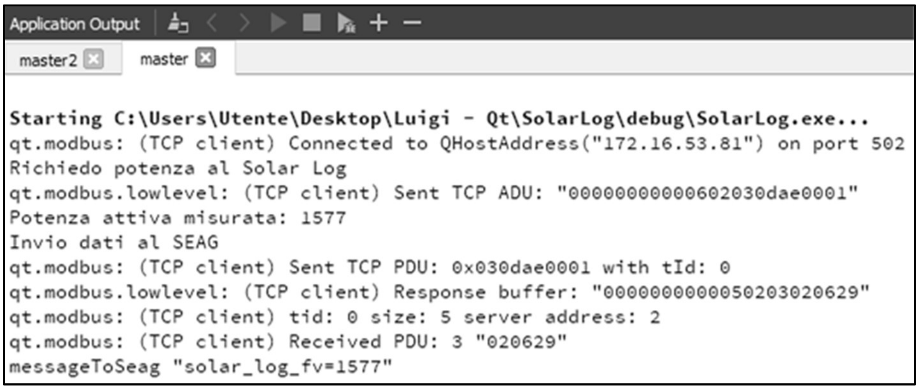
```
Invio stringa02: ($03030103E87A47)
Status_flags: 4
Engine_head_temperature_set_point: 525
Engine_control_head_temperature: 18
Engine_limit_head_temperature: 19
Coolant_inlet_temperature: 16
Coolant_inlet_temperature: 16
Ambient_temperature: 20
Back_end_temperature: 23
Coolant_flow_rate: 16
Engine_voltage: 0
Engine_current: 0
Engine_power: 0
Engine_frequency: 0
Engine_phase_angle: 0
Engine_energy_generated_to_date: 2

Invio al SEAG: potenza elettrica ed elettrica prodotta
messageToSeag "nG3_p_chp_el=0, nG3_p_chp_term=0"
InvioServer
```

*Fig. 43 − Stirling engine data monitoring*

In Fig. 44 the information acquired by the Raspberry designed for monitoring the SolarLog, is reported. In particular, each $5\,s$ the Raspberry connects to the server running on the SolarLog and requires to upload the last data; the latter sends to the Raspberry the values concerning the electric power produced by the corresponding photovoltaic plant.

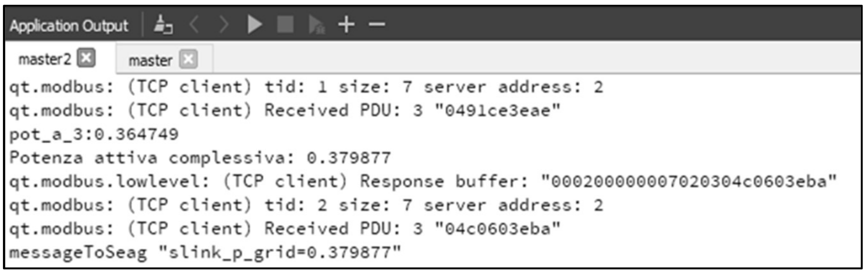
Consequently, the Raspberry send this information to the SEAG. In this case the last value is equal to $solar\_log\_fv = 1577W$.



```
Starting C:\Users\Utente\Desktop\Luigi - Qt\SolarLog\debug\SolarLog.exe...
qt.modbus: (TCP client) Connected to QHostAddress("172.16.53.81") on port 502
Richiedo potenza al Solar Log
qt.modbus.lowlevel: (TCP client) Sent TCP ADU: "00000000000602030dae0001"
Potenza attiva misurata: 1577
Invio dati al SEAG
qt.modbus: (TCP client) Sent TCP PDU: 0x030dae0001 with tId: 0
qt.modbus.lowlevel: (TCP client) Response buffer: "0000000000050203020629"
qt.modbus: (TCP client) tid: 0 size: 5 server address: 2
qt.modbus: (TCP client) Received PDU: 3 "020629"
messageToSeag "solar_log_fv=1577"
```

*Fig. 44 − Photovoltaic system data monitoring*

Fig. 45 shows the information regarding the electric power exchanged at the POD measured by the Schneider energy meter. That value is acquired by a suited Raspberry and sent to the SEAG. In the case in question the last value is equal to $slink\_p\_grid\ =\ 0.379877W$.



```
qt.modbus: (TCP client) tid: 1 size: 7 server address: 2
qt.modbus: (TCP client) Received PDU: 3 "0491ce3eae"
pot_a_3:0.364749
Potenza attiva complessiva: 0.379877
qt.modbus.lowlevel: (TCP client) Response buffer: "000200000007020304c0603eba"
qt.modbus: (TCP client) tid: 2 size: 7 server address: 2
qt.modbus: (TCP client) Received PDU: 3 "04c0603eba"
messageToSeag "slink_p_grid=0.379877"
```

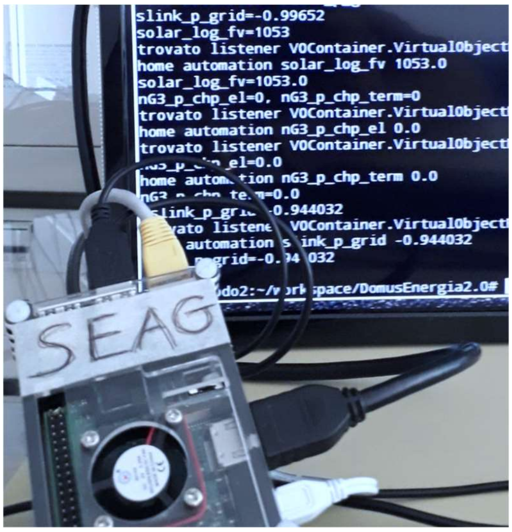
*Fig. 45 – POD data monitoring*

Fig. 46 shows a SEAG prototype used during the control phase of the experimental demonstrator communication systems; in particular, the monitor depicted reassumes the values previously acquired by the monitoring systems and received by SEAG, such as:

- thermal and electrical power produced by the micro–cogenerator (nG3_p_chp_el, nG3_p_chp_term);
- power exchanged at the POD, measured by the Schneider energy meter (slink_p_grid);
- power produced by the photovoltaic measured by the Fronius inverter (solar_log_fv).

