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Ph.D. Dissertation

Enabling technologies for innovative energy management systems in domestic applications

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“If you can't explain it simply, you don't understand it well enough”

“You do not really understand something unless you can explain it to your grandmother.”

[A. Einstein]

To all people that believe in a dream
and have the willpower to realize it…

Acknowledgments

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I would like to express my grateful appreciation for all the staff at the Mechatronics Laboratory for their constant support and help through my three years of work as a Ph.D. student.
I deeply thank my tutor Prof Marcello Chiaberge for his professional advice based on his extensive experience.
During the development of this project, I found invaluable help in my colleague Eng. Fabio Ghiso, who was involved in the design and experimental phase of our implementation. He has also provided important suggestions and contributions to the project. I'm also grateful to Eng. Roger Tonetti that manage all the economical part and was the main project manager.
I am grateful to all my friends and parents that always supported me all the time.

Diego Boero, January 2015.

Abstract

Storage systems became one of the most appreciated solution of some problems related with energy distribution and a fundamental part in the new energy system well known as Virtual Power Systems (VPS). A VPS is a new way to manage the energy, starting from production by standard power plants and renewable sources, to consumption in industries and villages. Actually, distributed generation from renewable sources starts creating electric stability problems in the distribution system/network due to the impulsive injection of energy and also for the non-predictable generation profile. For these reasons is absolutely necessary to guarantee a good integration of the new energy sources in the actual power system and storage can become the perfect joining link for the realization of a Smart Grid.

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Chapter 1 - Introduction

The evolution and the growth of the Smart Grid concept, characterized by high integration of renewable sources, smart meters and IT networks, brings new criteria to manage daily energy productions and consumptions [1]. Energy storage systems (ESS) have become increasingly important thanks to renewable sources that are characterized by non-deterministic and intermittent production profiles. An ESS can guarantee grid stability, improvement of power quality and can also maximize auto-consumption, reducing costs due to the energy purchase [2,3,4]. Furthermore, this scenario delivers new control strategies that can maximize efficiency.
The current reality require new system able to adapt their behaviour to various scenario and till now the most diffused solution is to interconnect complete systems able to satisfy only few or a single aspects.

1.1. Aim of the work

The aim of the present dissertation is to implement the standard technologies actually available on the market in real contexts such domestic building or small industrial application, in order to show advantages and disadvantages due to their introductions. From the technological point of view we wanted to develop the new concept of Virtual Power System (VPS) and Smart Grid, which is considered the natural evolution of the energy production, management and distribution. Until now we have been a one-way energy flow from the production centers to final consumers. Actually, distributed generation from renewable sources starts creating electric stability problems in the distribution system/network due to the impulsive injection of energy and also for the non-predictable generation profile. For these reasons is absolutely necessary to find a good integration of the new energy sources in the actual power system.

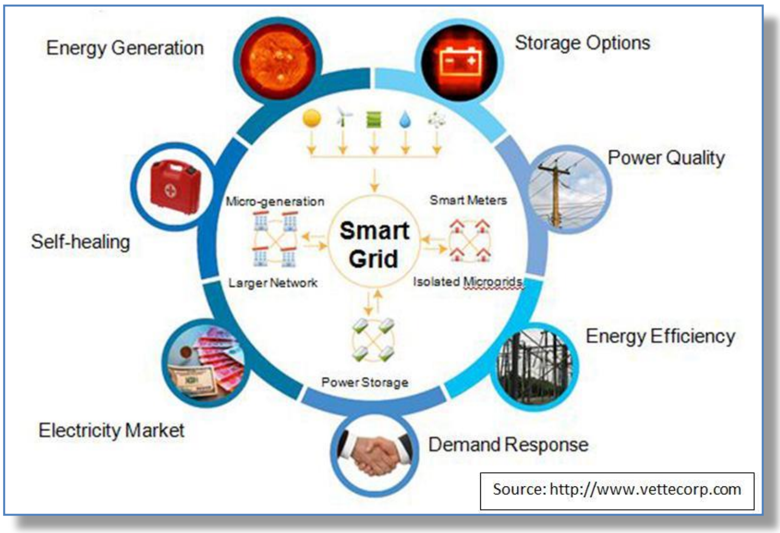

Figure 1: Smart grid main elements

The VPS, that means the use of Smart Grid associated with distributed generation, local electric energy storage and the active management of the consumptions, allows the decrease of those obstacles that cause this ”one way-direction”. But the VPS concept is still too abstract: we need to zoom with much more detail inside the elements of a Smart Grid and among the technologies necessary to implement it, especially finding simple solutions to implement a sort of “microgrid” also in small reality, like small villages or community.

It is desired to exhibit the potentialities and limitations of such technologies and how to manage their limitations and their evolutions.

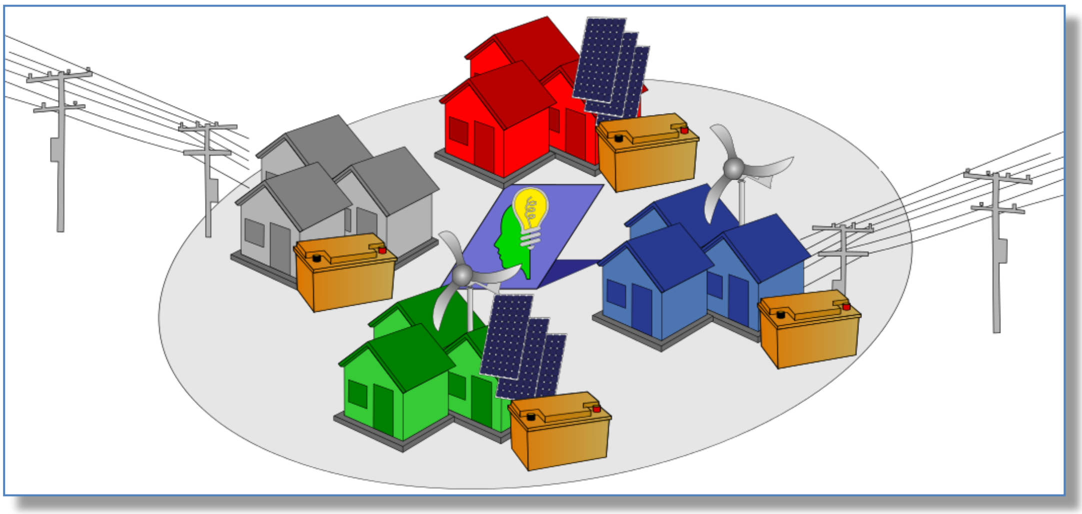

Figure 2: Microgrid representation

In order to achieve this objective, this work follows a model-based design that targets the particular application and the development and experimental validation of prototypes in microgrid context.

1.2. Research activity

This dissertation is mainly based on experimental results achieved thank to the close cooperation and integration of my research in the AlpEnergy Project.
The AlpEnergy project, started one year before the PhD beginning and concluded during the PhD period, was one of the most important activity that was developed and brought important results to the Smart Grid development in the Aosta Valley.
The close collaboration between Mechatronic Laboratory by Turin Polytechnic and the main department of industrial activities of Aosta Valley Region, bring the opportunity to study an develop new systems for the energy management.
AlpEnergy was an European territorial cooperation project funded by the Alpine Space Programme 2007-2013. It aimed to increase the competitiveness and attractiveness of the regions involved by studying the potential and applicability, in the Alps, of a new technological paradigm in electricity distribution, usually known

as “Smart Grids”, that the project has framed and redefined with the introduction of a new concept: Virtual Power Systems (VPS).
The Autonomous Region of Aosta Valley want to study the applicability of VPS concept to his territory, in particular concerning scattered villages. The aim was to analyse the technical and economical attractiveness of VPS. The project focussed on monitoring electrical consumptions and to forecast, on the other side, the potential of production with RES. With Virtual Power System technology developed in AlpEnergy, the responsibles of the region want to create and test a simple and easily practicable model to manage power supply in scattered habitat scenarios. The tests unveiled potentials for a 100 % power supply from renewable energies in such small villages.
Thanks to the collaborations between Assessorato alle Attività Produttive from Autonomous Region of Aosta Valley and Mechatronic Laboratory from Turin Polytechnic, I and a colleague of mine, Eng. Fabio Ghiso, were assigned as scientific partners and technology developers for the research and implementation part of the project. Our role were to study the real situation in the selected villages related to the energy production, distribution, management and consumption; then find a simple and cheaper solution to start a migration from actual topology of energy distribution, from one source to multiple consumers, to a distributed energy production and management.

To reach the goal, the research activity was splitted in several parts:

- State of the art analysis
- Real time consumption and production monitoring
- Design and development of simple and cheaper solutions
- Implementation of new technological solution to improve VPS stability

1.3. Thesis Outline

In order to explore the technical and partial economic impact of the research activity it’s necessary to Define specific areas of technology applicability, outlining the possible constraints and estimate the number of potential users and the number of devices required to satisfy the demand. Then the following information are required:

- Experimental data related to the equipment;
- Experimental data related to users (absorption and other technical parameters of private consumers and companies);
- Technical parameters provided by the utilities involved in the project;
- Technical parameters provided by other utilities;
- General information related to electricity distribution networks and smart grids.

This thesis is divided into x chapters:

- Chapter 1: briefly motivates and delimits the present work.
- Chapter 2: describe VPS and his analysis in this dissertation
- Chapter 3: includes a state of the art research that covers available technology for energy storage and conversion and then focus on the implementation location
- Chapter 4: report simulation and numerical evaluation of production and consumption of the real case study
- Chapter 5: report the implementation of hardware solution developed and their tests
- Chapter 6: discusses the obtained results, states the conclusions and indicates possible future developments.

Chapter 2 - Research Activity

2.1. What is a Virtual Power System

Generally, the VPS could be summarized as a system of distributed power production and consumption linked by an electric network (typically a distribution network), suitable completed by a communication system; it is mainly based on renewable energy resources including hydro, wind, photovoltaic and CHP plants.
The power production and consumption are managed (in terms of energy and/or power balance) in order to get some benefits (better defined in the specific definition). The spatial extension of the VPS may differ from country to country according by territorial restrictions or political/infrastructural restrictions.
The power production is supposed to be provided using one or more renewable technologies, by one or more power plants. In the VPS all the generation resources can be engulf in a single energy production profile. Similarly, for what concern the consumption, in the VPS the loads can be aggregated to shape a single power consumption profile (Virtual Load Plant, VLP). Exploiting a proper communication network (up to the development of an ICT system), the VPS can manage together all these elements in order to get maximum advantage.

From the technological point of view, the decrease of communication costs and the larger availability of new technologies (ICT) make effective to implement all the VPS potentials; in particular it is relevant to point out how the communication between electric grid (distribution and/or transmission) and dispersed entities (generators, loads, accumulation facilities) is useful for different point of view:

1) to effectively manage the energy balance and metering,
2) to implement the power balance between the generation and the load profile,
3) to enhance the network performances (power quality, management of the electric protections) in presence of dispersed generation.

In particular, while the energy management and metering is currently exploited in the distribution electric system, the power balance and the management network are needed to put together the enhancement of the power quality and the development of embedding dispersed generation. It’s relevant to point out the importance of these two evolution directions of the electric power system, expressed by the most important authority at EU level.
The VPS, coherently with the previous introduced definition, should be evaluated considering an holistic approach of the project sustainability, evaluating the efficiency and the efficacy of the renewable resources in terms of:

- environmental impact;
- overall costs;
- service continuity.

For the VPS implementation it is relevant the technological opportunities nowadays available in terms of energy conversion, energy storage and ICT communication and control.

Generally, in a VPS environment, generators and loads can be connected using the existing network or implementing a dedicated distribution network, like in scattered habitants with very remote costumers or in actually disconnected infrastructure. In the great major of the cases the generators or loads are connected to an existing network than can be exploited also like an energy buffer or for backup purposes; in the latter case the electrical service continuity is increased. Respect to the exploitation of the existing network like an energy buffer it is necessary to point out that it could result non-optimal, i.e. it can lead to a no increase in the overall efficiency of the electric system. For a full exploitation of the VPS concept, consumers should shape their energy profile according to the production plant technology, potentials and management. For the very small scale applications an energy buffer could be needed at the interface with the main network. Besides, in a general point of view, the energy buffer can be beneficial for the continuity of supply. Finally, respect to the scattered applications, the VPS represents an interesting solution for area with difficulties in accessing the main network or where the investments in improving the network would not be economically justifiable, or when special environment constraints exist.

Like previously introduced, exploiting a proper communication network, the VPS can manage together all these elements, generation, consumption and storage, in order to get maximum advantages. If the generation and consumption profile are synchronized, either in terms of energy and in terms of power, the power flows on the electric networks will decrease, reducing the losses[5,6,7].

This dissertation is devoted to depict the VPS applications developed in the project framework, in particular related to the technical VPS models.
As previously introduce, local resources (generation, consumer and electric grid) are exploited in order to maximize energy efficiency and push forward a renewable resources employment. Power injection from generation resources has to be coordinated with the consumer requirement in order to avoid peaks in power flows, better manage the electric power system, reduce losses on electric lines.

2.2. Why storage is necessary

Up to now the main use of storage systems has been the pure energy storage to supply users with no connection to the main grid such as wind and photovoltaic island plants.

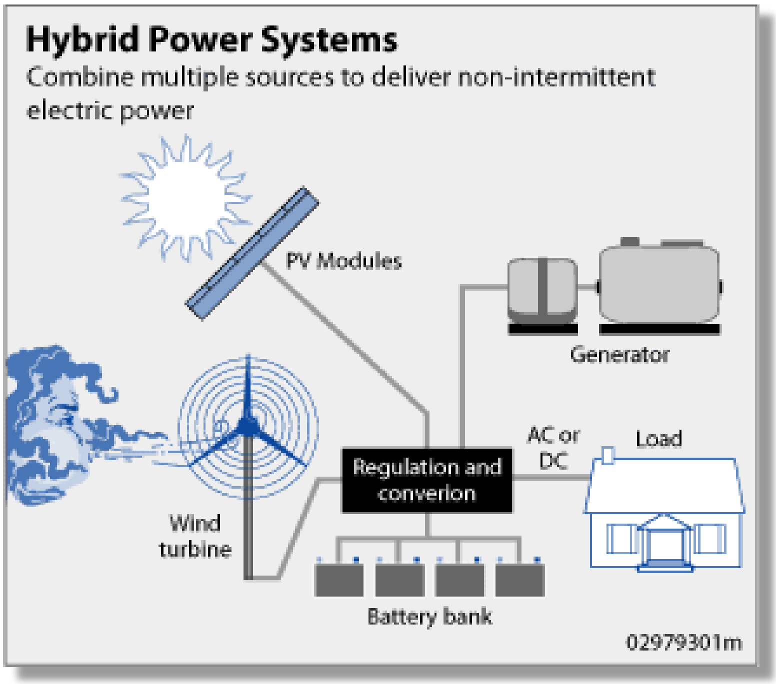

Figure 3: Standard storage implementation with RES disconnected from EDS (courtesy How Stuff Works)

With the increasing diffusion of renewable sources plant, both private and public facilities, this systems acquire new features in addition to the classic use to supply, in the inactivity hours of production, the utilities connected to such facilities [8]. New renewable sources are an advantage but they introduce several problems of management that, with the growth of the installed systems, are becoming more and more complex. The renewable sources typically have a discontinuous character caused by the presence or not of the main energy, as solar radiation or wind, but especially the intensity of this energy; considering a photovoltaic plant, its production is constrained by the presence or not of the sun, but also in the daytime hours of production there may be changes in the production of more than 80% of installed power for the simple presence of clouds that obscure the facility. Same example can be done on wind turbines that, for economic and energy conversion factors, are sized on the estimated average production; in case short but intensive gusts of wind, energy cannot be managed properly causing also proportional differences of the energy injected in the grid.

All these changes, if considered together, will add a new factor for the electricity grid instability. Up to now, in fact, the stability has been guaranteed by carrying out an adaptation of the production according to consumer demands; if this does not happen, an imbalance between production and consumption start to increase the grid instability that would result in a complete blackout of the entire electrical system. Considering these factors, the storage systems are presented as a attractive solution as stabilizer of the electricity grid, both in terms of loads, that from the point of view of production. Associated with production sources, they may be a necessary element to permit the transformation of all discontinuous sources into foreseeable sources of production but also adjustable if necessary.

Considering instead the combination of these systems to consumer facilities, they acquire a threefold function:

Peak shaving function

For the management of a load with a profile characterized by intense but short absorption peaks (> 500% of the average power), it’s important to size the power supply grid around to the maximum peak that is necessary to manage; also the contract with the electricity distributor must be adjusted to the maximum power involved. The introduction of these storage systems, properly sized to the circumstances, allows a saving on both the physical size of the distribution network, but also a contractual savings on the power that is request. Systems of this type usually consist in a reduced size storage system but with an energy conversion system capable of handling high power request.
For example in the graph below its possible to understand which energy (the red area) the system have to provide to a load instead of absorbing that energy from the grid. Under a specific threshold there are no changes but over that limit is the system that provide what is necessary to the loads and not the grid:

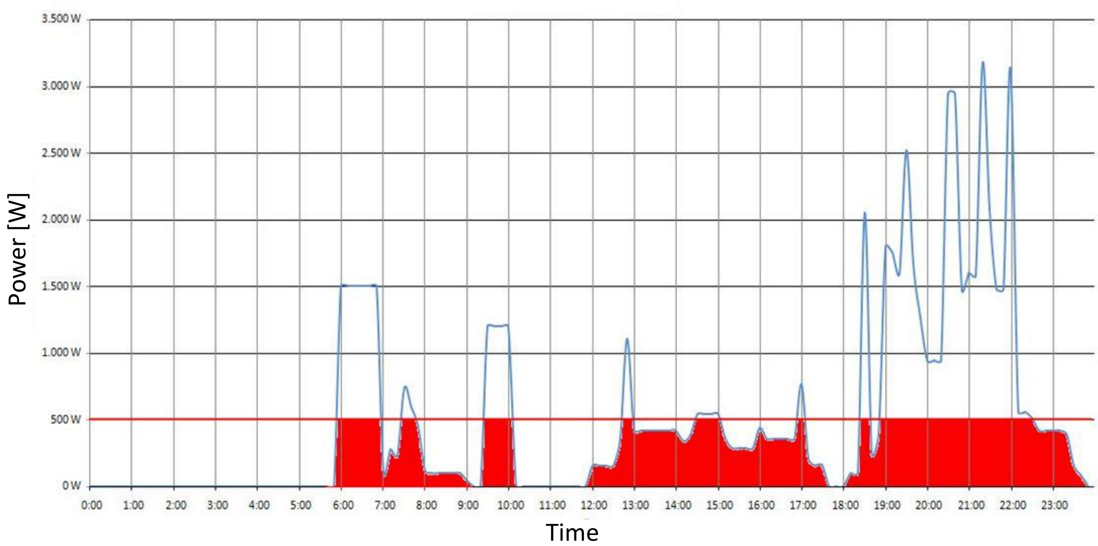

Figure 4: Peaks absorption example over average absorption threeshold

Linearization function

Considering instead discontinuous load profiles, characterized by absorption peaks with a reduced intensity as households (<500% of the average power), using storage systems with a capacity adequate for short periods sustain (i.e. ~15min @ 3kW for household), it's possible to transform a discontinuous load not only into a predictable absorption but also in a load that can be disconnected from the network in case of overload, while still providing a continuous and constant power to the end user. Thus, organizing planned disconnections, it's possible to lighten and balance the network in case of need.

Stabilization function

Using distributed islands of storage on the territory, you can imagine to have control on users that can be transformed from loads, that absorb energy, into sources of energy, all in a few instants according to programs or automatically in case of anomalies. This kind of systems are revealing as useful stabilizers of the network; their main feature is the adaption speed to the demands of the distribution network. If necessary they can provide energy in very short times compared to the time required to start production from plant used to balance the

grid actually, and, in the same way, they can become good absorbers of energy surplus that is injected into the network without notice, as what happen with intermittent renewable sources, but with the possibility to use the stored energy when is necessary. Usually these systems are characterized not only by a high storage capacity, even by a high power handling capacity. Moreover, these islands can be integrated with local renewable sources also discontinuous.
Evaluating the overall potential of these systems, these realities are good if not optimal solutions to the ever increasing need to adapt the electricity grid into a smart grid, able to adapt itself to the demands of all users connected to it, whether they are consumers, whether they are producers. This related to the fact that in the future there will be a growing distributed generation difficult to predict, but that will need particular attention to use energy at our disposal in a non-reckless way.

2.3. Operating step of research activity

The whole project was defined to be implemented in real locations to demonstrate the real feasibility of the solution adopted. The main needs was to find some places with landscape, power facilities, loads and distribution system that represent a critical location, where if VPS is applied, results can be transferred also in other location characterized by different but less complex implementation problems. For these reasons alpine space is the ideal location where to study and implement this kind of research.

Three main activities are identified:

- Monitoring of electric consumptions
- Analysing collected data
- Modify users' absorption behaviour using:
    - indirect notifications: change user absorption behaviour using custom notification according to the real time conditions;
    - direct operations: change user absorption profile using special equipment without changing standard user habits

First of all the test involves monitoring for a long period, more than one year, of utilities' consumptions, both public and private utilities. This was done in two different ways:

- Obtaining from the electricity provider the absorption data from the utilities' smart meters, provided in monthly way by the company, assembled for resort, in an anonymous way and with a rather long sampling period: 15 min. These data are used in the test to implement a long-range statistical analysis, in order to characterize, in approximate way, the behaviour of the entire absorption system, what in context VPS, is seen as "the load" that requires energy. Furthermore, these data are provided to individuals who specifically requested by tables and graphs available on the web portal by the Polytechnic of Turin for the project.

- Second step consists on installing on some citizens' residential building and on some public buildings, appropriately selected, an advanced control unit of consumption (EMU), to detect utilities' consumptions and energy production of RES plants available. These EMU allow data sampling much more dense than ordinary Deval's smart meter, even up to 1 sec., giving the opportunity to make a very detailed analysis of the consumption characteristics of a limited number of users. Moreover, through GPRS connection to a management and data collection server, they allow the consumption control in real time with immediate display on the web area as first feedback for who is interested.

- Then being able to set alert thresholds, it's possible to easily create a sort of direct feedback to the user, which can be adequately warned against momentary or prolonged over-consumption. All this to get close to a system that can adjust more or less independently, in order to keep under control the loading level of the VPS power grid.

The second phase, the analysing phase, consist in a set of software tools that process automatically data collected, according to the designed algorithm. These permit to evaluate the actual situation and simulate what can happen in the whole local reality with the introduction of new systems able to modify user behaviour or their real absorption profile.

In the third phase, as first step, the results of analysing process are traduced in actions sent to users by an electronic communication channel (i.e.: SMS or web information panel via GPRS). The users should collaborate in order to change their own way to use domestic electrical appliances, according to the communication sent. During test other activities were taken into account because of functional for the test, for its technology implementation, for the information collection and the results processing.

The main points of the above mentioned activities will be:

- Study of the area and available resources: analysis of the production of energy resources available in selected places to choose what type of generator set or combination of generators (solar, wind, hydro, biomass) is more suitable for the maximum yield in terms of energy production.
- State of Art Analysis: a brief report on currently available technologies for storage systems, their implementation cost and the problems from their installation, which will lead to the selection of the best solution based on the characteristics of the installation place.
- Simulation of the local distribution network combined with storage and production systems chosen.
- Realization of demonstrative prototypes: based on the chosen technologies, prototype demonstration of storage systems, processing and power generation. Realization of the interfacing of different systems and control system.
- Review and analysis of laboratory results: tests of installed systems, data collection.
- Implementation of the created system in the selected location: realization of the final prototypes, installation and implementation of the VPS network in St. Denis, system testing, data collection and report on the results production.

Chapter 3 - State of the Art

All the technologies used in this research are systems available on the market from several years. The main systems used in the study can be grouped into specific category according to their functionality:

- Monitoring systems: to monitor and collect data used for models and simulations
- Control and Simulation System: to analyse collected data and feedbacks management
- Distributed energy conversion and storage systems: to adapt absorption profile according to the new guidelines

But to really understand how to develop a Virtual Power System locally, it's necessary to understand which are the power facilities, the loads and the actual structures available inside the area of our interest. Only after this we were able to start considering which were the first actions necessary to realize the entire system.

Due to the heavy relation between research activity and his implementation, a short report about the implementation location is reported, to better understand the case study and his potential/limitations.

3.1. Available storage technologies

The stationary storage systems include those systems that either the structure or for their operation, require a fixed location for proper operation.
Inside this category we can identify different energy storage systems, primarily classified by the storage technology that is used:

- Chemical systems: they use chemical reactions to store energy, which in some cases require special attention during charge and discharge to avoid damage or simply to ensure a proper useful life. In this category are included all types of lead-based, lithium, sodium and nickel batteries usually used in industry.

- Electrostatic systems: in this category are included all those solutions that store energy using static electricity without chemical reactions; the most interesting solutions are those dictated by the use of supercapacitors, units that are able to store reduced quantity of energy, but with the advantage of having a high efficiency during charging and discharging as well as a long life characterized by many cycles of use, far superior to chemical batteries.

- Inductive systems: these systems are still in developing situation that present themselves as interesting solutions in case of large amount of energy that have to be managed in very short time. Unfortunately their constitution, based on the use of superconductors, turns out to be uneconomical at this time.

- Inertial systems: these systems are also a new concept in the electric management though is well spread their use as accumulators in mechanical systems (all the facilities that used at least one flywheel). Their use, associated with brushless motors and generators and magnetic suspension, transforms them into an attractive solution for the storage and subsequent generation of energy with high efficiency, low maintenance and a life expectancy of almost infinite use. Such systems are best suited as storage of medium/large capacity because in the small facilities the cost is currently still unfavourable.

- Water pumping systems: it's the procedure that now is more diffused to store the energy using the same plants of hydroelectric production. During periods of low consumption or when there is an over-production of energy or when it cost less, special pumps are used to transport the water again into the catch basin for a new use when needed. Some hydroelectric turbines can work also in reverse mode, as electrical generator using the water fall during production, or as pump using electricity during storage.

- Compressed air systems: using storage tanks, or in some cases underground quarries hermetically sealed, it possible to compress air inside them during periods in which there is electrical overproduction; when needed the compressed air is used by special generators to produce again electricity.

- Hydrogen systems: these systems are usually composed of two distinct units, a production and storage unit that use electricity to produce and store hydrogen, and the generation unit, the fuel cell, that use stored hydrogen to produce again electricity. Although in the last years the efficiency of fuel cells has increased significantly (> 70%), the generation and storage of hydrogen significantly reduce the total efficiency of the whole. On the other side the storage capacity is easily expandable at low cost using standard tanks currently used for LPG storage.

- Thermal storage systems (calories/refrigeration): the thermal and cooling generator powered by electricity, which typically use the technology of heat pumps, when properly sized and equipped with heat/fridge storage - even with phase change - can be used to store electrical energy as heat/cold that can be used after according to requirements of the load. These systems are very interesting because they use storage units that are already connected to the load requirements, however require that the load can be controlled.

In the following table is possible to see the main difference in the efficiency, energy and power density for the storage technologies above described:

Storage Type	Energy density [Wh/kg]	Power [W/kg]	Cell Voltage [V]	Min. Charging Voltage [V]	Average Efficiency [%]
Lead	30÷50	250	~2	2,3	<80
Ni-MH	60÷120	350	1,25	1,25	80
Li-ion	110÷160	400	3,7	3,7	90
Li-Po	130÷200	-	3,7	3,7	90
Ni-Zn	70	900	1,6	1,9	70
Va-ReDox	30÷50	170	1,4 ÷1,6	2	75÷90
SuperCAP	-	~10000	2,5÷125	-	90
H_2 Cell	-	100÷300	0,6	-	70
SMES	low	high	-	-	95
Flywheel Low Speed	2,8÷9,8	>25000	-	-	90
Flywheel High Speed	depending on ω, r, m	>25000	-	-	93

Table 1: Main storage technologies specification

3.2. The research and implementation

Thanks to the great participation of some villages of Aosta Valley Region, it was possible to find a perfect location to test the implementation of an approximation of VPS; multiple factors, such as village configurations, RES availability, communication systems availability, were analysed. The territory of Aosta Valley is 3263,25 km^2 and is principally mountainous. The most interesting pilot implementation founded was Saint-Denis (AO) , a scattered village in the centre of Aosta Valley, situated between 500÷1500 m a.s.l. and strongly facing south, 26 Km far from Aosta along the highway Aosta-Torino. It is characterized by sunny and windy weather condition that allow to exploit, with high efficiency, solar and wind production plants. The village is connected at the national grid line and the energy is provided by the Deval S.p.A. society, that is the main electric distributor in the region. In the village there is also a small number of private and public photovoltaic plants, for a total amount of 13,6 kW peak power; but the City Council, led by the Major, is very interested in themes like RES power supply and energy efficiency. Their aim to become a 100% RES village, is to develop in the near future:

- the already existing photovoltaic plants;
- the mini-micro hydroelectric (where possible because of the lack of exploitable big rivers);
- the wind power (cooperation with a private society to build on a territory owned by the municipality, a $3MW_{peak}$ big plant);
- the biomass CHP (ORC).

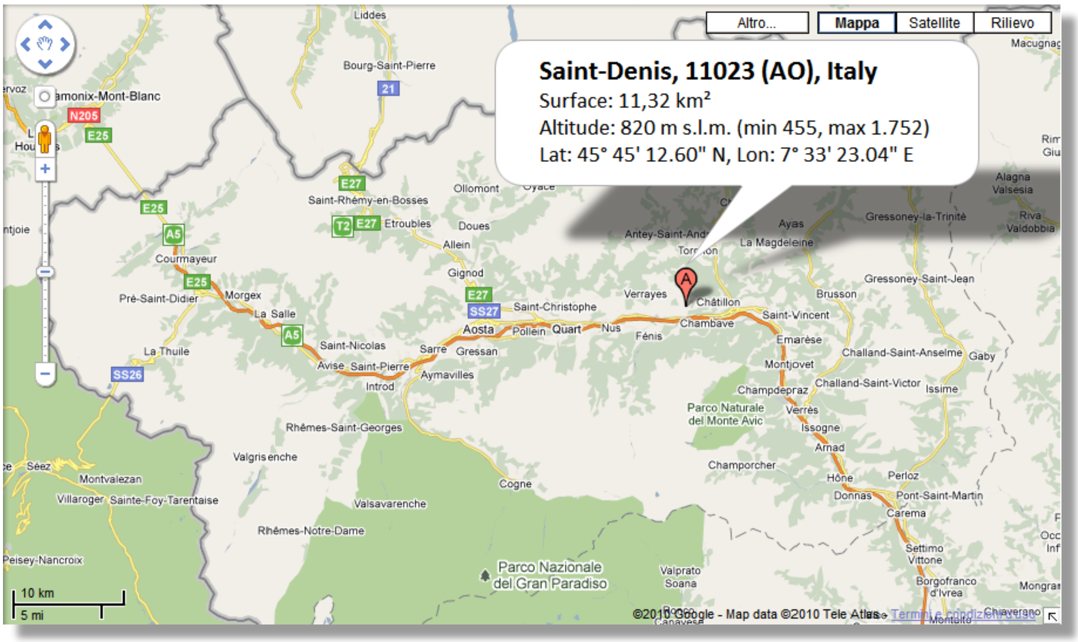

Figure 5: Saint Denis(AO) position on Google Maps

Details:

- 369 inhabitants (01/01/2009 - ISTAT) for a number 159 families (this is also the estimated number of electric users)
- 310 buildings
  - 221 single family buildings (13.680 m^2)
  - 81 multi-families for 221 apartments (12.339 m^2)
  - A total of 450 (26.019 m2) of 100.540 buildings in all the Aosta Valley
  - 85 non-civil building (school, church, small factory,...)
- Density is about 33 inhabitants/Km^2

The research activity aim is to explore the basic concepts for the implementation of a model of "soft" VPS (Virtual Power System), allowing on one side to analyse and monitor the production from renewable sources and the consumptions of Saint-Denis citizens, on the other side to check the availability of the user to embrace a new concept of efficient use of available energy resources.

The term "soft" indicates that the test doesn't interfere heavily on the electric infrastructures in the citizen utilities and it doesn't require modifications on the existing distribution grid, rather, it focuses on the interaction with the user who, responding positively to the warnings given him, will contribute, also with the energy storage system, to the so-called "Peak Shaving" (suppression of energy peak), operation requested by a VPS.

From the technological point of view the new concept of Virtual Power System is developed, considered the natural evolution of the energy production system, management and distribution.

Until now we have been a one-way energy flow from the production centers to final consumers. The VPS, that means the use of Smart Grid associated with distributed generation, local electric energy storage and the active management of the consumptions, allows the decrease of those obstacles that cause this ”one way-direction”.

In particular the research activity will interact with the user who, on a voluntary basis, contribute to the so-called "peak shaving", operation requested by a VPS system.

3.3. Power supply facilities and loads

To realize the Virtual Power System in Saint Denis, we have to understand which are the power facilities, the loads and the actual structures inside the area of our interest. Only after this we can start considering which are the first actions necessary to realize the entire system.

3.3.1. Power Generation

At the moment the village is connected at the national grid lines and the energy is provided by the Deval S.p.A. society, that is the main electric distributor in the region. At the moment there are 23kWpeak of installed power, more than one half in public buildings and other in private buildings. Considering only the public plant (private plants are not considered due to legal restrictions) is possible to consider a total amount of 13,6 kWp. In this location is estimated a year production of 1230 kWh with an installed power of 1kWp.
(source http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php)
Within the end of 2010 the municipality want to start the realization of a new photovoltaic plant with 315kWpeak power installed.

$$13{,}6\ kWp \cdot 1230 \frac{kWh}{kW \cdot year} = 16{,}728\ MWh/year$$

In term of load if we consider the average of electric consumption for every inhabitant that is 1495 kWh/year (statistic data 2008 from Terna S.p.A), we can find the total consumption for domestic sector of the whole village:

$$369\ \text{inhabitants} \cdot 1495\text{kWh/year} = \sim 552\ \text{MWh/year}$$

Other RES:

- Water: unfortunately inside the village of Saint Denis there isn't any kind of energy production derived from water and so we can't consider this type of power supplies for our VPS.

- Cogeneration: due to the difficulty to find the primary fuel to run a cogenerative power supply, at the moment there isn't any plants inside the village. But this solution is really interesting for a local regulation of power productions and for an emergency power supply in case of a lower production coming from RES.

3.3.2. RES update

When research activity started, it was already planned an evolution in the next future of the power supply facilities, with the real realization of the plant within the end of the project. The main update were:

- Photovoltaic Plant: realization of a power plant of 315 kWp (year production of 1230kWh for 1 kWp installed).

$$315\ kWp \cdot 1230 \frac{kWh}{kW \cdot year} = 388\ MWh/year$$

- Wind Plant: when project start there wasn't any wind turbines, but the municipality has rented an area to an external society that want to realize a new plant of 3 MWp in the earlier months after. At the end of the activity plant was available and completely working with 1400 equivalent hours of work every year.

$$3\ MWp \cdot 1400\ h/year = 4{,}2\ GWh/year$$

3.4. Load Estimation

3.4.1. Official estimation

Starting from information in the official Aosta Valley Regional Energetic Report (source BER 2006) an approximation of the local consumption can be obtained through the estimation.

Consumptions in the civil sector (1 tep=11,63 MWh):

- Gas: 33,61 ktep
- Solid: 0,15 ktep
- Oil: 101,32 ktep
- Other: negligible
- **Tot: 135,08 ktep**

Consumption in the civil sector: $135{,}08 ktep \cdot 11{,}63 = 1571 GWh$

Average consumption for building: $1571\text{GWh}/100540 = 15{,}62\text{MWh}/\text{building}$

Consumptions in families buildings: $15{,}62 MWh \cdot 450 = 7{,}03 GWh$

Minimum consumptions in non-civil buildings: $15{,}62 MWh \cdot 85 = 1{,}33 GWh$

Total consumptions: $7{,}03 GWh + 1{,}33 Gwh = 8{,}36 GWh$

3.4.2. Statistics estimation

Starting from consumptions evaluated through cube meter (source WEB):

Amount of energy needed to heat a class C building: 200kWh/m^2

$$200 kWh/m^2 \cdot (13680 + 12339) m^2 = 5{,}20 GWh$$

+25% for hot water production: $5{,}20 GWh + 20\% = 6{,}24 GWh$

Average energy needed to heat a class C building in 1 year considering 15MWh/buildings:

$$15 MWh/building \cdot 450 = 6{,}75 GWh$$

+25% for hot water production: $6{,}75 GWh + 20\% = 8{,}1 GWh$

The two estimation are quite similar and so at the moment it’s possible to consider an average consumption in civil buildings in the municipality of Saint Denis that is around 7 GWh without considering the non-civil buildings.

3.4.3. Electric Distribution Grid

With the collaborations of Deval, the regional energy distributor, it was possible to analyse the actual situation of the infrastructure inside the village, allowing us to understand the real distribution of the loads and the critical point of the grid. There was also the opportunity to share the result with other project developed by Deval. In this field the actions that are developed within the project are:

- Study and description of the characteristics of distribution net (cartographic data and Deval schemes).
- Operations on MT power lines (link with the project “Smart Grids” by Deval).