Each day, the user represented by the experimental demonstrator participates in the demand response program coordinated by the DOMUS energy district.

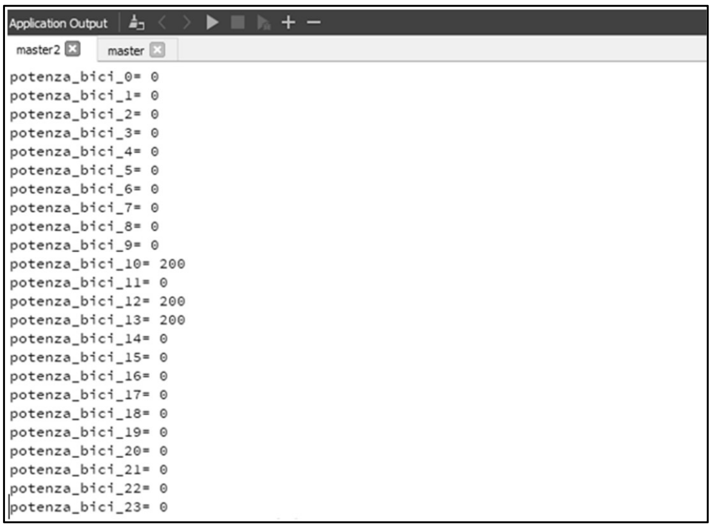
As described in the previous chapters, completed the execution of the demand response program, each SEAG elaborates and stores a proper scheduling plan. The following day, the nano–Grids and the home automation systems require to the electrical SEAG the scheduling plan related to their schedulable loads and the controllable plants. The scheduling plane is so applied.



```
slink_p_grid=-0.99652
solar_log_fv=1053
trovato listener VOContainer.VirtualObject
home automation solar_log_fv 1053.0
solar_log_fv=1053.0
nG3_p_chp_el=0, nG3_p_chp_term=0
trovato listener VOContainer.VirtualObject
home automation nG3_p_chp_el 0.0
trovato listener VOContainer.VirtualObject
[illegible] el=0.0
home autom tion nG3_p_chp_term 0.0
nG3 [illegible] te m=0.0
link_p_gri -0.944032
ato listene VOContainer.VirtualObject
automation s ink_p_grid -0.944032
grid=-0. 94 032
do2:~/w rk pace/DomusEnergia2.0#
```

*Fig. 46 – SEAG prototype used during the control phase of the communication systems*

For clarity, the scheduling plan relating to the charging point for electric vehicles is described. For this schedulable load, the user had indicated (the previous day) a preferential interval between 10:00 am and 3:00 pm, for a total of 3 hours of charge. At the end of the demand response program, the SEAG had solved the prosumer problem and identified the solution at lower cost.
The following day, the scheduling plan is requested by the home automation system and implemented. As showed in Fig. 47, the home automation system receives a scheduling plan relating to the charging point for electric vehicles scheduled for 10:00 am, 12:00 pm and 1:00 pm.



```
potenza_bici_0= 0
potenza_bici_1= 0
potenza_bici_2= 0
potenza_bici_3= 0
potenza_bici_4= 0
potenza_bici_5= 0
potenza_bici_6= 0
potenza_bici_7= 0
potenza_bici_8= 0
potenza_bici_9= 0
potenza_bici_10= 200
potenza_bici_11= 0
potenza_bici_12= 200
potenza_bici_13= 200
potenza_bici_14= 0
potenza_bici_15= 0
potenza_bici_16= 0
potenza_bici_17= 0
potenza_bici_18= 0
potenza_bici_19= 0
potenza_bici_20= 0
potenza_bici_21= 0
potenza_bici_22= 0
potenza_bici_23= 0
```

*Fig. 47 – Scheduling plan for charging point for electrical vehicles*

According to the previous plan, the home automation system enable the charging and discharging phase by controlling the operating status of the actuator DP18 (see Fig. 48) connected to the 10th channel of the Acti9Smartlink RS-485, downstream of which the electric vehicle is connected (see Fig. 49).

*Fig. 48 – Actuator DP18 (ON/OFF status)*

*Fig. 49 – Electrical vehicle in charging*

# 7 Contributions in SmartGems Project

In this chapter, the work carried out during the experience at the Exergy Ltd Company (UK), concerns the Project Marie Skłodowska-Curie SMART GEMS and focused on Research and Innovation Staff Exchange (RISE), is reported.

The work concerns the study and energy analysis of an energy comunity located in Spain. In particular, the residential complex, named Urberoa, is located in San Sebastian village and consists of 584 neighbours. It is a cooperative society formed in 1985, where the neighbours, who are the proprietaries, manage the own thermal energy supply.
At the beginning, the plant operated with fuel, but it was replaced with natural gas after a reform of all the facilities. After a great concern of the environment from the neighbours, they start studying the possibility of a new way to generate the energy. In 2009, the main station started using a CHP plant, while a biomass boiler was installed 2 years ago.

Nowadays, the heating system and domestic hot water supply implemented in the cooperative society of Urberoa consists of three natural gas boilers connected in parallel, one biomass boiler and a CHP system that generates electricity to be exported to the general electrical grid. The main system features a distribution circuit from the central power station to 7 substations distributed in the neighbourhood of Urberoa (see Fig. 50).