In the next map (schematics lines) and in the next page map the coloured lines indicate:

- **GREEN** – Medium Voltage Power Lines (5 to 25 kV);
- **RED** – Low Voltage Power Lines (3 phase 400V);
- **BLUE** – Road Lighting Lines (3 phase 400V);

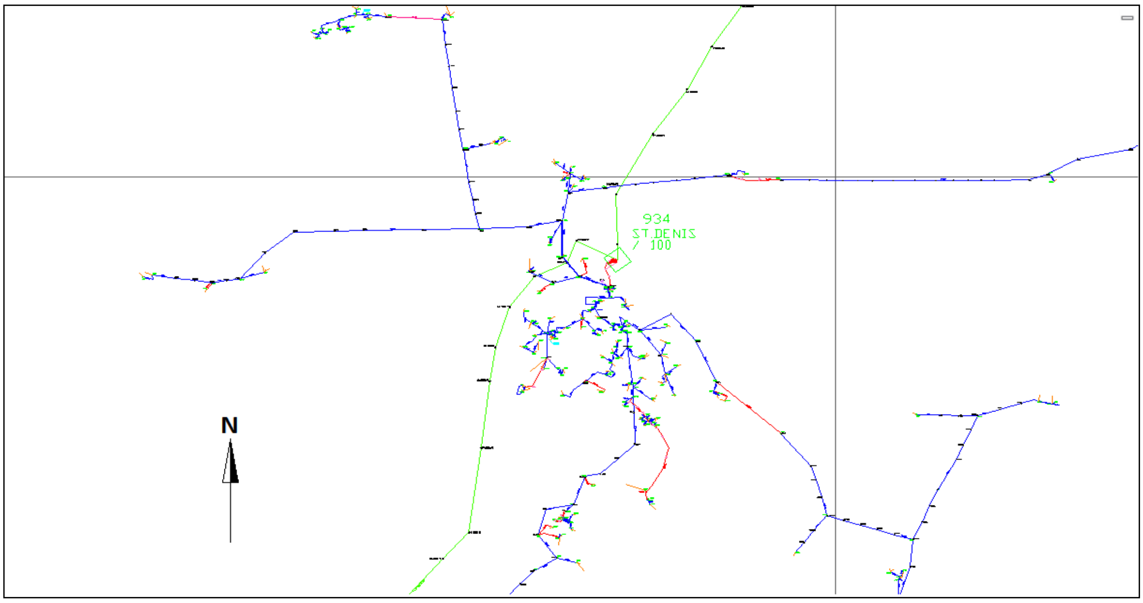

Figure 6: Topographic map of the lines (Courtesy of Deval SpA)

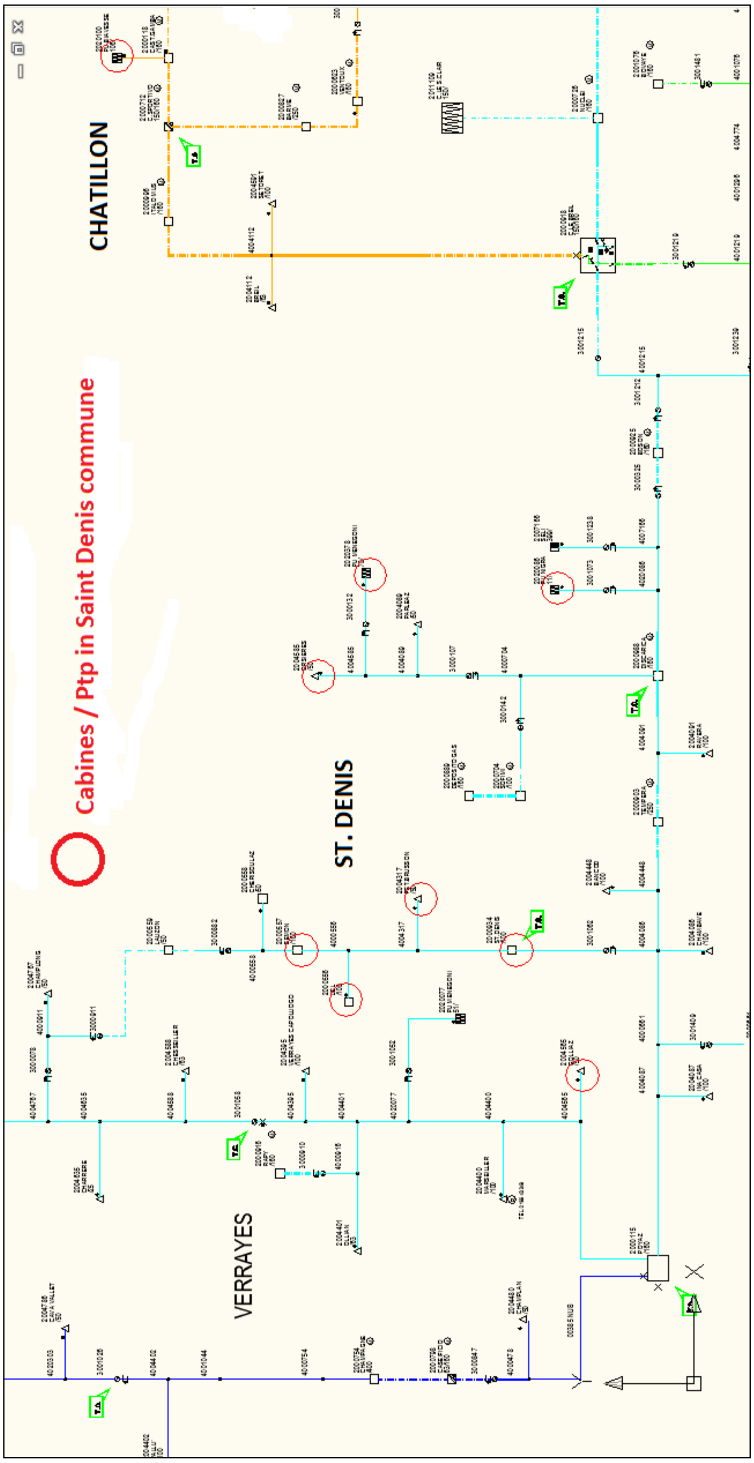

Figure 7: Saint Denis EDS nodes (Courtesy of Deval SpA)

Chapter 4 - Analysis and Simulations

Starting from the previous analysis the goal is to create a virtual model of the load inside the village using all the data available. Right now about 90% of the users in the municipal area are equipped with the electronic meter installed by the distributor, Deval S.p.A. the local DNO.. Thanks to this instrument, starting from the 1^{th} of June 2010 and for a period of one year, the monitoring data from about 425 electronic meters installed in Saint-Denis are available to be used for analysis.

Main research actions are:

- Monitoring and logging of home consumption in the village of Saint-Denis with the collaboration of DNO. Collection of the data of all 435 household and analysis of the more representative situations.

- Analyse characteristics of load an power plant actually available and future impact of upgrade on these plants;
- Identification of more representative loads (among them some municipal buildings) in which to install from Energy Management Unit (EMU) for a more detailed analysis.
- Study the better solutions for the information of the user about the electric energy consumption:

    - Consumption graphics by web interface
    - Direct alarm using the EMU
    - Information using SMS information
    - Possible use of dynamic costs for consumer sensitization

- Find solutions to interact with actual distribution grid in order to increase power quality without changing user consumption behaviour. This is done using a system, the ESS, able to modify autonomously the absorption profile of domestic buildings.
- Analysis of benefits from the introduction of a local storage system in combination with all the previous systems.

After the realization of the primary system is possible to select three types of user:

- Not informed or not motivated user;
- User that wants to know his consumption profile in the past month/week;
- User that wants to know his daily/real time consumption and agree to change his load profile according to the request of the VPS manager. These users are all volunteers, motivated by a public communication campaign with the collaboration of the municipality of Saint-Denis. Their participation is subjected to a load profile evaluation that will consider the standard consumption profile in order to not consider user that don’t reflect a standard consumption profile.

To all the informed users (only the small group where the Energy Management Unit is installed) are also provided some information about the status of his consumption, through Web interface, SMS alarms and display information. From this analysis is possible to understand which is the better solution (HW and logical) to give a feedback. Every user equipped with the EMU knows that, after the monitoring period, four of them can be selected for the implementation of the. The user obtain a system that provides a protection in case of over consumption without disconnection from the grid or a protection in case of blackout. This system also transforms an uncontrollable load like a private building into a load that can be autonomous respect to the grid for a short period.
Another important result is to find solutions for load regulation, not invasive for the final user, because today it’s not admissible to switch off remotely some loads without the permission of the customer.

4.1. Block scheme of VPS in Saint-Denis

Starting from the state of art analysis inside the village, it’s possible to imagine the ideal long term structure of the VPS and, starting from this one, the short term structure that we will implement in the project. First of all we have to start from the ideal long term structures to better understand the general configuration of the VPS: after this, considering all the aspects like budget, time limits, degrees of freedom of interaction with citizens, municipality and physical structures, we can start the implementation of the real system in the project.

It’s possible to divide the Virtual Power System into three groups:

- The Virtual Load Plants (VLP)
- The Virtual Power Plants (VPP)
- The VPS Control System

The Virtual Load Plants are the aggregation of all the loads present inside the village. It’s possible to divide this in two sub-groups:

- Public Buildings composed of all the structures of the municipality;
- Private Buildings composed of all the houses and apartments where families live.

We want to know all the consumption of these loads and where is possible send information about the real time status of the systems in order to manage the load request with the collaboration of the user.
If a load regulation is not possible due to any causes, it’s possible to install a storage system, dimensioned depending from the structures, where energy can be stored when available and then used during the emergency period.

In the Virtual Power Plants there is all the production of energy using renewable sources. All the plants are monitored to know the real time production and all the data are sent to the VPS Control System. In some cases it’s possible to connect in parallel to the generator a storage system: this configuration it’s useful to transform a discontinuous production of a RES into a continuous or less discontinuous controlled generator.

In the VPS Control System there are all the elements that decide which are the better management of the energy in order to ensure the energy provision when there are over consumption or under production. These decisions are taken using the data coming from loads, power supplies and using historical data about past consumption, production and weather forecasting. All the regulation are sent to the information panel or to the system that have to be controlled.

4.2. Simulation and expected results

Consumption data, useful for the analysis of the village behaviour, are obtained from all the 425 DNO's smart meter located throughout the territory.
The main simulation program (written in Matlab) allows the estimation of the required power to all 6 cabins located in the village in a period of time selectable by the user. The program will show the salient data for the period under consideration: the number of meters analysed, the number of days, maximum power, minimum and average. Then it displays two types of graph, "instant" and "averaged over the day," reporting on the horizontal axis the time (in hours), highlighting the transition from a day to the day after and from a week to week after, while on y-axis there is the value of the power in watts [W]. In this way behaviour of the network is simulated, and could be considered a full, or a part of, smart grid. However, the full study is possible only with another category of data, those of the energy provision from production systems or local storage systems.
Unfortunately, this kind of analysis isn't possible due to lack of measurement systems located throughout the territory, so the fast solution was to simulate also the energy production, considering all the declared characteristics of photovoltaic and wind power plants, both those already on the territory than those in phase of construction, and providing as input the anemometric and solar radiation data acquired by the weather station present in Raffort zone.
This solution permit to analyse the amount of energy produced by the entire photovoltaic plant, and report data as the peak power reached, the maximum and minimum energy produced and generate a plot of the PV production . Similarly the program analyses the anemometric data and extracts the energy production data for the 3MW wind farm under construction.
Finally, it studies the overlap of two patterns of production and consumption, 15 minutes after 15 minutes, going to estimate what is the requirement that the production system from RES could meet and what is the gap for which the distribution network had to provide.

In order to evaluate the effectiveness of different control functions aimed to shape the energy consumption of the village's domestic users, a preliminary analysis has been exploited. Respect to the preliminary analysis goals it has been chosen to analyse the energy consumption profile of only the Medium Voltage (MV) / Low Voltage (LV) transformer feeding the village center, available thanks to the DNO electronic meter solution, in order start from aggregate data and simplify and reduce the amount of data that have to be evaluated (there is only one transformer that feed all the village center).

The reported power flow take into analysis corresponds mainly to the domestic user and to some institutional building (city hall, school, library, etc.) due to the fact that in the village there aren't any industrial activities with relevant absorption and the only non-civil facilities are negligible.

Available data correspond to the transformer power flow from June to December, with a range from 10 kW up to 55 kW, with an increasing trend during the winter season, in particular the figure reports the energy consumption [kW] with a sampling time equal to 15 minute.

Actually the distribution network operator (DNO) has to operate the network with respect to the worst case scenario, consequently, for the electric system perspective one of the most useful VPS objective function is the "peak shaving".
VPS include demand side management function useful to correctly shape the final users consumption profile and a limited number of storage apparatus able to provide many auxiliary services as the energy back-up, regulation reserve, energy cost minimization, and so on.

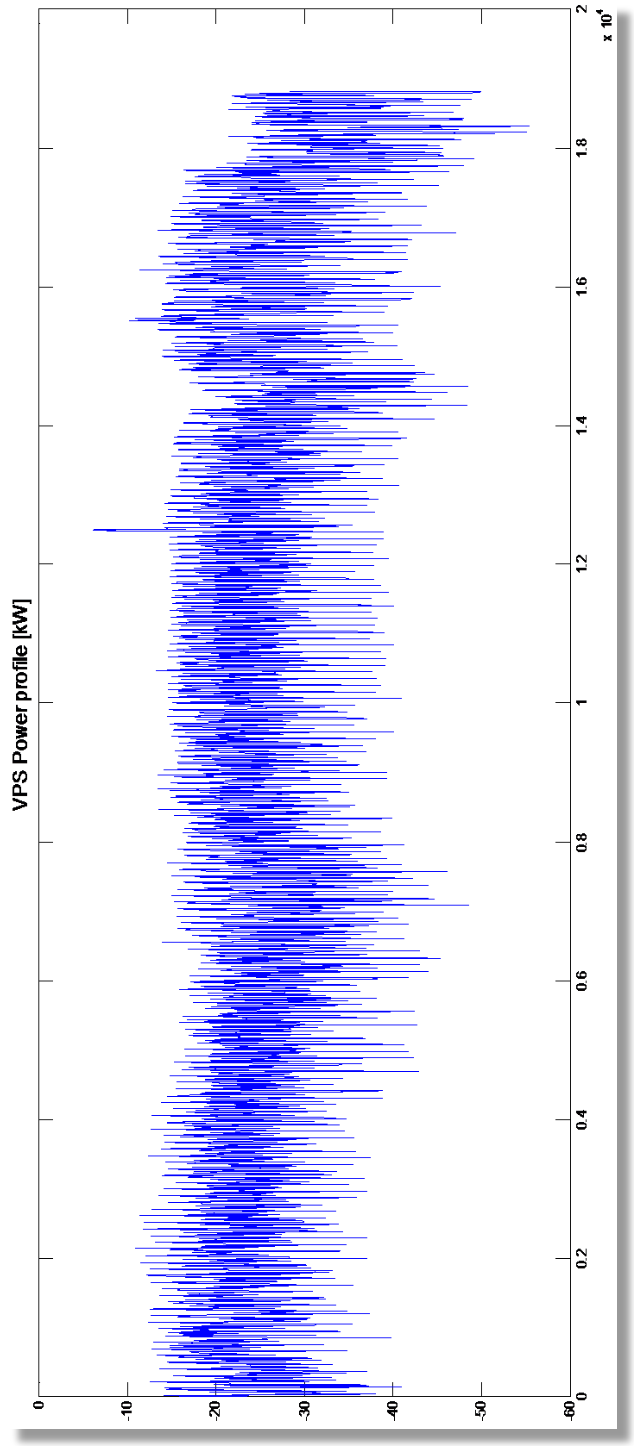

Figure 8: MV/LV transformer power consumption

With respect to the demand side management function it is quite complex to simulate the effectiveness in the final user feedback; for the preliminary design of the VPS, in the following the impact of storage apparatus has been analysed.

Figure 9 depicts, blue line, the MV/LV transformer power flow introducing, thanks to the storage apparatus, a peak shaving function set to 50 kW; red line correspond to the limitation introduced in the consumption i.e. the power injected by the storage devices, Figure 10 reports the same simulation for a target peak shaving equal to 40 kW.

Figure 9 and Figure 10 show the capability of storage devices in limiting the power peak in most of the situation, with some limits due to the saturation of the energy capacity bound, such saturation is more evident in Figure 11 where a peak target equal to 30 kW has been set.

In conclusion, VPS storage devices designed for a power equal to 5 kW and an energy equal to 5 kWh results to be adequate to obtain an effective peak shaving.

To appreciate the improvement achievable thanks to a greater storage devices, Figure 11 reports the same simulation introducing an apparatus double sized than the previous one (10 kW and 10 kWh), while Figure 12 depicts the energy stored in the devices for every time sample. Figure 12 clearly depicts a saturation of the storage devices also introducing only the peak shaving function.

In the real life application storage devices will be exploited with respect to different objective function in order to maximize the efficiency/economic improvements, the preliminary simulation here reported demonstrates the storage apparatus effectiveness in the power flows control, also for a device with a limited power/capacity, and, even more, demonstrates the importance of the VPS experimental application to collect data useful to evaluate the global economic cost (design cost, capital cost, maintenance cost, and so on), the benefits achievable (peak shaving, energy bill minimization) in order to better set the numerical simulation.

In the end it will be possible, crossing numerical simulation results and experimental data, to obtain a more clear picture, about pros and cons of the solutions under investigation.

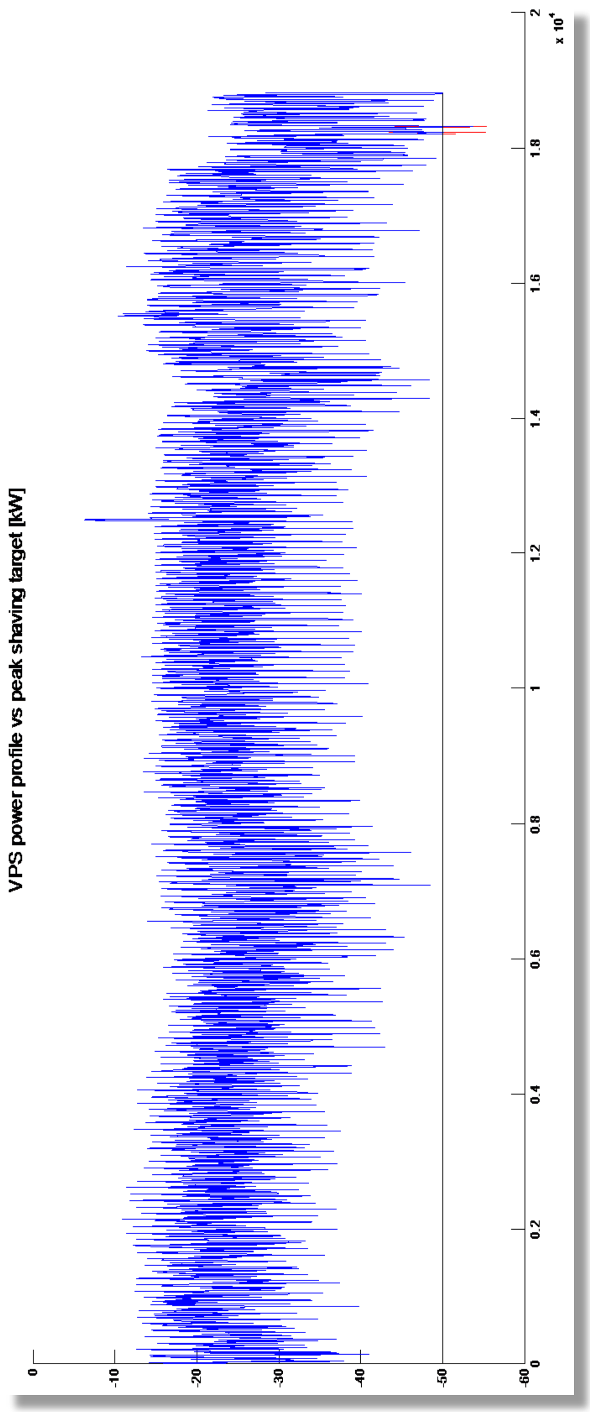

Figure 9: VPS power consumption profile adopting a peak shaving function with a limit equal to 50 kW (storage apparatus sized at 5 kW and 5 kWh)

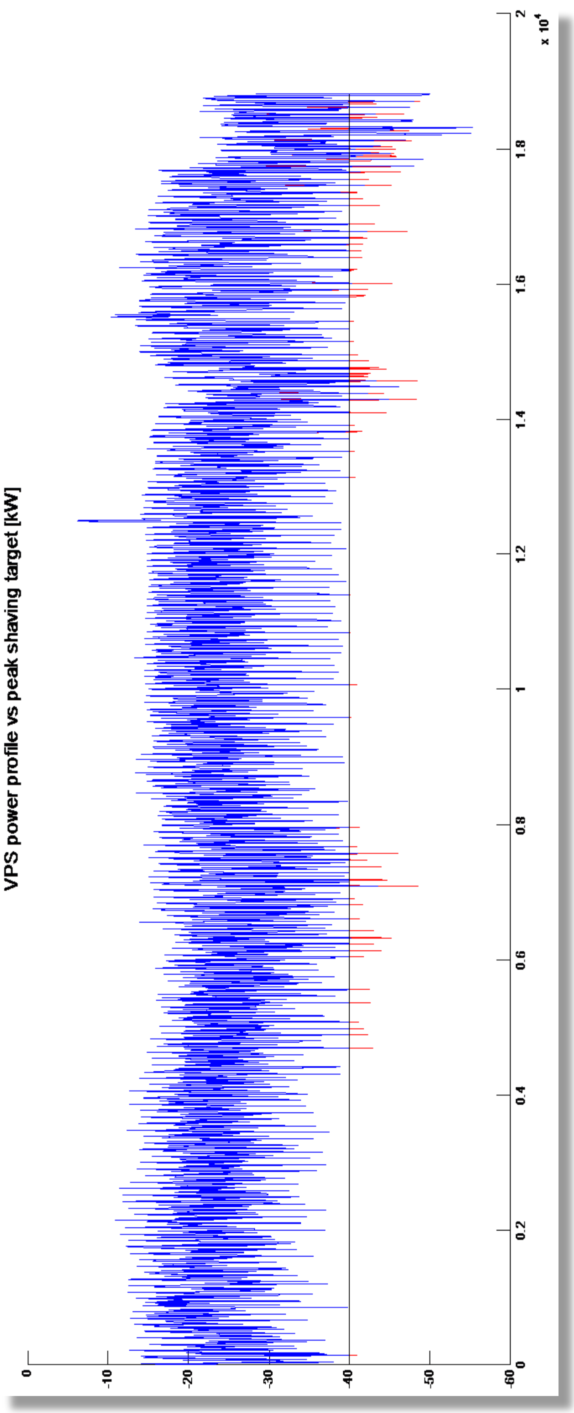

Figure 10: VPS power consumption profile adopting a peak shaving function with a limit equal to 40 kW (storage apparatus sized at 5 kW and 5 kWh)

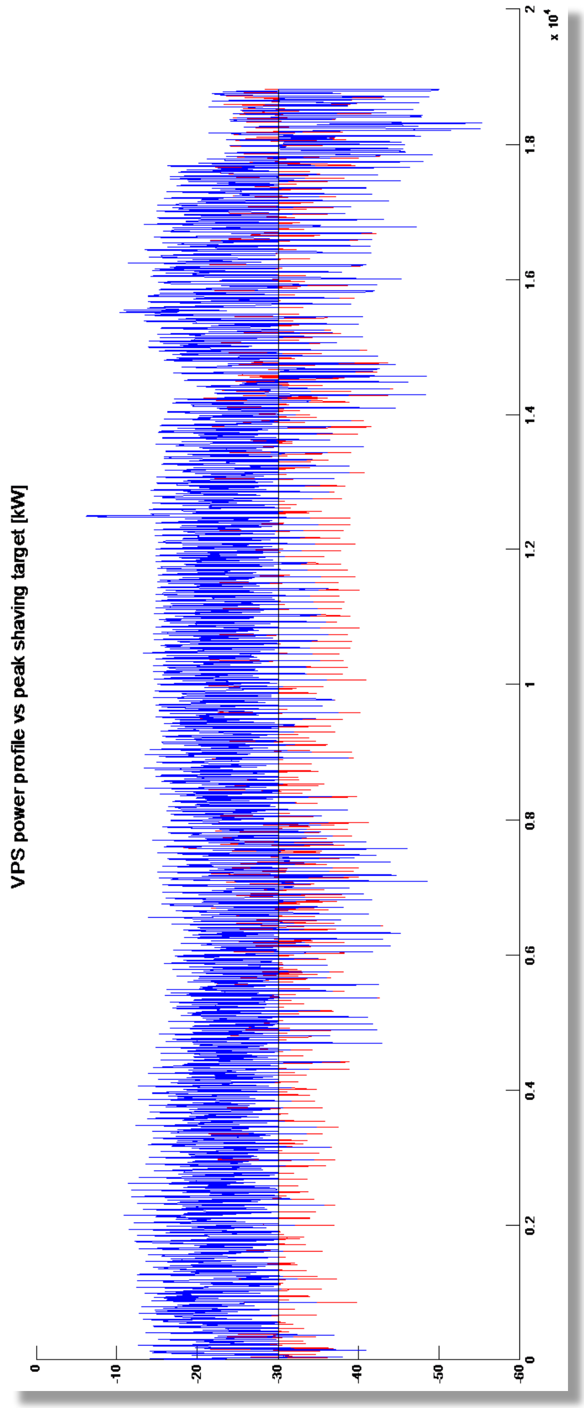

Figure 11: VPS power consumption profile adopting a peak shaving function with a limit equal to 30 kW (storage apparatus sized at 5 kW and 5 kWh)

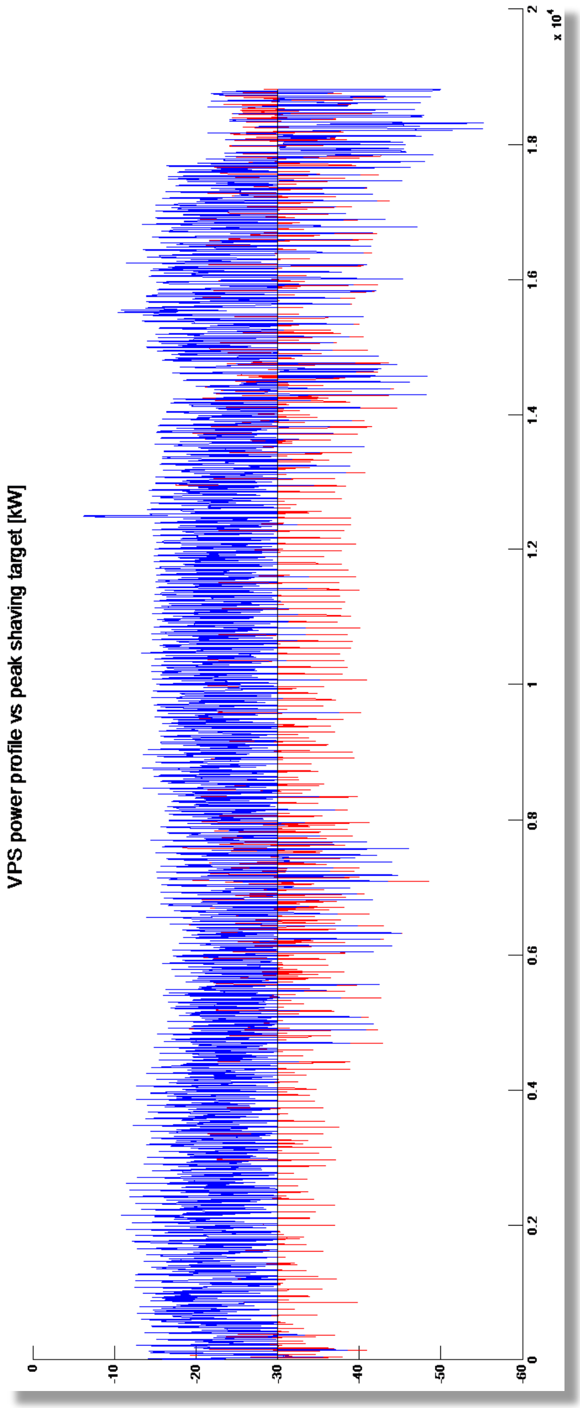

Figure 12: VPS power consumption profile adopting a peak shaving function with a limit equal to 30 kW (storage apparatus sized at 10 kW and 10 kWh)

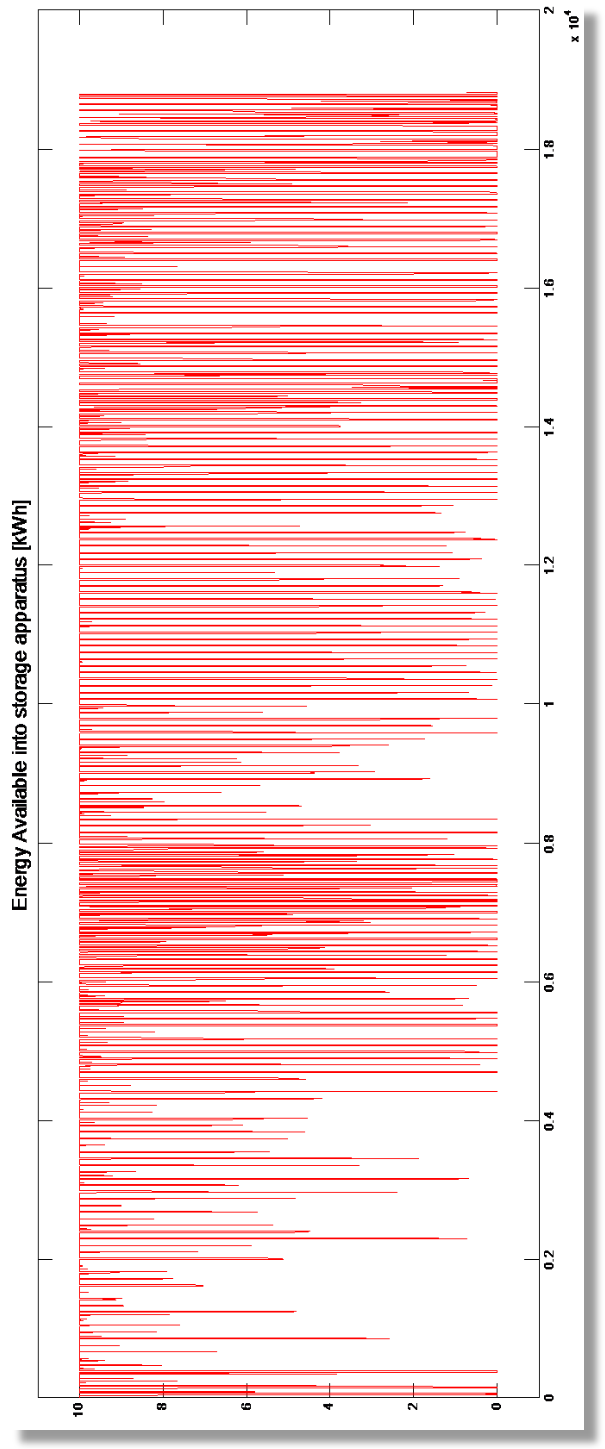

Figure 13: Energy available in the VPS storage apparatus vs time

Finally, to better appreciate the storage apparatus effectiveness on the global consumption peak shaving a more general simulation has been performed. On the database available, has been evaluated the number of days over a year with a global consumption correctly limited within the defined threshold, iterating the analysis with respect storage apparatus capability.
Table 2 depicts the results obtained setting a threshold equal to 30 kW, the lines represent the storage energy capability while the rows introduce the power capability. Actually, with a storage apparatus characterized by 5kW power and 5kWh capacity the power flow could be correctly limited for 248 days a year, considered to be a quite interesting results for a small scale application; nevertheless in the Saint Denis VPS storage apparatus will be coordinated with demand side management functions in order to improve the control action capability.

Storage Energy Capability [kWh] \ Storage power Capability [kW]	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
1	190	201	206	211	213	214	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216	216
1,5	190	201	206	216	219	222	226	227	228	228	228	228	228	228	228	228	228	228	228	228	228	228	228	228	228	228	228	228	228
2	190	201	206	217	221	227	232	234	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237
2,5	190	201	206	217	222	229	235	237	240	242	242	242	242	242	242	242	242	242	242	242	242	242	242	242	242	242	242	242	242
3	190	201	206	217	222	229	235	238	241	243	243	243	243	244	244	244	244	244	244	244	244	244	244	244	244	244	244	244	244
3,5	192	201	206	217	222	229	236	239	243	245	246	247	247	249	249	249	249	249	249	249	249	249	249	249	249	249	249	249	249
4	192	201	206	217	222	229	237	240	244	247	248	250	250	251	251	252	252	252	252	252	252	252	252	252	252	252	252	252	252
4,5	192	202	206	217	222	229	237	241	247	250	251	252	253	254	254	255	255	255	255	255	255	255	255	255	255	255	255	255	255
5	192	203	207	217	222	229	237	242	248	250	254	255	256	257	257	258	258	258	258	258	258	258	258	258	258	258	258	258	258
5,5	192	203	207	217	223	229	237	242	250	253	259	260	261	263	263	264	264	264	264	264	264	264	264	264	264	264	264	264	264
6	192	203	208	218	223	229	238	243	250	254	259	261	262	264	264	265	266	266	267	267	267	267	267	267	267	267	267	267	267
6,5	192	203	209	218	223	229	238	243	251	256	261	263	264	266	267	268	269	269	270	270	270	270	270	270	270	270	270	270	270
7	192	203	209	218	223	229	238	243	252	257	263	266	268	270	270	272	273	273	274	274	274	274	274	274	274	274	274	274	274
7,5	192	203	209	219	223	230	238	243	252	257	263	266	269	270	271	273	274	275	276	277	277	277	277	277	277	277	277	277	277
8	192	203	209	220	223	230	239	244	252	257	263	267	269	272	272	275	276	277	277	278	278	278	278	278	278	278	278	278	278
8,5	192	203	209	221	225	230	239	244	253	257	264	267	270	273	273	276	277	278	279	280	280	280	280	280	280	280	280	280	280
9	192	203	209	221	225	231	239	244	253	258	265	269	271	275	277	281	282	284	284	285	285	285	285	285	285	285	285	285	285
9,5	192	203	209	221	226	231	240	245	254	259	266	269	273	278	281	285	287	289	290	290	290	291	291	291	291	291	291	291	291
10	192	203	209	221	226	232	240	245	254	260	267	270	274	279	283	287	290	291	293	293	293	294	294	294	294	294	294	294	294
10,5	192	203	209	221	226	232	241	246	254	260	267	270	275	281	285	290	292	294	296	296	296	297	297	297	297	297	297	297	297
11	192	203	209	221	226	232	241	246	255	260	267	271	276	282	286	292	295	298	300	300	300	301	301	301	301	301	301	301	301
11,5	192	203	209	221	226	233	241	246	255	260	267	271	277	284	288	294	297	300	303	304	304	304	304	304	304	304	304	304	304
12	192	203	209	221	227	233	242	247	255	260	267	271	277	284	289	294	297	301	304	305	305	305	305	305	305	305	305	305	305
12,5	192	203	209	221	227	233	242	247	255	260	267	271	277	284	289	295	298	302	304	306	306	306	306	306	306	306	306	306	306
13	192	203	209	221	227	233	242	247	255	261	267	271	277	284	289	296	299	303	305	306	307	307	307	307	307	307	307	307	307
13,5	192	203	209	221	227	233	242	247	256	261	268	271	277	284	289	296	299	303	306	308	308	309	309	309	309	309	309	309	309
14	192	203	209	221	227	234	242	247	256	261	268	272	277	284	290	297	300	304	307	309	310	310	310	310	310	310	310	310	310
14,5	192	203	209	221	227	234	243	248	256	261	268	272	278	285	291	298	302	306	309	311	312	313	313	313	313	313	313	313	313
15	192	203	209	221	227	234	243	248	256	261	268	272	278	286	291	298	303	307	310	312	313	314	314	314	314	314	314	314	314
15,5	192	203	209	221	227	234	243	248	257	261	268	272	278	286	291	298	303	307	311	313	314	315	316	316	316	316	316	316	316
16	192	203	209	221	227	234	243	248	257	262	268	272	278	286	291	299	303	308	311	314	315	316	317	317	317	317	317	317	317
16,5	192	203	209	221	227	234	243	249	257	262	268	272	278	286	291	299	303	308	311	314	315	317	317	317	317	317	317	317	318
17	192	203	209	221	227	234	243	249	257	262	269	272	278	286	291	299	304	309	312	315	316	318	318	318	318	318	318	318	318
17,5	192	203	209	221	227	234	243	249	258	262	269	272	278	286	291	299	304	309	313	316	317	318	319	319	319	319	319	319	320
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20,5	192	203	209	221	227	234	243	249	258	264	271	274	280	288	294	302	306	311	316	318	321	323	324	324	324	324	324	325	325
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21,5	192	203	209	221	227	234	243	249	258	264	271	275	280	288	294	302	307	312	317	319	322	324	325	325	326	326	326	327	327
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22,5	192	203	209	221	227	234	243	249	258	264	271	275	281	288	294	302	307	312	317	320	323	325	326	327	328	328	328	329	329
23	192	203	209	221	227	234	243	249	258	264	271	275	281	289	294	302	308	313	318	321	324	326	328	329	330	330	330	331	331
23,5	192	203	209	221	227	234	243	249	258	264	271	275	281	289	295	303	308	315	319	322	325	327	329	330	331	331	331	332	332
24	192	203	209	221	227	234	243	249	258	264	271	275	281	289	295	303	308	315	319	322	326	328	329	330	331	332	332	332	333
24,5	192	203	209	221	227	234	243	249	258	264	271	275	281	289	295	303	309	315	319	322	326	328	330	331	332	333	333	334	334
25	192	203	209	221	227	234	243	249	258	264	271	275	281	289	296	303	309	315	320	322	326	328	330	331	333	333	333	334	335

Table 2: Peak Shaving Effectiveness vs storage apparatus capabilities

4.3. Consumption

Using the consumption profiles created by sampling the loads we started the construction of the simulator for the VPS analysis. By simulating numerically the system, we want to get a result to be compared with laboratory tests and with the analysis of data coming from the same data logger of the systems, verifying in this way the real goodness of the models.