Starting from the design data, the domestic utilities involved were analysed and the thermal and electrical requirements of each substation were calculated. Follow an economic analysis based on the purchase costs of the various primary resources including natural gas, biomass and electricity. An optimized scheduling plan is proposed in order to satisfy the estimated needs at the lowest cost. Finally, an economic comparison is made in order to evaluate the improvements obtained through the energy efficient operations proposed. In particular, the improvement operations concerns the installation of a thermal solar plant; moreover a traditional HP and an innovative hybrid HP are installed on the return of the domestic hot water in substation 1.

Thermal solar panels and hybrid heat pump are installed will heat the return water before it passes the local heat exchanger. The solar panels will operate whenever there is solar radiation, but the heat pumps will operate as long as it is the most affordable option.

*Fig. 50 – Distribution circuit of Urberoa complex*

The energy efficiency operations concern exclusively the residential complexes served by the thermal substations 1 and 7. Therefore, we will refer to these substations only. All the plant installed inside Urberoa complex are shown in Fig. 51**Errore. L'origine riferimento non è stata trovata.**. For each plant the primary source is indicated among natural gas, electricity, biomass and sun energy. All of them contribute to supply the required thermal energy demand.

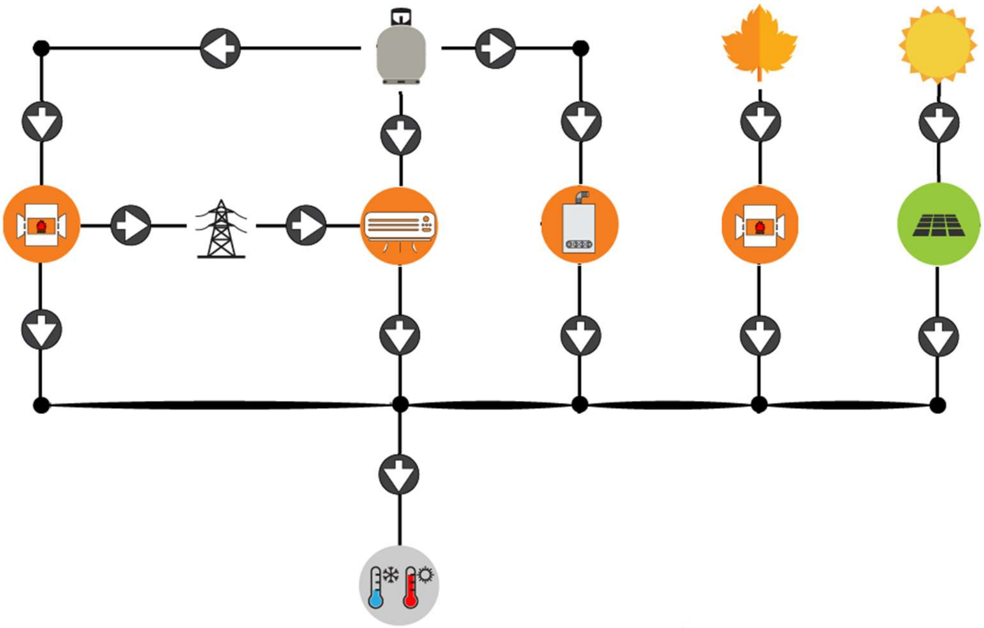


*Fig. 51 – Scheme of the thermal power plants*

A hybrid (dual fuel) heat pump system is the combination of renewable heating with a traditional system. One component is a traditional heat pump and the other is a traditional gas, oil heating. This hybrid system is unique, because there are two key components working together to maintain efficiency all year round. The key benefit for a hybrid system is efficiency: the system switches between renewable and fossil fuel, choosing the technology that is most efficient at any given time. This ensures consistent comfort, but it also means that neither technology must work so hard to achieve the desired performance. If the outside temperature is ideal, the heat pump operate to keep home warm and energy use low. When the outside air reaches lower temperatures (below zero), the heat pump shut down and the system switches to the traditional fossil fuel boiler. This will generate the heat needed to keep home comfortably warm in the colder months.

## 7.1 Daily profile of thermal energy demand

Hot water supply accounts for a significant share of energy consumption in different types of buildings. Achieving a detailed characterization of domestic usage profiles is of great relevance, as this information will allow for a more reliable assessment of the energy efficiency of systems and buildings. A deeper knowledge of the features of demand profiles allow for the design of innovative control strategies based on consumption patterns. To this purpose, the typical seasonal power profile have been valued.

In the following figure, the seasonal thermal demand profile are reported: as expected, the demand for thermal energy increases in the winter season (with a peak of about 1400 kW), while it decreases during the summer season.