Starting from the analysis of DNO's smart meter data sampled along one year, starting from June 2010 till to June 2011, a first approximation of the power required by all the loads in the village is obtained:

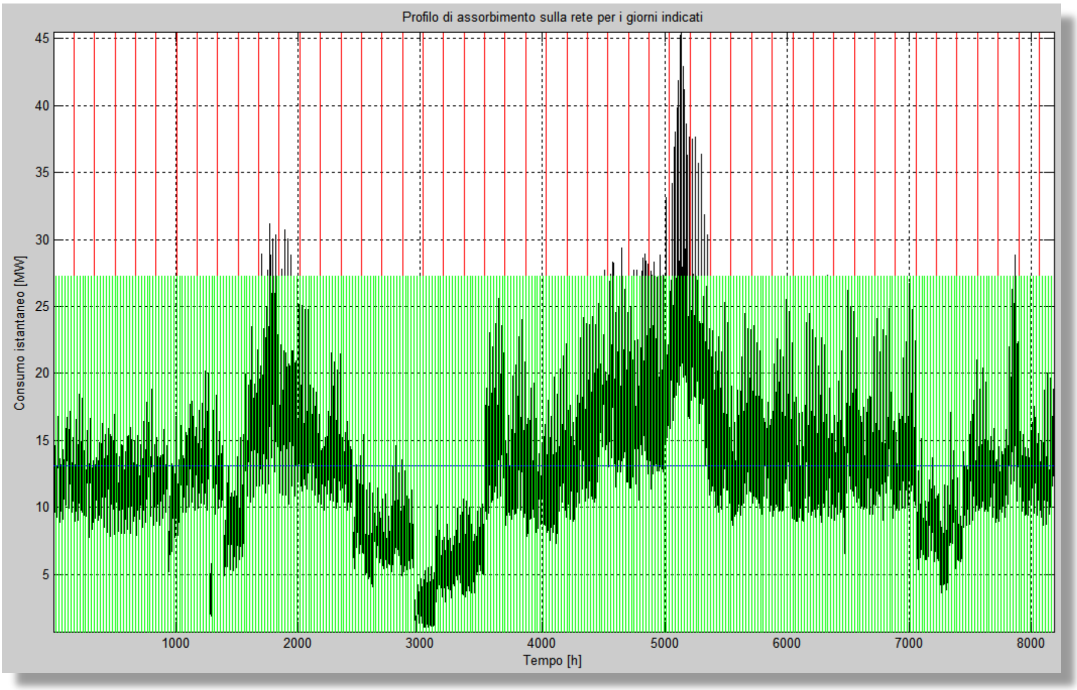


Figure 14: Complete simulation of villages consumption profile

It's possible to see that the consumption are related not only to the users' behaviour but also to the seasonal period during year; the consumption is lower during summer (in mountain nobody use air conditioning) and higher during winter, reaching more than 45kW of absorption respect to the year average of about 14kW.

4.4. Wind simulation

Using data collected from the automatic weather station sited close to the area where the wind mill was realized, Blavesse locality, the theoretical production of the 3 MW turbines is simulated. When simulation were realized the real wind plant was under construction so was not possible to use the real data of power production.

According to the below profile is possible to see that the main production is during summer, spring and first part of autumn due to seasonal wind stream with a great reduction during winter. The average production along the whole year is around 250 kW÷300 kW, 10% of the power installed. To better appreciate the difference between the higher and lower production, if we consider a summer month, between July and August, and a month during winter, across January and February, there is a decrease of energy production of 85%, from 313 MWh to 45 MWh, also if in summer there are still some spot of high power production.

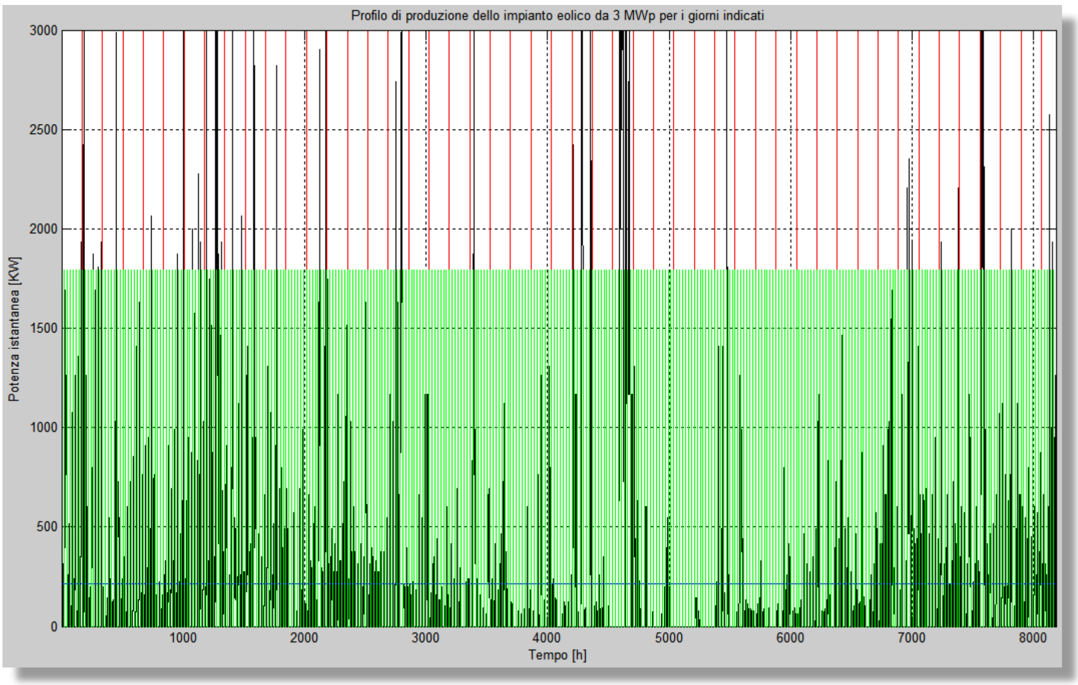


Figure 15: Complete simulation of wind production

4.4.1. The real plant

Figure 16: The real wind turbine after realization in Saint Denis (AO)

The wind turbines are V52-850KW have a nominal power of 850kW for a whole power installed of 2,55MW. According to the real characteristics of the wind along the year, a production of 4590MWh is calculated, so quite the same of the amount estimated with the simulation. Each tower is 55m high with a windmill blades diameter of 52m and 90 tons of whole weight.
Plant is located Puy de Saint-Evence site (1.334m÷1.417m a.s.l.) in Saint Denis(AO).

4.5. Photovoltaic simulation

As the previous case also the production of the 315 kW photovoltaic power plant, that the municipality of Saint-Denis want to realise Derochà locality, is simulated.

Using values sampled by solar sensor in the Raffort weather station the following profile is obtained:

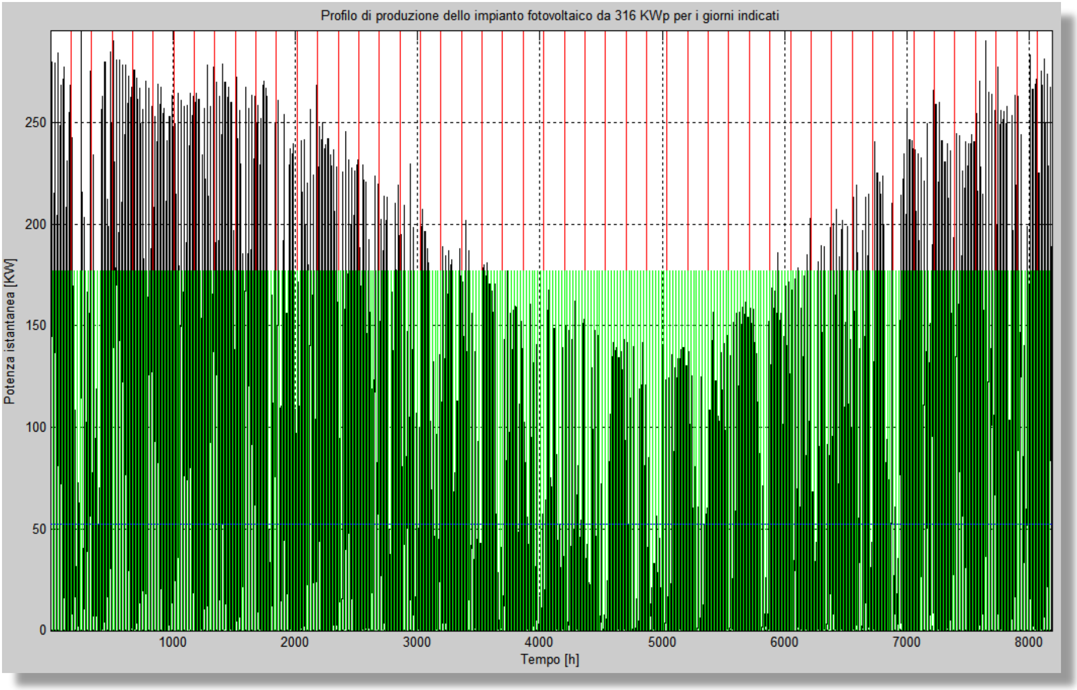


Figure 17: Complete simulation of photovoltaic production

It's immediately clear the difference between summer and winter production (middle of the graph) where production is about one half of the maximum production of the summer. The best production is estimate around 290 kW with 315 kW of power installed.

Analysing the same period used in the comparison before, there is a great difference between summer and winter production. During summer the plant generate a maximum of 63 MWh, in winter only 14 MWh, with a total decrease of 77% of energy production.

4.6. The bidirectional energy flow

In this case the program analyse the overlap between production and consumption, making between them an arithmetical difference, 15 minutes after 15 minutes, and so estimating the energy injected in the grid by RES production systems and the gap with the distribution network. If we consider to supply the village of Saint Denis using only the two renewable plant previously described, there is the necessity to satisfy two main aspect that required attention:

- The energy produced is more than enough for the only village of Saint Denis, reaching a value of 40 times more than what is really necessary; so there is a big overproduction that have to be managed in a correct way.

- The two generation plant are not enough to satisfy the request of energy of the village without a proper storage to afford a correct supply during period of lower or no production. These storage have to consider not only the daily request of energy but also the seasonal difference between the maximum and minimum production. If we consider a distributed storage system in each village. It’s possible to supply with only these two plant more than 30 village like Saint Denis.

Considering the worst period of the year, winter time, and creating a direct comparison between production and consumption, there is an important difference between night and day profile. Taking a look to the graph, part of the curve is under the zero threshold, that mean that a lot of energy should be provided by the national network especially during night.

In this case 10 MWh of the 15 MWh required should be provided by the national grid; in the same period, especially during the day, we would have an inversion of the energy flow, i.e. 53 MWh of 59 MWh produced, would be injected into the net.

During summer period instead only 2,3 MWh of the 8,9 MWh required by the load are provided by the national grid (only 25% against the previous 66%) in fact in this period the wind activity is much more important than in winter and also the daily "window" of sunny hours is larger (15h instead of 8h) and so with a major coverage of consumption, in the early morning and in the evening, from the energy point of view. Finally, especially during day, we note an inversion of the energy flow i.e. 370 MWh, of 377 MWh produced, injected into the net.

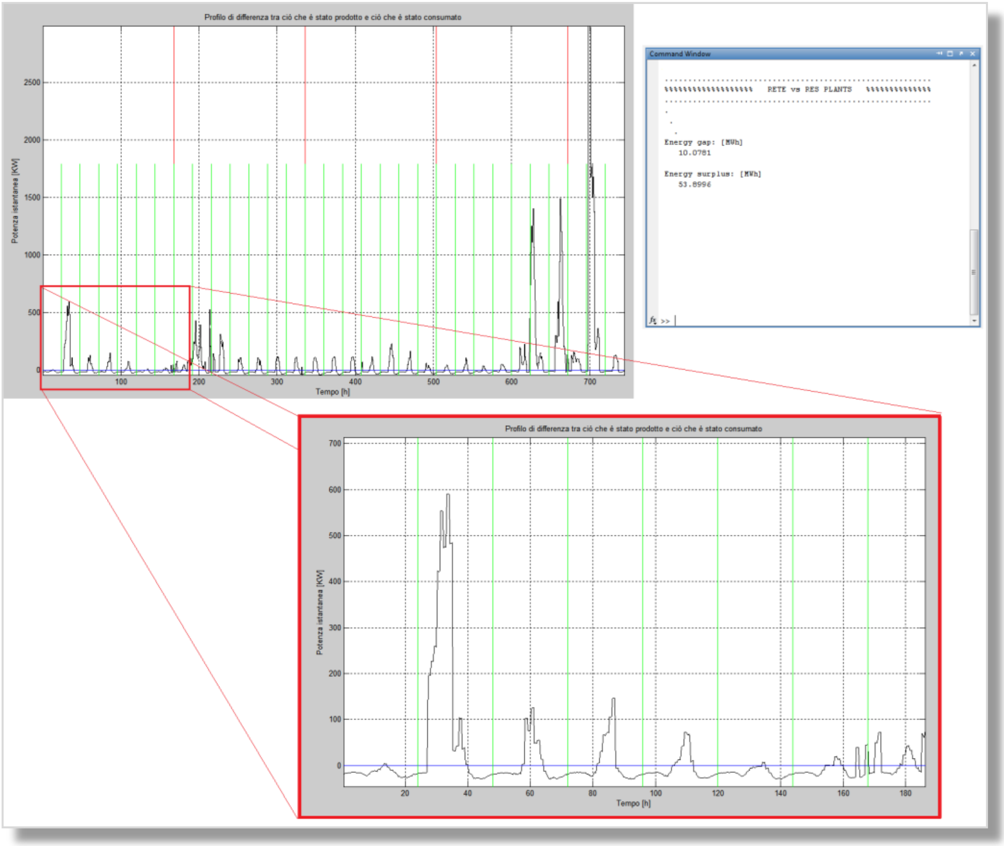


Figure 18: Village winter simulation, consumption vs production profile

In conclusion without a storage that during day store the energy request, during night there is an increase of energy flow requested from grid and the consequent energy losses in conversion and transport for distribution. Analysing the entire year of consumption and production and comparing these results with the initial estimation we can observe that the energy consumption in the village (only domestic) is very different:

- Estimation: 369 inhabitants · 1495kWh/year = ~552MWh/year

- Simulation: ~115MWh/year

The big difference between these two values, it may depend on several reasons:

- The fact that in the village there are a lot of holiday houses, and then the real number of people that leave all the year is less than 369;
- Another similar reason is that the number of the inhabitants is 369, but divided in 159 families; so the real amount of the energy consumption is ~780kWh/year instead of1495kWh/year previously estimated.
- Another problem for the simulation is the high quantity of power data lost in the period: some user have only 8 days lost over 341, but in other case this value increases to 205 days lost over 341, with an average value of 30-40 days lost for each user. The program takes note of these wrong values but converts every data lost in a 0W value, that means "no consumption", resulting for the final analysis an error that have to be always considered.

So, to optimize the simulation result, we need a consumption database as much complete as possible. However it's quite good to obtain an idea of the whole consumptions in a short and well determinate period.

If we consider the actual production from RES and the new power plant, the village will produce a 100% of the energy from RES without using hydroelectric plant (also mini and micro hydroelectric):

- Actual photovoltaic production: $13{,}6\ kWp \cdot 1230\ kWh = 16{,}728\ MWh/year$
- Future photovoltaic production: $315\ kWp \cdot 1230\ kWh = 388\ MWh/year$
- Total Power Production: $16{,}8\ MWh + 388\ MWh = 404{,}8\ MWh$

If we consider the average of electric consumption for every inhabitant that is 1495 kWh/year, we can find that the only production from photovoltaic is inadequate. The consumptions, only in the domestic aim, are the 36,3% greater than the production. But if we consider also the production from the wind farm the situation changes:

- Wind production: $3\ \mathrm{MWp} \cdot 1400\ \mathrm{h/year} = 4{,}2\ \mathrm{GWh/year}$

Total Power Production from RES:

$$16{,}8\ \mathrm{MWh} + 388\ \mathrm{MWh}\ + 4200\mathrm{MWh} = 4604{,}8\ \mathrm{MWh}$$

In this case we have that the consumption is 12% of the production and we have the 88% (about 4 GWh/year) of electric over production that can be used to supply local factory or that can be sold to the national grid.

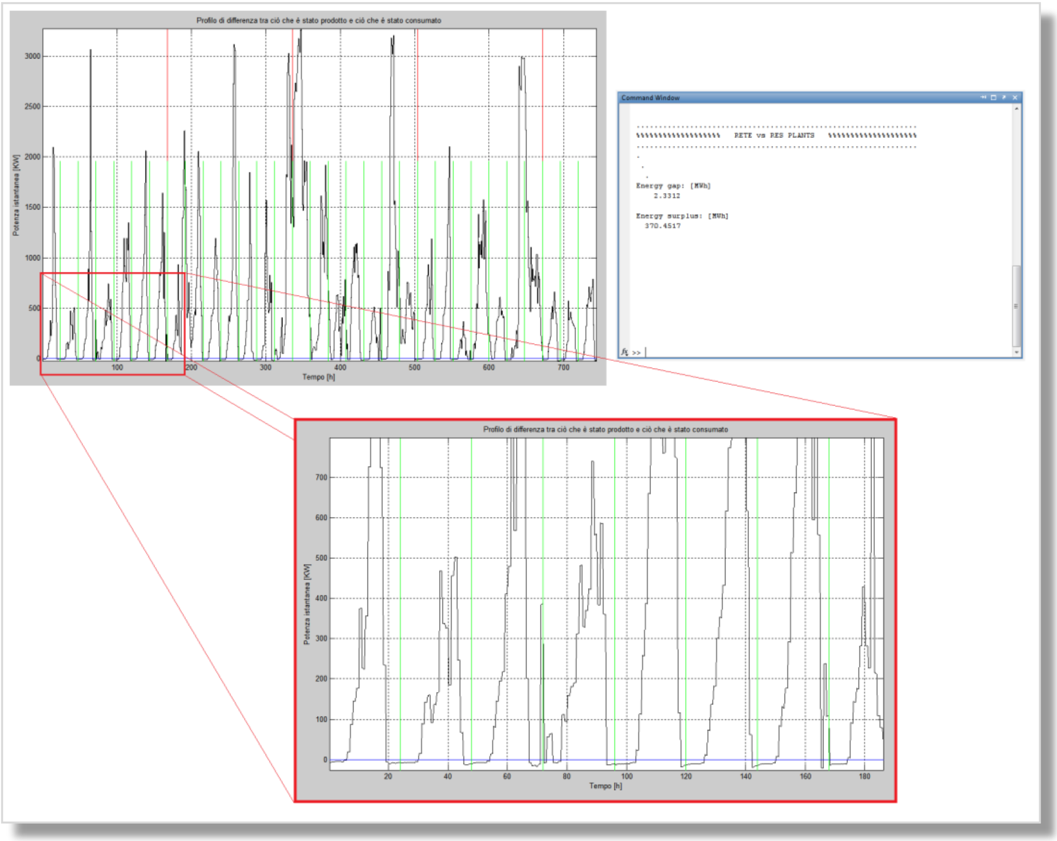


Figure 19: Village summer simulation, consumption vs production profile.

NB: All the simulations till now are realized using DNO's data collected with standard smart meter installed for each grid customer. For the next evaluation and simulation of the distributed storage systems a more detailed profile related to the energy absorption is necessary. For this reason it was necessary to install specific data logger able to sample power consumption every 5 second. More detail are explained in the next chapter.

4.7. Storage system simulation

The last kind of simulation realized regards distributed storage system, that deeply characterized and distinguished the research activity and the pilot implementation.
This system, thought to be interposed between the user and the electronic meter, has the ability to lighten the network in case of overload, ensuring a good supply of energy for the citizens, both in continuity and in quality of service. When consumption remains below a predetermined threshold of absorption, programmed through a relay which includes a current monitor, the user is connected directly to the national grid and the energy is drawn directly from this; when the threshold is exceeded, the system switches to the auxiliary system, with the activation of the inverter that compensates the energy requirements above the threshold drawing it from batteries.
If the power consumption falls below the threshold imposed the user returns to draw power directly from the network and the batteries are recharged, ideally during lower energy cost hours or when, in the local network, there is a surplus of energy produced from renewable sources.
The Energy Storage Systems developed, realized and then installed in the civil houses of the St. Denis village are first-generation prototypes that are designed to make the load levelling or peak shaving to a well determined level of power, and indirectly they provide the function as UPS in case of power failure. They are designed according to some parameters resulting from a previously analysis of users' consumption profile developed with software analysis and depending on the characteristics of the internal components like batteries, battery chargers and inverters. Detail on design, specification and implementations are reported in the next chapter.
Considering that is not possible to develop and distribute more than 400 ESS for all the village, we decided to build and test only 4 ESS and to simulate all the distributed storage as previously done with consumption and production from RES plants. The calculation is more or less similar, but considering also these active elements in parallel between load and net. The effect is a modification in the shape of the absorption curve: from very "nervous" to quite continuous.

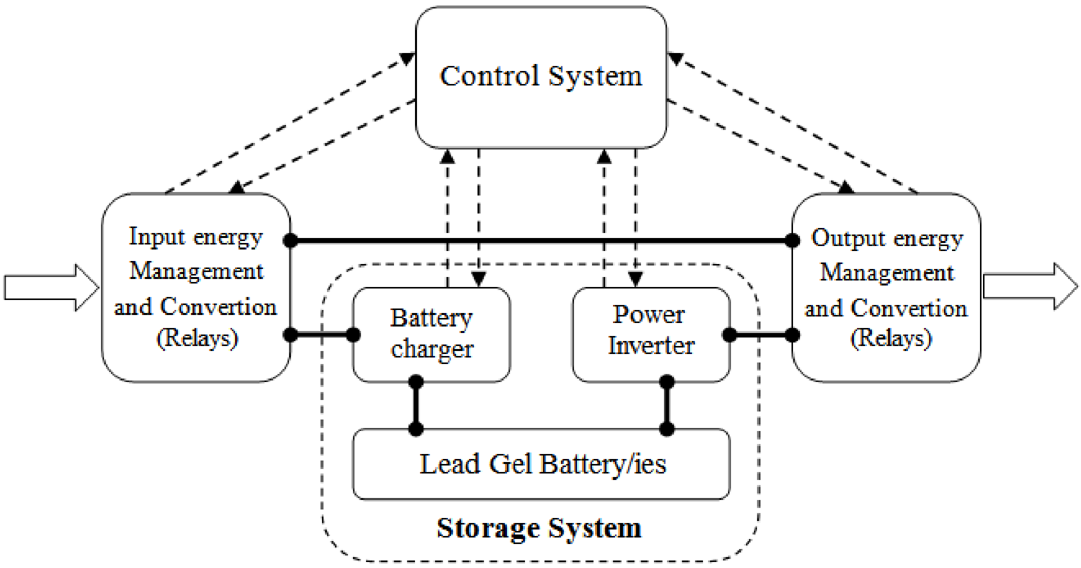


Figure 20: Logical scheme of an Energy Storage System

Using consumption profiles obtained by sampling the utilities, the construction of the storage systems simulators started. By simulating numerically the system, we wanted to get a result to be compared with laboratory tests and with the analysis of data coming from the same data logger of the systems, verifying in this way the real goodness of the models.

As a first step, the analysis system initializes the main parameters imposed as the system efficiency during charge and discharge, the minimum charge which we want to maintain inside the storage system and the initial charge which the system have to be when the simulations starts. After this, the program continues with the upload of consumption data from the database into local variables: by analysing an initial vector that defines the sequence of profiles to simulate, these are assembled consecutively in a single vector as if you have to analyse a single profile that consists of several samples of the daily ones:

1 day	→	~40000 values
2 days	→	~80000 values
.....	→	.....

1 week	→	~280000 values
…..	→	…..
1 month	→	~1200000 values

The voltage value is set equal to the average of the voltages of all the selected profiles. Next step is to convert the current and voltage values in the "real" power consumption values, using appropriate correction techniques to compensate the errors introduced by measurement instruments and by discretization.
Using the results obtained previously, is now possible to simulate the behaviour of the storage system, setting as main parameter the cutting power beyond which the system must take action.

4.7.1. Simulation

The Matlab program starts managing the 6 matrix of consumption data, these are the values that can't change after the simulation: the idea is that the user doesn't realize the presence of ESS and its functioning, theoretically they must continue behaving as before the introduction of ESSs. What will change is the consumption seen from the national grid that expect to be limited to a quite fixed value near the average consumption of the utilities.
From simulation is expected a great reduction of power absorption peaks and an increase of the energy consumption respect to standard condition; that is the energy needed to maintain the batteries charged. The storage simulation regards single load or the entire VPS, considering that every house has the same type of ESS. As in previous simulations, selecting the time period, program provides the peak power, average power, energy consumption of the load, energy delivered by the net and finally a graph made of three curves:

- Energy delivered by the net;
- Energy required by the load;
- Energy stored in the ESS.

By setting the power cut that you want to absorb from the network, the maximum energy amount of the storage system and the level of initial charge, the program performs the all the simulation printing on the screen the main data from the analysis and a plot, as shown in the figure below, where you can find the profiles of:

- consumption without accumulator
- "charge/discharge" of batteries
- uptake in the presence of the network storage system

The two following examples show an example of ESS simulation:

- Simulation of 117 users under the n.6 cabin (Semon), days from 01/08/2010 to 31/08/2010

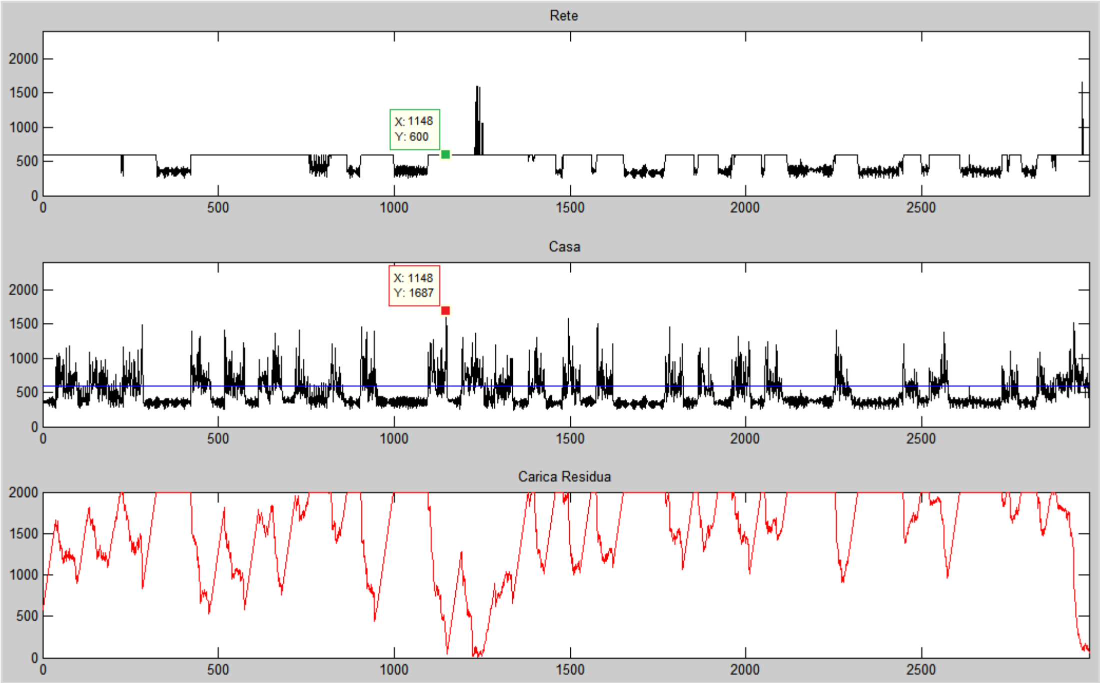


Figure 21: Energy profiles under ESS action – TOP = power request to the EDS, MIDDLE = power request from load, NOTTOM = battery SOC

It's clear the peak shaving effect in the ESS graph related on the curve of power required by the load. In the maximum power peak point of the period (1687 W) it's measured that the maximum request form the grid is constant and equal to 600 W, no more. This happens also if the power peak is 2000 W or 3000 W, but the discharge time of the storage system is the only thing that will change; in the example, considering those moments of maximal peak absorption the discharge time is about 6 hours, considering that the ESS is designed to guarantee a maximum power of 5 KW continuously for 15 minutes.

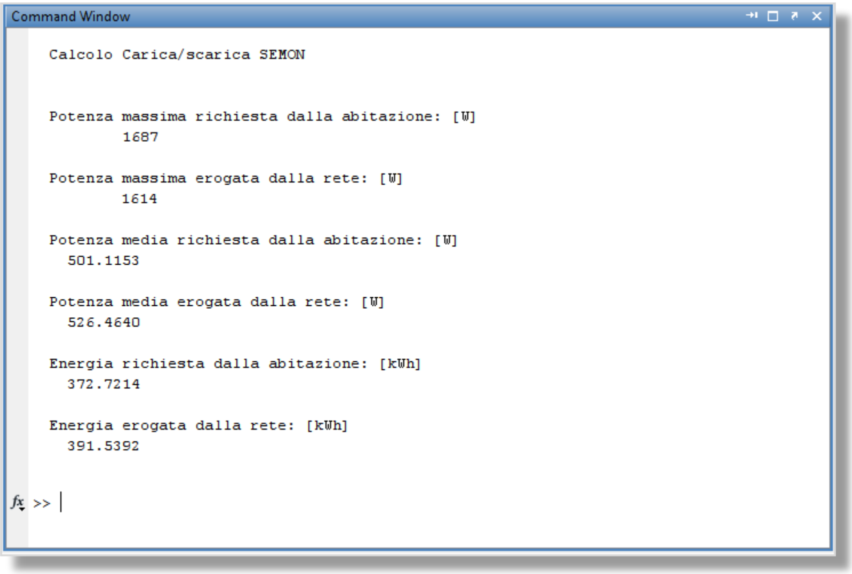


Figure 22: Numerical simulation

Is possible to extend the analysis to bigger period and considering more utilities; the analysis of the entire Saint-Denis VPS using all the 417 meters data along the 341 days (from 1/06/2010 to 7/05/2011) is showed in the following graphs.

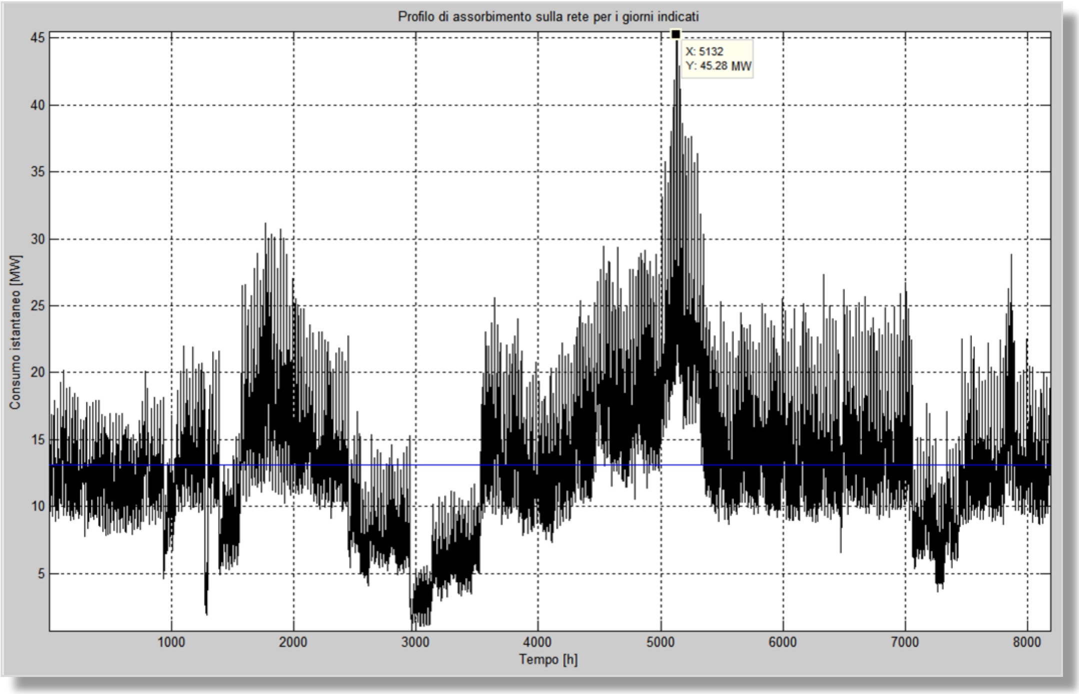


Figure 23: Absorption profile without ESSs

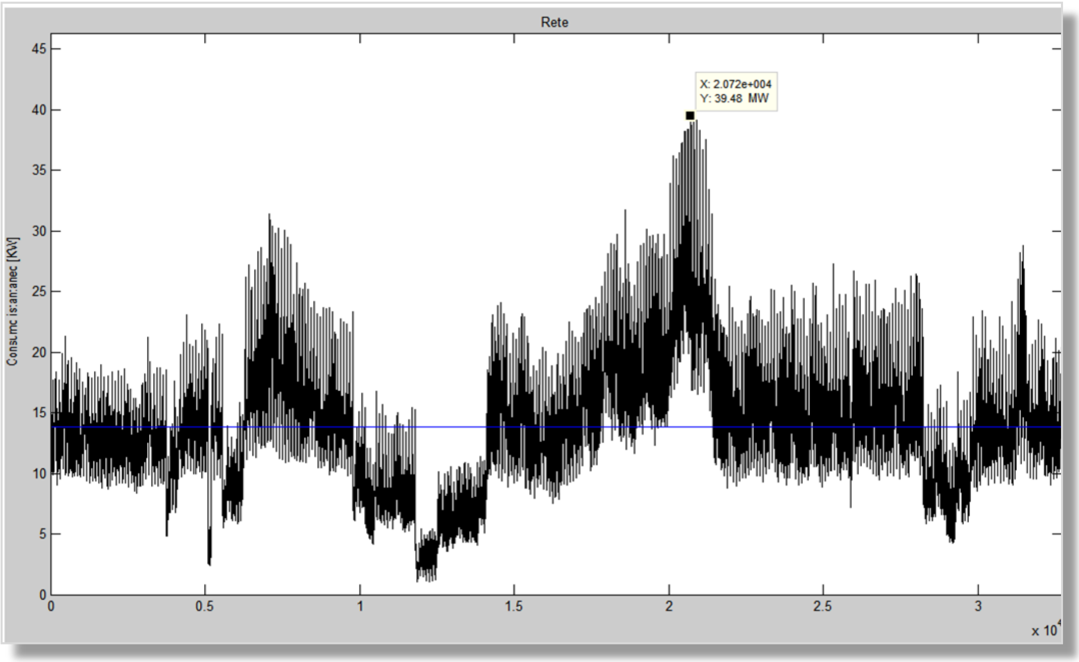


Figure 24: Absorption profile with the ESSs

These two graphs show the difference between the actual situation and a future possible situation where every house could have a smart storage system inside to help the management of the load on the net.