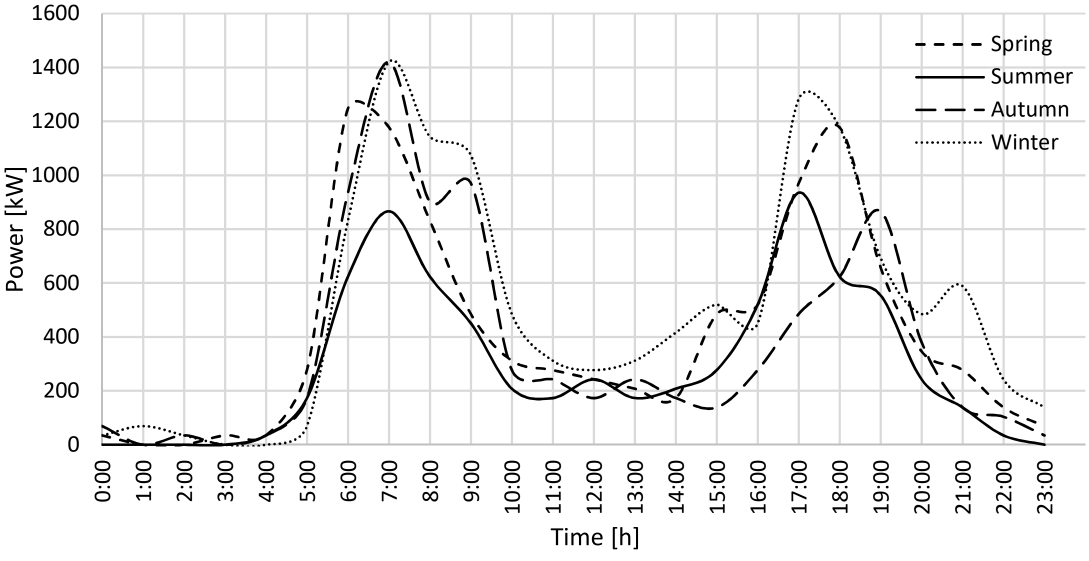


*Fig. 52 – Seasonal thermal power profile*

## 7.2 Optimal scheduling plan for thermal generators

In Table 11, all the plants installed inside Urberoa are listed. For each, nominal power, type of used primary resource, unit cost referring to primary source and unit cost related to the thermal energy produced are valued. In order to use of all power plant in a more efficient combined way, a comparison based on the specific production costs is carried out. How shown in the last line the solar thermal plant have absolute priority of scheduling due to null cost of production; follow the HHP (electrical side), the HHP (gas side), the CHP, the gas boilers and the biomass plant that represents the most expensive solution.

*Table 11 – Thermal power plants*

| | PLANTS | | | | | | |
|---|---|---|---|---|---|---|---|
| | CENTRAL STATION | | | SUBSTATION 1 | | | SUBSTATION 7 |
| Plants | Gas boiler | CHP | Biomass plant | HHP (el. side) | HHP (gas side) | Thermal solar panel | Heat Pump |
| Rated power [kWt] | 1400<br>1400<br>3800 | 586 | 600 | 17 | 30 | – | 17 |
| Primary source | gas | gas | biomass | el. energy | gas | RES | el. energy |
| Primary source cost [€/kWh] | 0.04637 | 0.04637 | 0.07855 | 0.02780 | 0.03537 | 0.000 | 0.02780 |
| Thermal production cost [€/kWht] | −0.05040 | −0.04985 | −0.08594 | −0.00577 | −0.03845 | 0.000 | −0.00577 |
| PRIORITY | 5 | 4 | 6 | 2 | 3 | 1 | 2 |

Starting from the priority model, an optimal seasonal scheduling plane for the thermal power plants is carried out. The optimal scheduling allows to satisfy the thermal energy demand through a smart use of the available plants. The management model finds the minimum cost scheduling plane taking into account technological constrains and production costs of each thermal plant. The scheduling plane is based on a simplified version of the prosumer problem model introduced in the previous chapters. The purpose of this analysis is to obtain the power profiles produced by plants so as to evaluate the total cost incurred to support the request for thermal energy, and how, by performing energy improvement operations, this cost can be reduced.

In Table 12 the season costs and the annual cost are listed. In particular, two cases are compared: in the first case only traditional plants are considered; in the latter even thermal solar plant, HP and hybrid HP based on the optimal scheduling plan, are considered.

The comparison shows how, by installing new production systems of thermal energy from renewable energy sources (thermal solar thermal) and adopting high efficiency technology (hybrid HP) combined to a smart use, the annual costs are significantly reduced.

*Table 12 – Annual cost for thermal energy supply*

| | Spring | Summer | Autumn | Winter | Annual |
|---|---|---|---|---|---|
| only tradition plants | 45500.99 € | 32333.88 € | 39654.40 € | 55002.81 € | 172492.09 € |
| with<br>thermal solar panel<br>HP<br>hybrid HP | 42757.78 € | 29250.19 € | 37067.60 € | 53056.55 € | 162132.11 € |

The previous values show an annual cost saving of 10359.98 €/yr. Moreover, taking into account installation costs equal to 40068 € for the thermal solar panel, 9010 € for the HP and 11365 € for the hybrid HP, a payback time on the investment of 70 month and an internal profitability rate of 16.30% are obtained. To compute the previous values, a useful life of 20 years is considered.

# Conclusions and Outlook

In this Ph.D. thesis a new models and enabling IoT technologies for energy districts is proposed, which aims to optimize the energy exchange within the district between the prosumers with the goal of improving the energy efficiency and reducing the costs.

In this framework, a new DR program envisioned at the energy district level where each prosumers joining the district take part in a distributed architecture and set autonomously their own need and preferences, is presented. Constantly, a central aggregator determines the energy prices based on energy market conditions and monitors the electrical energy flows so to coordinate the prosumers among them.

In general, an energy district comprises a number of dwellings joined together in order to optimize the exchange of energy and reduce costs. In particular, there can be dwellings equipped with only loads who import energy from the distribution grid in order to fulfil the energy requirement, i.e., consumers. Conversely, a producer has only local generation plants, which allow it to sell energy to the grid. In the frequent case in which a dwelling is both a consumer and a producer can be referred to as a prosumer.

All the prosumers in the energy district communicate with a cloud component, which is in charge of managing the whole district. Each individual prosumer is equipped with an EMS, named Smart Energy Aware Gateway (SEAG), which enables the interaction with the centralized cloud component and is in charge of both the nano–grids and the home automation systems.

Starting from the previous general framework, a novel model for the optimal management of prosumers is introduced. As previously detailed, the “unified prosumer problem” has been modelled as a mixed integer linear optimization problem and solved with a Branch and Bound algorithm. The solution of the problem consists in the definition of the usage schedule of electrical and thermal appliances and of renewable–based generators, allowing each prosumer to maximize the revenues and minimize the costs while respecting the local constraints.

The efficiency and novelty of the approach mainly rely on two features: the first concerns the concurrent management of electrical and thermal energy, which leads to a significant cost saving when compared to the approaches where the two aspects are managed separately. The second pertains to the definition of the energy district architecture, which combines the computational power of a Cloud service provider, in charge of computing aggregated information and supplying it to the prosumers, with the limited but distributed power of end-user energy boxes.

The main novelty with respect to the state-of-the-art is the introduction in the optimization process of a second stage that, starting from the energy exchanges determined in the first stage, re-distributes to the prosumers the surplus energy, i.e., the energy produced locally that exceeds the demand of the prosumers. The first stage optimizes the energy flows and computes the global energy profile when considering the prosumer needs, the energy prices and the energy production forecast. At the second stage, the aggregator identifies the surplus hours, i.e., the hours at which the produced energy exceeds the overall demand of prosumers, and puts on sale the surplus energy at a more convenient price, to redistribute this energy within the district.

The two-stage approach benefits have been assessed in a real-life energy district, named Domus district, performed at the campus of the University of Calabria under the academic/industrial Italian project PON03PE_00050_2, “Sistemi Domotici per il servizio di brokeraggio energetico cooperativo”.

An experimental demonstrator was developed as conclusion of the previous project in order to provide a real test bed of the methods, prototypes and demand responsive programs developed during the project.

Details about the general architecture of the user in question and its interaction with the rest of the Domus district is provided. Particular attention is paid to the description of the SEAG device, of the nano-Grid prototypes and of the home automation systems installed in it. Follows the description of the loads, generation plants, and storage systems. Finally, the communication protocols adopted for controlling the home automation systems, as well as the communication tools between nano-Grids and SEAG are described.

Future developments will concern the evaluation of SEAG's performance in terms of resolving the prosumer problem and choosing the most economically advantageous energy management strategy; to this end, it will be necessary to perform further simulation tests within the Unical Campus District, so as to provide real forecast data and purchase and sale prices (provided by the Cloud services) and obtain real and non-simulated consumption data, production from local generation plants using renewable sources, user preferences, energy flows exchanged between users and the distribution network. In the subsequent development phase it will be necessary to compare the scheduling results obtained by the SEAG with the real scheduling trend of the controllable loads and generation plants.

This comparison will allow to confirm the planned scheduling plan or to quantify the forecast errors related to the production forecast from non−controllable generation plants, to the consumption of non−schedulable electrical loads and to the consumption of the thermal load. Further evaluation will focus on quantifying the deviation between the planned overall energy expenditure and the real one.

Energy storage is widely used to stabilize renewable energy fluctuations. However, the charging or discharging behaviour of storage, particularly the behind−the−meter storage, is difficult to model and meter. Advanced data analytical methods need to be adopted for anomaly detection, forecasting, outage management, decision making, and so forth in high renewable energy penetration environments. Moreover, the consumptions for electricity, heat, cooling, and gas are coupled in the future retailer market. One smart meter can record the consumptions of these types of energy simultaneously. Smart meter data analytics is no longer limited to electricity consumption data. For example, joint load forecasting for electricity, heating, and cooling can be conducted for multiple energy systems.

How to process, to manage, to store and to analyse data collected by smart meters has received extensive attention and rich literature studies related to this area have been published. Several problems, development opportunities and outlooks on smart meter data analytics in the future smart grid are: big data issues, new machine learning technologies, data privacy and security.

Substantial works in the literature have conducted smart meter data analytics. However, the size of the dataset analysed can hardly be called big data. How to efficiently integrate more multivariate data with a larger size to discover more knowledge is an emerging issue. Only possessing enormous memory capacity and storing all consumption data, it is possible to obtain sufficient historical data so to analyse user' behaviors in detail.

Big data issues with smart meter data analytics include at least two opened aspects: the first is multivariate data fusion, such as economic information, meteorological data, and energy consumption data; the second is high performance computing, such as distributed computing, GPU computing, fog computing and cloud computing.

In particular, cloud computing can provide different types of big data analytics services, including platform, software and infrastructure. How to make full use of these resources for smart meter data analytics is an important issue. In addition, a majority of smart meter data analytics methods that are applicable to small data sets may not be appropriate for large data sets. Highly efficient algorithms and tools such as distributed and parallel computing should be further investigated.

Smart meter data analytics is an interdisciplinary field that involves electrical engineering and computer science, particularly machine learning. The development of machine learning has had great impacts on smart meter data analytics. The application of new machine learning technologies is an important aspect of smart meter analytics.

Deep learning has been applied in different industries, including smart grids. Different deep learning techniques have been used for smart meter data analytics, which is just a start. Designing different deep learning structures for different applications is still an active research area. The combination of these emerging machine learning techniques may have widespread applications.

As it is known, the concern regarding smart meter privacy and security is one of the main barriers to the privilege of smart meters. Many existing works on the data privacy and security issue mainly focus on the data communication architecture and physical circuits [70]. How to study the data privacy and security from the perspective of data analytics is still limited [10].

Other areas to investigate are new business models in retail market. Further deregulation of retail markets, integration of distributed renewable energy, and progress in information technologies will hasten various business models on the demand side.

As further possible line of development, a comparison with management methodologies of Energy Hubs in multivector networks, is suggested.

Finally, a future research can concern the development of hardware and software platform integrated with the home automation systems with the goal to communicate and to manage smart appliances from different vendors. For the home automation aspects the power system technology is ready and also the European and national standards are ready, while the integration with the smart appliances is complicated and still not playing.

# References

[1] R. Belhomme , M. Sebastian, A. Diop, M. Entem, . F. Bouffard e G. Valtorta, ≪Deliverable 1.1 Address Technical and Commercial Conceptual Architectures,≫ Technical Report; Interactive Energy: Lucerne, Switzerland, 2009.