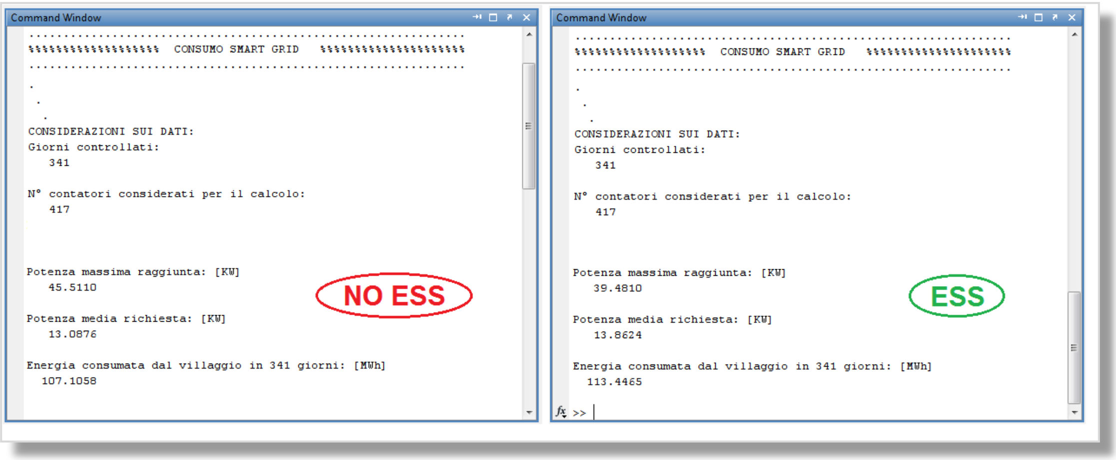


Figure 25: Data comparison between actual case and future case with storage

Considering system like the ESS distributed in each families, the main result is a **-13%** of peak power required from the grid by the load, with an increase of energy used of **+5.5%** due to the quite constant charge of batteries, operation which is afflicted by losses in the energy conversion.

These losses can be reduced developing a system optimized in the energy conversion and storage, but they can't be completely removed.

However the Matlab program is simply adjustable increasing the number of variables that we need to take into account to analyse deeply the real behaviour of all the systems that compose the VPS.

Chapter 5 - Implementation

5.1. Control System

All the previous analysis was done in order to evaluate if implementation of simple system actually available permit an implementation of a micro VPS inside a real community where entities are not virtual model but real customers, everyone characterized by his habits and is behaviour. So not an ideal case study but a real interaction with final users, that at the end is the main important figure inside VPS.
Before starting the implementation description it's important to emphasize that all selected system used for this research activity are commercially available for two main reason:

- The main aspect of the activity is to show that using cheaper and easy solution actually available, is possible to increase energy management efficiency and improve final users' service and power quality
- For the Italian law is not admissible that any kind of prototype, design and developed, can be installed and tested in real application without national and European conformity certification. Due to the enormous amount of time

and resources necessary to obtain these kind of certification, it was not admissible to proceed on that way, so the only solution was to use already certified system, with some adaptations to the specific implementation cases.

To realize our micro VPS, four system are necessary:

- Monitoring system: Energy Management Unit Gt-621
  This unit has the role to constantly monitor loads/power plants and supply data to the control system in order to have the real time situation under constantly under control and also create the historical database useful for future prevision on system behaviour. In this implementation the main role is to monitor power consumption/production and then send data through GPRS connection to the main database; if for some reasons the connection with the main database falls down, it can continue to store data inside its internal memory and then send them when the connection will be restored.

- Database & Hardware Management: the “Cell Controller”
  This is the main “Cell Controller” that has different tasks:

  - Maintain the connection with all the EMU
  - Manage and Store data incoming from EMU
  - Provide all the data to the Web Service Server
  - Manage and Control all the EMU sending them the proper command
  - Manage the Storage System through the EMU

  Different application continuously run on the machine to manage all the connected systems; specific process will have to manage the incoming data and database, the status of EMU and communication, the information request from the web service and the storage system.

- Feedback system: Web Service and local feedback
  This service is provided in several way; the web service was realized in collaboration with “Area IT” of Turin Polytechnic. All the website and the information service will be send to a private area on the Polytechnic’s

server. The Area IT will ensure all the web communication and the security procedures that are necessary for a web service; users can in each moment request their data about historical or real time energetic behaviour. All data that are requested are provided through a constant interaction between the Web Service Server and the Cell Controller. In this way the database and the application that control the VPS are separate from outside and from internet access, to avoid also security problems.

- Interactive Storage System: the ESS1.0
  This is the system that will be provide the energy in case of blackout but that mainly transforms, in some situation, an uncontrolled load into a time constant load. A detailed explanation of the characteristics of the storage system is given in next section.

5.1.1. Local monitoring system

One of the main problem in the VPS realization was that data provided from local distributor were not in real time mode and they were also conveyed in aggregate form. It was natural to choose to install in selected residential building, but also in some power plant and public buildings, specific instrument to log in a real time way all the electrical characteristics necessary to our purpose. With this data it was also possible to start the design of the storage system that was implemented in the final part.
A long selection of similar system actually available on the market was done and at the end the selected Energy Management Unit (EMU), for instantaneous consumptions monitoring of the 24 selected houses, was the GT-621 produced by the NxN Technology Co., LTD.
Unit logs various electric and physical quantities and store it into the internal memory; when a stable GPRS connection is available it dispatch all logged data to the remote server, the cell controller. If data connection is always available data are sent in real time mode with a minimum delay not bigger then 5s.
GT-621 is equipped with standard analog and digital I/O (voltage and current input), with industrial serial connection and some outputs (open collector, relay). Standard

sensors with compatible outputs can be linked directly to the unit, while other quantities can be acquired by external adapters. Data transmission is done through GPRS modem. Unit can be customizable adapting his FW to the implementation needs. Selection of this unit respect to other product on the market was made thanks to multiple functions for output control and feedback to the customers. It was also more appropriate for the control of the storage system through the standard I/O and serial port.

Specification:

- Quad band GSM/GPRS 900/1800/850/1900MHz
- 1 x Selectable RS-232/485 serial port, 1x RS-232 serial port, 8 X Digital Input, 2 x Digital Output and 2 x relay output,4 x analog input , 16 bit, with isolation
- Continuous and automatic GPRS VPN Management (GPRS Data Tunnel)
- Industrial design with surge protection
- C++ API
- Real-time Clock (RTC)
- Local and remote configuration over the air (OTA)
- Remote firmware upgrade over the air (OTA)

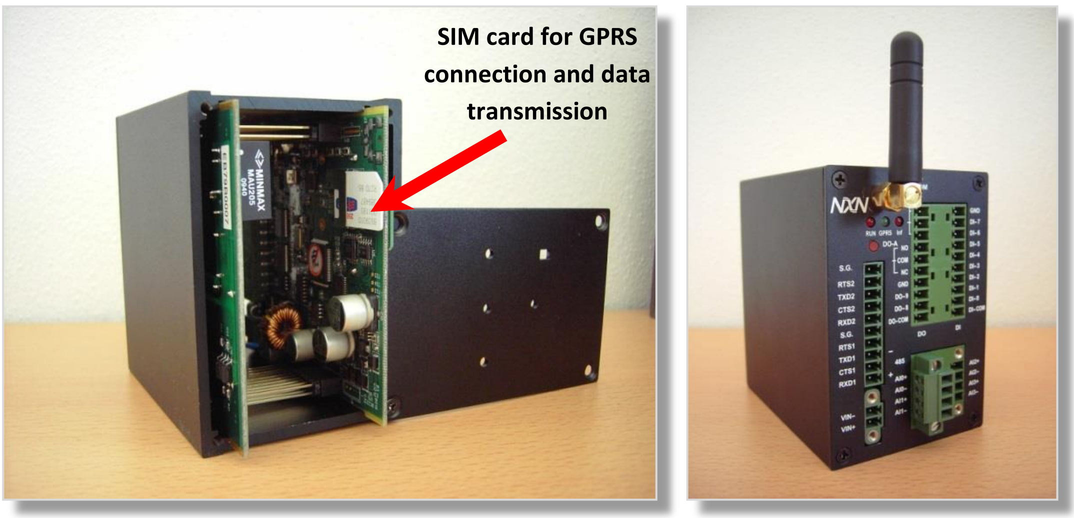


Figure 26: Internal view of NxN GT-621 - Courtesy of SISAV & NXN

All the units are equipped with a M2M SIM data card for Mobile Communication through; using the GSM/GPRS network they can communicate with the main server (cell controller) and send all acquired data to store them. Furthermore all the modules can send specific SMS according to some basilar rule, like excess specific limits or by specific command sent by the cell controller. Unfortunately was not possible to use unit as they come from factory because the implementation required some HW modification to made it compatible to our needs.

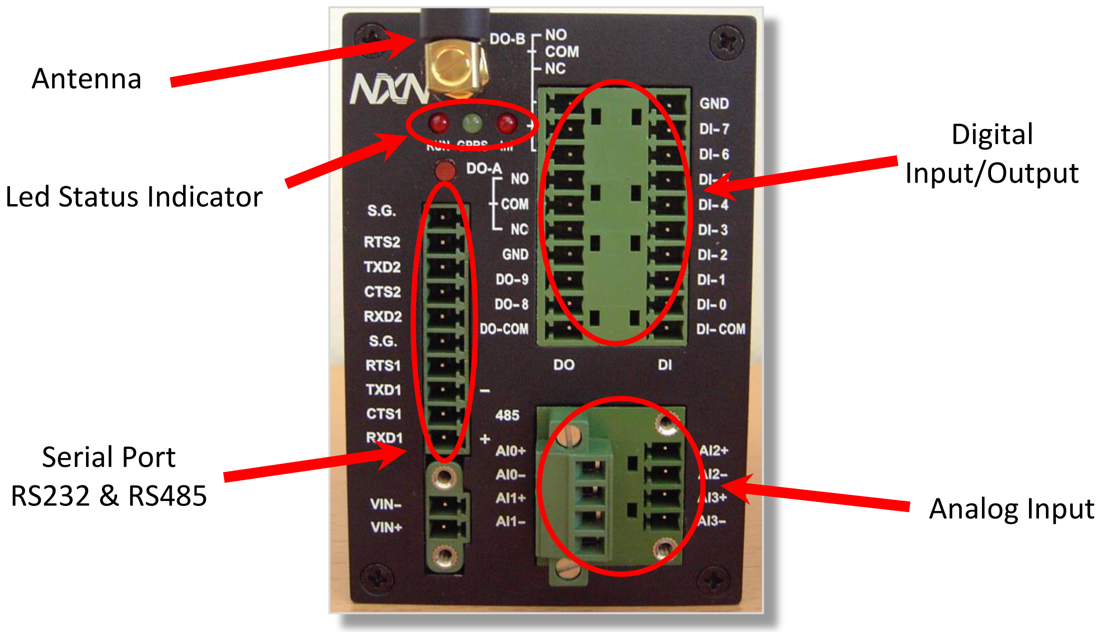


Figure 27: Rear I/O connections of NxN GT-621 - Courtesy of SISAV & NXN

As reported before, this module is equipped only with standard I/O connection, there aren't any kind of add-ons that can help user to understand a sort of feedback sent to him. Following the rule that the easier way to give an instantaneous tangible reference related to the instantaneous consumption is something that do not give a lot information but something very simple, each GT-621 was equipped with two simple coloured LEDs, one green and one red. LEDs had the function to show the real time condition of related absorption profile of the house.

Three condition are supported:

- LEDs are off: the connection with the cell controller is not available and so the real time monitor and feedback is not possible
- Green LED is ON and RED is OFF: energy consumption are in the admissible range and no problem are revealed.
- Red LED is ON and GREEN is OFF: energy consumption are over the suggested threshold according for the specific time slot (band F1/F2/F3). If user continue to use an amount of power greater than how much suggested for more than 10 minutes, system start to notify overconsumption by specific SMS.

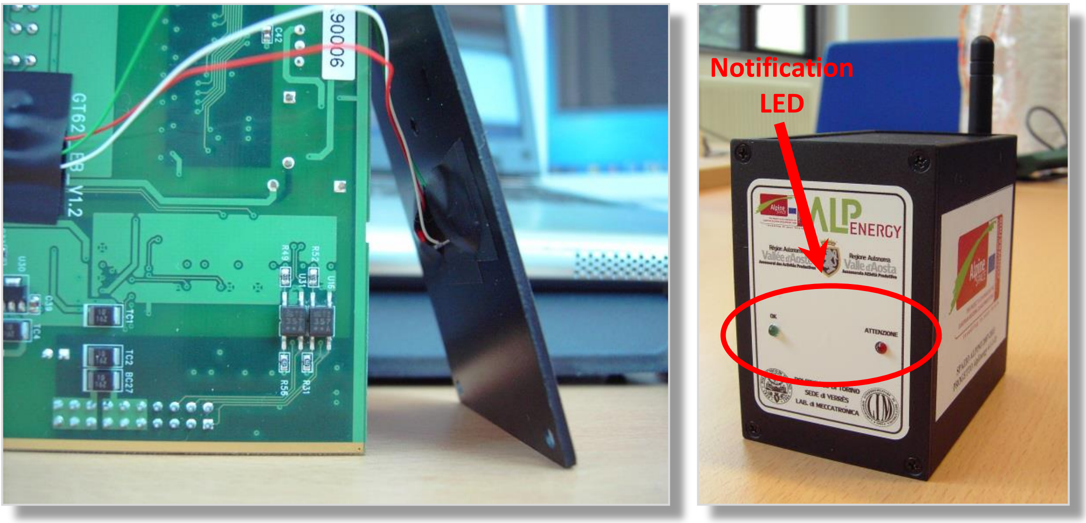


Figure 28: HW modification of GT-621 for feedback functionality

All the feedbacks were controlled directly by the cell controller and never directly from the module, due to the dynamic limits used to generate them. If the whole power absorption from all monitored users was in standard condition, cell controller can decide to increase the upper value of the notification threshold. If absorptions were high, notification threshold decrease to his lower value in order to try to reduce the grid overload.
To instantly monitor power absorption of residential buildings each module need to be equipped with a sort of sensor. The easiest way was to interpose this “sensor”

between the user DNO's smart meter and the internal electric plant but as said before it was not possible to modify in any way the internal electric plant of any plants. The only way to measure consumption was using a sort of "wireless" measure; the fastest and less invasive way adopted was using an hall current sensor produced by LEM. This is a current sensor characterized by a split-core transducer for the electronic measurement of AC waveform currents, with galvanic isolation between the primary circuit (power that is measured) and the secondary circuit (measurement) with the output reported between 0-10V_{DC} proportional to the RMS value of the primary current. It's connected with a simple clamp to one of the two wire that comes out from smart meter, without change the electric plant configuration. The same solution is used to monitor and measure the energy production of public RES.

Features:

- 0-10V DC voltage output with RMS (average) output
- Split-core type with Ø 16 mm sensing aperture for non-contact measurement and isolated plastic case recognized according to UL 94-V0.

An example of one of the selected sensors is reported below:

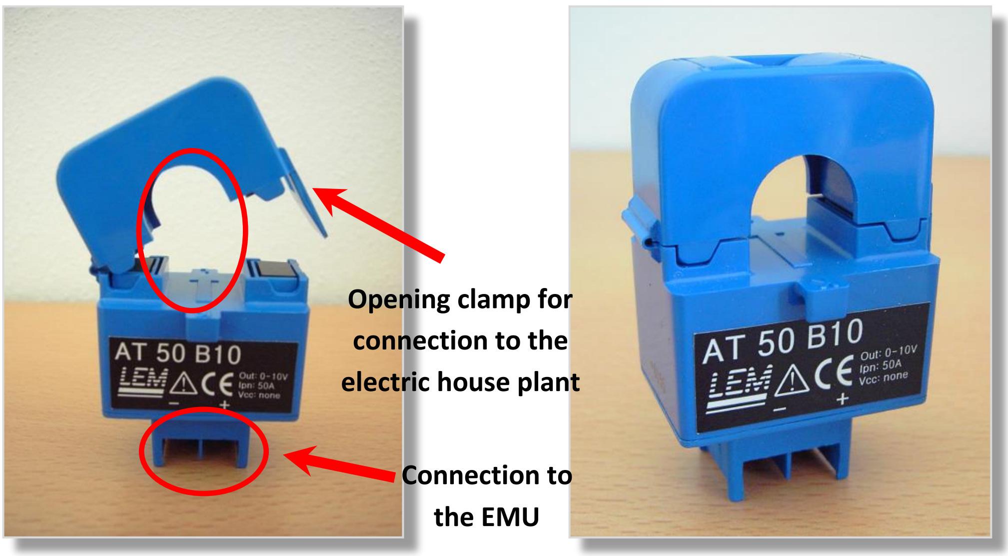


Figure 29: AC 50A current sensor with voltage output – Courtesy of LEM

At the end of the implementation process the following structure were monitored:

- 24 residential building (22@3kW and 2@6kW single phase)
- 1 private PV plant (3kW s.ph.) + 2 public PV plant (6kW + 3kW s.ph.)
- The city hall loads (12kW triphase)
- The Lavese's autonomous centre (4,2kW PV + 8kW GPL generator + 48V 1100Ah lead acid storage, grid disconnected)

Figure 30: Residential building installation example

Figure 31: Public PV plant installation example

5.1.2. Cell Controller

The cell controller is main important system inside all the VPS due to his multiple functionality:

- Connection, synchronization and management function for remote distributed EMU;
- Management of sampled data and storage into local database;
- Data elaboration for web service interface;
- ESS control and supervision.

The EMU modules, previously chosen, are all data loggers that sample continuously the power consumption every 5s and store these values inside the 2MB memory; this memory allows an independent sample time of more than a day without the need to connect to the cell controller and without losing data; exceeded the maximum data storage will gradually discard the oldest sampling to store the most recent. Once the connection is established again data are sent to the MySQL database to be used later. This procedure is not a simple transmission due the possible error during sampling caused from several factor. The main cell controller have to check each single data received before to store it into the database to remove any king of mismatch.

Unfortunately EMU units were provided with some applications for a first configuration, but to fully exploit the potential of these modules development of specific software was necessary. The only way to establish a communication between cell controller and the EMU units was developing specific routines based on proprietary API, ".dll" libraries that permit access to the lowest functionality or HW configuration of the modules. All the library are C++ based so the chosen way was to develop all single routine using Visual Studio 2010; thank to this SW it was possible to create a first EMU interface to establish all the connection and the configuration procedure.

The second but not less important functionality of the cell controller was the VPS database: the only way to manage all the data coming from logging system was to store it into a local database in order to obtain a simple and efficient solution to have all data always available from everywhere. For data management an open source systems was chosen such as MySQL and other related boundary management applications. A complete month was necessary to develop only a secure connection between Visual Studio routines and the MySQL database. A lot of exception routine were necessary to avoid data loosing during receiving. Solved the main problem , development of management routines was natural and grow and became more efficient while the time goes. Each single sample was received, converted into a useful data (from binary to decimal), compared with some VPS management rule (i.e. threshold according to time slot) and then stored into database. This operation seems easy but the amount of data available was really enormous if we consider all the monitoring system. An average evaluation of the amount of received data can be done in the following way:

1 sample each 5 second = 720 samples/h

24 single phase load + 3 PV plant + 3x3 loads (city hall) + 4 Lavese's samples (consumption, PV production, battery SOC, emergency generator production) = 40

40 samples/5s → 28800 samples/h

1 day → 691.200 samples
1 week → 4.838.400 samples
1 month → 20.736.000 samples
1 year → …..