[2] M. Razmara, G. R. Bharati, D. Hanover, M. Shahbakhti, . S. Paudyal e R. D. Robinett III, ≪Building-to-grid predictive power flow control for demand response and demand flexibility programs.,≫ Applied Energy, n. 203, pp. 128-141, 2017.

[3] J. Torriti, Peak Energy Demand and Demand Side Response, Routledge Taylor & Francis Group, 2016.

[4] H. T. Mouftah e M. Erol-Kantarci, SmartGrid Networking, Data Management,and Business Models, Taylor & Francis Group, 2016.

[5] Department for Business Energy and Industrial Strategy, ≪Smart Meters, Quarterly Report to end December 2016, Great Britain,≫ Tech. Rep., 2017.

[6] ≪How many smart meters are installed in the united states, and who has them?,≫ [Online]. Available: https://www.eia.gov/tools /faqs/faq.php?id=108&t=3. [Consultato il giorno 31 July 2017].

[7] ≪Number of electric smart meters deployed in the u.s. from 2008 to 2016,≫ [Online]. Available: https://www.statista.com/statistics /499704/number-of-smart-meters-in-the-united-states/. [Consultato il giorno 31 July 20117].

[8] R. R. Mohassel, A. Fung, F. Mohammadi e K. Raahemifar, ≪A survey on Advanced Metering Infrastructure,≫ International Journal of Electrical Power & Energy Systems, vol. 63, pp. 473–484, 2014.

[9] J. Yang, J. Zhao, F. Luo, . F. Wen e Z. Y. Dong, ≪Decision-Making for Electricity Retailers: A Brief Survey,≫ Transactions on Smart Grid, 2017.

[10] Y. Wang, Q. Chen, . T. Hong e C. Kang, ≪Review of Smart Meter Data Analytics: Applications, Methodologies, and Challenges,≫ Transactions on Smart Grid, 2018.

[11] G. N. Sorebo e M. C. Echols, SMART GRID SECURITY An End-to-End View of Security in the New Electrical Grid, Taylor & Francis Group, 2012.

[12] C. Keerthisinghe, G. Verbič e A. C. Chapman, ≪A Fast Technique for Smart Home Management: ADP With Temporal Difference Learning,≫ IEEE Transactions on Smart Grid, vol. 9, n. 4, 2016.

[13] . A. Pratt , D. Krishnamurthy, M. Ruth, H. Wu, M. Lunacek e P. Vaynshenk, ≪Transactive Home Energy Management Systems: The Impact of Their Proliferation on the Electric Grid,≫ IEEE Electrification Magazine, vol. 4, n. 4, 2016.

[14] T. Morstyn, N. Farrell, . S. J. Darby e M. D. McCulloch , ≪Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants,≫ Nature Energy, vol. 3, p. 94 - 101, 2018.

[15] G. Strbac, ≪Demand side management: Benefits and challenges,≫ Energy policy, vol. 36, n. 12, p. 4419 - 4426, 2008.

[16] Internation Energy Agency, ≪The power to choose. Demand response in liberalized electricity markets,≫ Energy market reform, 2003. [Online]. Available: https://tinyurl.com/kmdtasl.

[17] M. H. Albadi e E. El-Saadany, ≪A summary of demand response in electricity markets,≫ Electric power systems research, vol. 78, n. 11, p. 1989 - 1996, 2008.

[18] J. Aghaei e M. I. Alizadeh, ≪Demand response in smart electricity grids equipped with renewable energy sources: A review,≫ Renewable and Sustainable Energy Reviews, vol. 18, p. 64 - 72, 2013.

[19] H. P. Chao, ≪Price−responsive demand management for a smart grid world,≫ he Electricity Journal, vol. 23, n. 1, p. 7 ‑ 20, 2010.

[20] S. Ruthe, . C. Rehtanz e S. Lehnhoff, ≪On the problem of controlling shiftable prosumer devices with price signals,≫ International Journal of Electrical Power & Energy Systems, vol. 72, p. 83 ‑ 90, 2015.

[21] K. Alanne e A. Saari, ≪Distributed energy generation and sustainable development,≫ Renewable and sustainable energy reviews, vol. 10, n. 6, p. 539 ‑ 558, 2006.

[22] A. D. Rathnayaka, . V. M. Potdar, . T. Dillon, O. Huss e S. Kuruppu, ≪Goal−oriented prosumer community groups for the smart grid,≫ Technology and Society Magazine, vol. 33, n. 1, p. 41 ‑ 48, 2014.

[23] J. Ferdous, M. P. Mollah, . M. A. Razzaque, M. M. Hassan, A. Alamri, . G. Fortino e M. Zhou, ≪Optimal dynamic pricing for tradingoff user utility and operator profit in smart grid,≫ IEEE Transactions on Systems, Man, and Cybernetics: Systems, pp. 1−13, 2017.

[24] M. N. Faqiry e S. Das, ≪Double auction with hidden user information: Application to energy transaction in microgrid,≫ IEEE Transactions on Systems, Man, and Cybernetics: Systems, pp. 1−14, 2018.

[25] K. Meng, Z. Y. Dong, . Z. Xu, Y. Zheng e D. J. Hi, ≪Coordinated dispatch of virtual energy storage systems in smart distribution networks for loading management,≫ IEEE Transactions on Systems, Man, and Cybernetics: Systems, pp. 1−11, 2017.

[26] European Commission, ≪Directive of the european parliament and of the council on common rules for the internal market in electricity,≫ Tech. Rep., 2017.

[27] E. Mengelkamp, P. Staudt, . J. Garttner e C. Wein, ≪Trading on local energy markets: A comparison of market designs and bidding strategies,≫ in 14th IEEE International Conference on the European Energy Market (EEM), Dresden (Germany), 2017.

[28] A. Burgio, . A. Giordano, . A. A. Manno, C. Mastroianni, D. Menniti, A. Pinnarelli, L. Scarcello, N. Sorrentino e M. Stillo, ≪An IoT approach for smart energy districts,≫ in 14th IEEE International Conference on Networking, Sensing and Control, 2017.

[29] Y. Parag e B. K. Sovacool, ≪Electricity market design for the prosumer era,≫ Nature Energy, vol. 1, p. 16032, 2016.

[30] E. Koliou, . C. Eid, . J. P. Chaves-A ́ vila e . R. A. Hakvoort, ≪Demand response in liberalized electricity markets: Analysis of aggregated load participation in the german balancing mechanism,≫ Energy, vol. 71, pp. 245-254, 2014.

[31] R. Carli e M. Dotoli, ≪Cooperative distributed control for the energy scheduling of smart homes with shared energy storage and renewable energy source,≫ 20th IFAC World Congress, vol. 50, n. 1, p. 8867 – 8872, 2017.

[32] M. R. Blouin e R. Serrano, ≪ "A decentralized market with common values uncertainty: Non-steady states,≫ The Review of Economic Studies, vol. 68, n. 2, p. 323 – 346, 2001.

[33] P. Vytelingum, S. D. Ramchurn, . T. D. Voice, A. Rogers e N. R. Jennings, ≪Trading agents for the smart electricity grid,≫ in 9th International Conference on Autonomous Agents and Multiagent Systems (AAMS), Toronto, Canada, 2010.

[34] K. Kok, . B. Roossien, . P. MacDougall, O. Van Pruissen, . G. Venekamp, R. Kamphuis, J. Laarakkers e C. Warmer, ≪Dynamic pricing by scalable energy management systemsfield experiences and simulation results using powermatcher,≫ in IEEE Power and Energy Society General Meeting, 2012.

[35] G. Belli, A. Giordano, C. Mastroianni, D. Menniti, A. Pinnarelli, L. Scarcello, N. Sorrentino e M. Stillo, ≪A unified model for the optimal management of electrical and thermal equipment of a prosumer in a DR environment,≫ IEEE Transactions on Smart Grid, 2017.

[36] M. Ampatzis, P. H. Nguyen e . W. Kling, ≪Local electricity market design for the coordination of distributed energy resources at district level,≫ in 5th IEEE Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Istanbul (Turkey), 2014.

[37] N. Good, E. Karangelos, A. Navarro-Espinosa e P. Mancarella, ≪Optimization under uncertainty of thermal storage-based flexible demand response with quantification of residential users discomfort,≫ IEEE Transactions on Smart Grid, vol. 6, n. 5, p. 2333 – 2342, 2015.

[38] S. Althaher, P. Mancarella e . J. Mutale, ≪Automated demand response from home energy management system under dynamic pricing and power and comfort constraints,≫ IEEE Transactions on Smart Grid, vol. 6, n. 4, p. 1874 – 1883, 2015.

[39] J. M. Lujano−Rojas, C. Monteiro, R. Dufo−Lopez e J. L. Bernal−Agust ́ ı n, ≪Optimum residential load management strategy for real time pricing (rtp) demand response programs,≫ Energy Policy, vol. 45, p. 671 - 679, 2012.

[40] V. Pilloni, A. Floris, A. Meloni e L. Atzori, ≪Smart home energy management including renewable sources: A qoe−driven approach,≫ IEEE Transactions on Smart Grid, 2016.

[41] D. Livengood e . R. Larson, ≪The energy box: Locally automated optimal control of residential electricity usage,≫ Service Science, vol. 1, n. 1, p. 1 - 16, 2009.

[42] F. Fernandes, H. Morais, . Z. Vale e C. Ramos, ≪Dynamic load management in a smart home to participate in demand response events,≫ Energy and Buildings, vol. 82, p. 592 - 606, 2014.

[43] G. Brusco, A. Burgio, D. Menniti, A. Pinnarelli e N. Sorrentino, ≪Energy management system for an energy district with demand response availability,≫ IEEE Transactions on Smart Grid, vol. 5, n. 5, p. 2385 - 2393, 2014.

[44] H. Aalami, . M. P. Moghaddam e G. Yousefi, ≪Demand response modeling considering interruptible/curtailable loads and capacity market programs,≫ Applied Energy, vol. 87, n. 1, p. 243 - 250, 2010.

[45] G. Brusco, . G. Barone, A. Burgio, . D. Menniti, A. Pinnarelli, L. Scarcello e . N. Sorrentino, ≪A smartbox as a low−cost home automation solution or prosumers with a battery storage system in a demand response program,≫ in 16th International Conference on Environment and Electrical Engineering, 2016.

[46] R. Bruno, . G. Pizzuti e N. Arcuri, ≪The prediction of thermal loads in building by means of the en iso 13790 dynamic model: A comparison with trnsys,≫ Energy Procedia, vol. 101, p. 192 - 199, 2016.

[47] T. . J. Hammons, ≪Integrating renewable energy sources into European grids,≫ International Journal of Electrical Power & Energy Systems, vol. 30, n. 8, p. 462 - 475, 2008.

[48] J. Markard e B. Truffer, ≪Innovation processes in large technical systems: Market liberalization as a driver for radical change?,≫ Research Policy,, vol. 35, n. 5, p. 609 - 625, 2006.

[49] E. Commission, ≪Communication from the commission to the European parliament, the council, the european economic and social committee and the committee of the region,≫ Europe 2020 Flagship Initiative Innovation Union, [Online]. Available: http://eur-lex.europa.eu/legalcon.

[50] G. Brusco, G. Belli, D. Menniti, N. Sorrentino, A. Pinnarelli e . A. Burgio, ≪In the future smart cities: Coordination of micro smart grids in a virtual energy district,≫ International Symposium on Power Electronics, Electrical Drives, Automation, 2014.

[51] . A. Burgio, P. Vizza, D. Menniti, N. Sorrentino, A. Pinnarelli e G. Belli, ≪Local electricity market involving end-user distributed storage system,≫ in IEEE 15th International Conference on Environment and Electrical Engineering, Rome, Italy, 2015.

[52] G. Belli, G. Brusco, A. Burgio, D. Menniti, A. Pinnarelli, N. Sorrentino e P. Vizza, ≪A multiperiodal management method at user level for storage systems using artificial neural network forecasts,≫ Transactions on Environment and Electrical Engineering (TEEE), vol. 1, n. 4, p. 29 - 36, 2016.

[53] E. Cesario e D. Talia, ≪Distributed data mining patterns and services: an architecture and experiments,≫ Concurrency and Computation: Practice and Experience, vol. 24, n. 15, p. 1751 - 1774, 2012.

[54] A. Forestiero, C. Mastroianni, M. Meo, G. Papuzzo e M. Sheikhalishahi, ≪Hierarchical approach for efficient workload management in geo-distributed data centers,≫ IEEE Transactions on Green Communications and Networking, 2017.

[55] E. Heydarian-Forushani, . M. Shafie-khah, M. Y. Damavandi e . J. P. Catalão, ≪Optimal Participation of DR Aggregators in Day-Ahead,≫ in Doctoral Conference on Computing, Electrical and Industrial Systems, Springer, Berlin, Heidelberg, 2014.

[56] L. Gkatzikis, I. Koutsopoulos e T. Salonidis, ≪The Role of Aggregators in Smart Grid Demand,≫ IEEE Journal on Selected Areas in Communication, vol. 31, n. 7, pp. 1247-1257, 2013.

[57] A. Burgio, G. Brusco, . D. Menniti, . A. Pinnarelli, . N. Sorrentino e P. Vizza, ≪Economic evaluation in using storage to reduce imbalance costs of renewable sources power plants,≫ in 14th International Conference on the European Energy Market, 2017.

[58] P. G. Da Silva, D. Ilic e S. Karnouskos, ≪The impact of smart grid prosumer grouping on forecasting accuracy and its benefits for local electricity market trading,≫ Transactions on Smart Grid, vol. 5, n. 1, p. 402 - 410, 2014.

[59] E. Bullich−Massagu ́ e, M. Arag ̈ u ́ es−Penalba, P. Olivella−Rosell, P. Lloret−Gallego, J.−A. Vidal−Clos e A. Sumper, ≪Architecture definition and operation testing of local electricity markets. the empower project,≫ in International Conference on Modern Power Systems (MPS), Napoca, Romania, 2017.

[60] M. Ampatzis, P. Nguyen e W. Kling, ≪Implementation and evaluation of an electricity market operated at district level,≫ PowerTech, p. 1 - 6, 2015.

[61] G. Brusco, A. Burgio, D. Menniti, A. Pinnarelli, N. Sorrentino e L. Scarcello, ≪An Energy Box in a Cloud−Based Architecture for Autonomous Demand Response of Prosumers and Prosumages,≫ Electronics, vol. 6, n. 4, p. 98, 2017.

[62] C. Wang, J. Wu, J. Ekanayake e N. Jenkins, Smart electricity distribution networks, Taylor & Francis Group, 2017.

[63] G. Brusco, A. Burgio, . D. Menniti, A. Pinnarelli, N. Sorrentino e P. Vizza, ≪Quantification of forecast error costs of photovoltaic prosumers in italy,≫ Energies, vol. 10, n. 11, p. 1754, 2017.

[64] ≪https://www.ibm.com/us−en/marketplace/ibm−ilog−cplex,≫ [Online].

[65] A. Giordano, G. Spezzano e A. Vinci, ≪Rainbow: an intelligent platform for large−scale networked cyber−physical systems,≫ in International Workshop on Networks of Cooperating Objects for Smart Cities (UBICITEC), Berlin, Germany, 2014.

[66] M. Wooldridge, An introduction to multi−agent systems, John Wiley & Sons, Ltd., 2002.

[67] M. Motta, Control system for a nanogrid for home application: dynamic analysis and implementation aspect using a behaviour tree, University of Calabria, Science and Engineering of Enviroment, Construction and Energy (SIACE − XXX cycle): Ph.D. Thesis, 2018.

[68] T. Q. Company, ≪Qt | Cross−platform software development for embedded & desktop,≫ [Online]. Available: https://www.qt.io/. [Consultato il giorno 14 June 2018].

[69] H. Farhangi, Smart Grid – Lessons from Campus Microgrid Design and Implementation, Taylor & Francis Group, 2017.

[70] Y. Wu, B. Chen, J. Weng, Z. Wei, X. Li, B. Qiu e N. Liu, ≪False Load Attack to Smart Meters by Synchronously Switching Power Circuits,≫ IEEE TRANSACTIONS ON SMART GRID, 2018.

[71] V. Hodge e J. Austin, ≪A Survey of Outlier Detection Methodologies,≫ Download PDF, vol. 22, n. 2, p. 85 - 126, 2004.

[72] J. Peppanen, X. Zhang, S. Grijalva e . M. J. Reno, ≪Handling bad or missing smart meter data through advanced data imputation,≫ IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2016.

[73] R. Granell, C. J. Axon e D. C. H. Wallom, ≪Impacts of Raw Data Temporal Resolution Using Selected Clustering Methods on Residential Electricity Load Profiles,≫ IEEE Transactions on Power Systems, vol. 30, n. 6.