The cell controller has not only to manage all measurements from EMU but also:

- Manage all the light feedback;
- Manage SMS notifications for personal user information;
- Provide information to users through the website;
- Provide suggestion to users using SMS advice;
- Manage storage systems for peak shaving functionality;
- Get statistics on consumption;

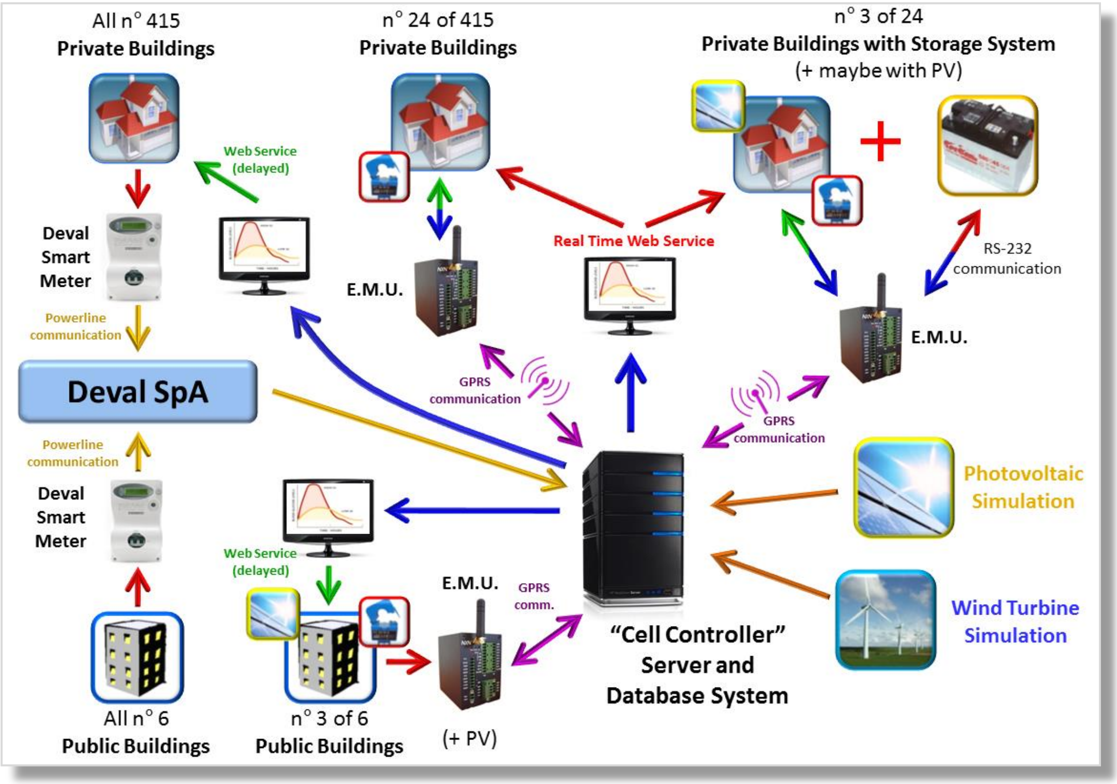


Figure 32: Complete VPS implementation

This type of implementations will lead to an early version of a micro VPS realized using existing infrastructures and providing new service to final users, in order to reach some sort of Smart Grid.

5.1.2.1. SW Routines

At the end of the implementation activity five software routines were developed to satisfy all VPS requirements, one as the main core of the VPS and other four to provide the information service to the user:

- "Server Console and Database" routines: this routine is the core of cell controller. Automatically launched every startup it establish a connection with all the EMUs, update their configuration according to the real time needs, start the MySQL interaction and start incoming raw data management. Main functionalities are:

- EMU connection
- EMU HW configuration
- EMU synchronization
- SMS configuration
- Management of LEDs' feedbacks
- Consumption analysis and internal reconfiguration of threshold

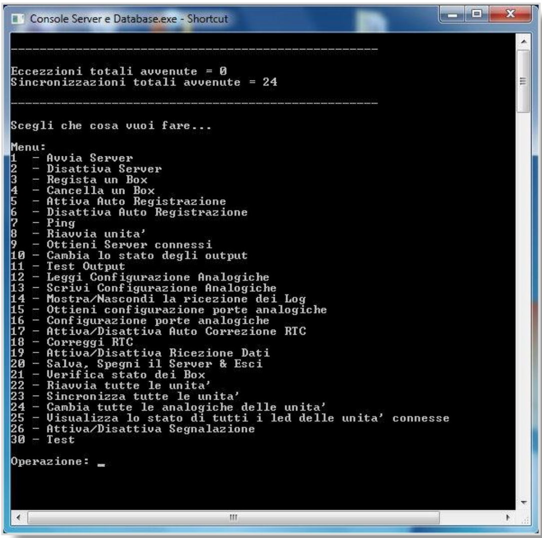


Figure 33: Ceil Controller (the real server) and core routines menu

The core routines has not only the role to manage data but mainly to send the correct feedbacks to the users. The simple logic developed was to set different power absorption threshold for each time slot. If some user exceed the amount of power ideally set for the specific time period a first notification made using the installed LEDs was sent to notify that a possible overload of the net can happen. Obviously actually there is no risk of an overload on the electric distribution grid, but in order to simulate them it was necessary to assume that it can happens. Another way is to assume that during period when the load absorption increase also the energy cost increase; our feedback can be viewed as a simple way to advise user that is using a lot of energy when the cost is high and, if he can, he can save some money delaying the absorption in a more affordable time slot. Unfortunately these are only assumption due to the actual type of contract actually available with the energy distributor.

List of user information routines:

- “Average exportation on AreaIT” routines: this routines as the role to extract from MySQL database user consumptions for residential building, calculate some parameters (i.e. max/min/average consumption), aggregate all the data in time interval not smaller than 3 minute and send it to the web interface located in the main web server of AreaIT society at Politecnico di Torino. This was necessary due to the fact that all the web interface developed was installed on the web server located in Turin, to avoid the necessity to create an infrastructure like that one also in Verrès(AO) where the VPS server, the Ceil controller, was installed.

Figure 34: example of data exportation routines

- “Triphase Load Exportation on AreaIT” routines: as the previous routines, this SW has the role to export data coming from triphase load. A distinction was necessary due to the different approach with data stored inside database.

- “PV Exportation on AreaIT”: this software export the photovoltaic production from public and private plant. For RES production SW calculate also the amount of CO2 saved for electricity production.

- "Lavese exportation on AreaIT" routines: the last routines has the similar role as the previous one, but due to the fact that Lavese is an autonomous center, disconnected from grid with a local storage system, it was necessary to make a distinction in order to manage correctly all data coming not only from PV plant and loads but also from storage and from the emergency generator.

The fact to create single routines completely disconnected from the ceil controller, to export and manage data, was made in order to increase system stability. At the beginning there was a single routines to manage all the system. Due to the development phase of software it was quite common that sometimes some errors, not well considered, crash the application. If this happen to information routines the problem was not so dangerous, maybe information service goes offline for a short period. But if this happen to the main routines, the Server Console and Database, all the system crash because connection with EMU and with database was lost. In order to avoid or simply reduce this kind of situations all the routines were extracted from the main one and developed singularly. In this way system acquired a lot off efficiency and also SW upgrade are available with the system running.

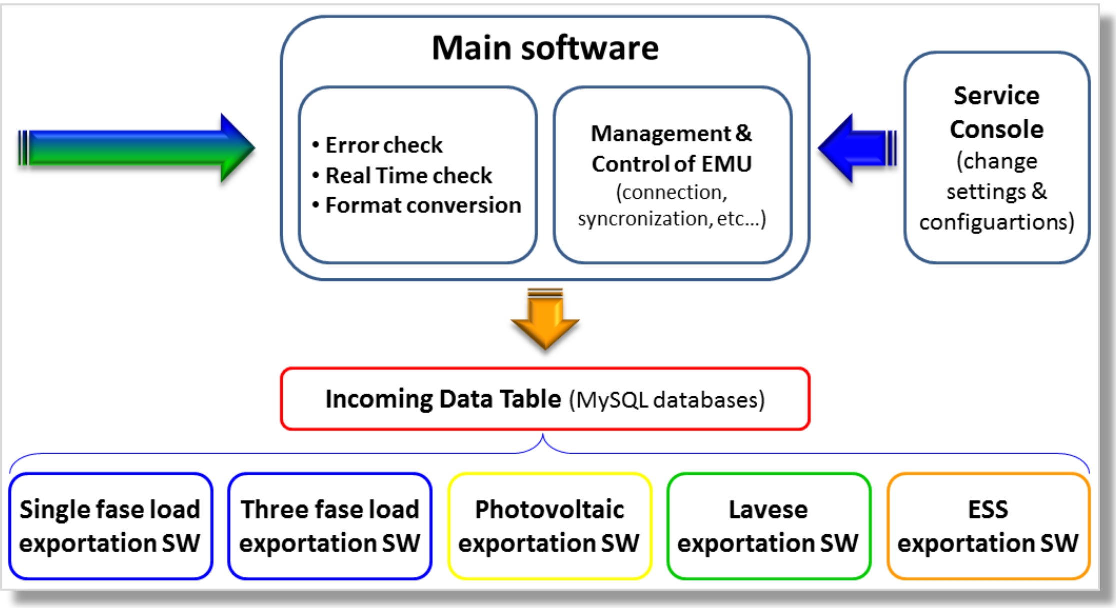


Figure 35: Schematic Block of Ceil Controller functionalities

Once the cell controller was implemented all the monitoring, super visioning and information system was finally realized.

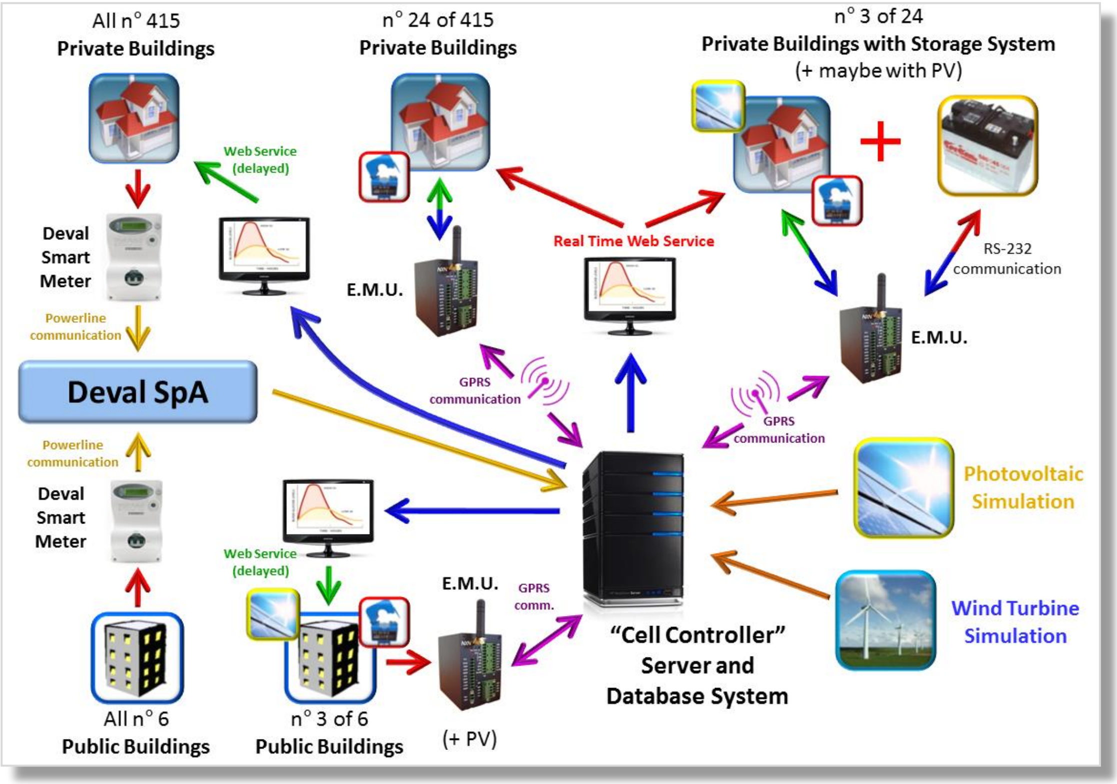


Figure 36: Micro VPS interconnection

5.1.2.2. WEB Interface

One of the most important task of the research activity was the interaction with the final user, supplying the correct feedback in each situation in order to help him to understand how to increase efficiency about energy consumption.

The request was to realize something to provide data to each single user, in an easy way, like using graph, and in a private form.

The faster solution adopted was developing a simple web interface (www.polito.it/alpenergy) where, in addition to specific page about project description, each users can access and see their specific information about energy consumption/production and other informations.

Each user equipped with the EMU was registered on the main website and a private area was created; once the access was done through username and password, user can surf several pages reporting information about his utilities and specific pages about his consumption or his PV production.

Main pages are the "User Information page", where personal data, contact information, geographical position of the utilities are reported, and consumption/production pages. In the daily consumption pages is possible to see the own consumption along the 24hours and the instantaneous comparison with the previous day or of a specific day selectable by the user.

Figure 37: Website login page

The daily consumption pages report the energy absorption in a real time mode with a maximum delay of 3 minutes, the minimum aggregation time set for data exportation. Other informations like the F1/F2/F3 bands are reported in order to see immediately if consumption are well addressed in the correct time slot. Also the specific threshold used for feedback notification, by LED and SMS, are reported according to the real time conditions.

Figure 38: Example of a daily consumption web pages

Same information are reported for weekly and monthly consumption pages. All the pages reported till now are completely protected and accessible only after user login. The public photovoltaic plant instead are completely public and data are available for everyone.

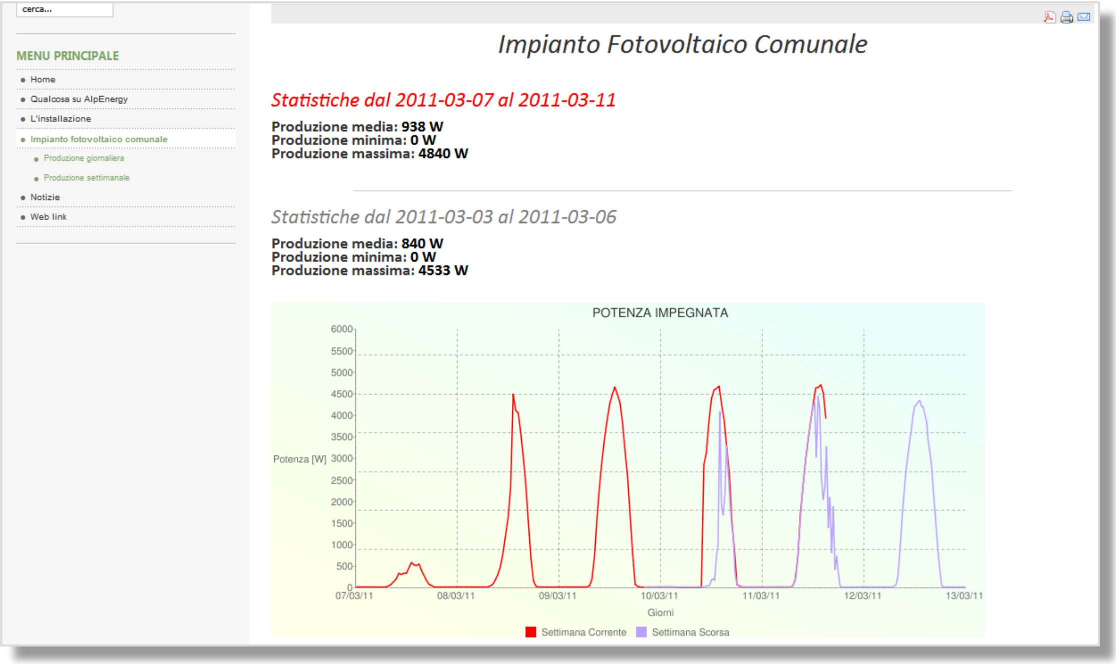


Figure 39: Example of a weekly report of photovoltaic production

The last implementation was made for center of "Lavese" an eco-sustainable building situated on the edge of the town of Saint Denis. This center has resulted more work for his monitor due to the complete disconnection from the mains energy grid and also because it's powered by an island photovoltaic system with an emergency generator supplied with butane. The monitoring system was designed to monitor:

- Production from 4,2kW of photovoltaic polycrystalline panels
- State of Charge of lead acid battery storage (48V_{DC}@1100Ah)
- 8kW_{AC} 230V_{AC} emergency generator
- 3kW 230V_{AC} inverter that supply the center (supplied from storage system)

All these data were then made available on the web site in the same way as the example before.

5.1.3. Load shift analysis

Research activity want to show if consumption behaviour can be changed only using simple feedbacks sent to the user. To perform this analysis two specific actions were necessary:

- First sampling period to identify standard user behaviour: during this period monitoring system were used only to create an historical archive useful for next comparison. When the study start all the user had a fixed tariff contract with local distributor, so the energy cost the same amount of €/kWh, and they are used to consume indifferently along all the day. Data were available on the website but all type of feedbacks, as the notifications LED or the SMSs were disabled. User can behave as in standard condition without any intervention of the system. For this study also DNO’s data were used.

Feedbacks period: as explained before during the second period and till the end of the activity each user involved in the study was subjected to the notifications in case of “bad” behaviour. That means that each time the utilities exceed the threshold imposed, at first the LED notification and then the SMSs were sent till when user modify his consumption and return to safe conditions. All these actions were performed especially during time slot where the cost of the energy is higher, between 8:00 and 19:00 during weekdays.

Using data logged from January 2011, when the monitoring network of domestic consumption started, till to the end of the year, it was possible to make an analysis of the influence of the alert messages sent to citizens and how they interacted with the loads shift in the F2-F3 time slot characterized by lower consumption and price.
Comparing these behaviours with the first sampling periods without notification could be deduced, considering the global average consumption, what is the percentage of the total loads that is shifted in our bands of interest.
Starting from January citizens start to receive small amount of notification, like one SMS every 30 minute, but during time the amount of notifications increase constantly, till to one SMS each 5 minute. Notifications were sent immediately if user required more than 80% of the available power, 2,4kW for 3kW contract, with

the only purpose to instantly limit absorption, consuming energy more distributed throughout the all day.

From July 2011 until the end of the project such notification occurred not only in the case of high absorption but also in case of lower absorption, till to 50% of available power (1500W for 3kW contract), during F1 band, from 8:00 to 19:00 on weekdays. This has led some users to move in the evening or at night the use of some appliances that request more energy for normal use, like washing machine and dishwasher.
Users began to move their loads in different time zones in order to avoid receiving notifications via SMS. Even when the notifications were decreased according to some predefined time filters, they continued to maintain their consumption more in the same time band without going back to the old habits.

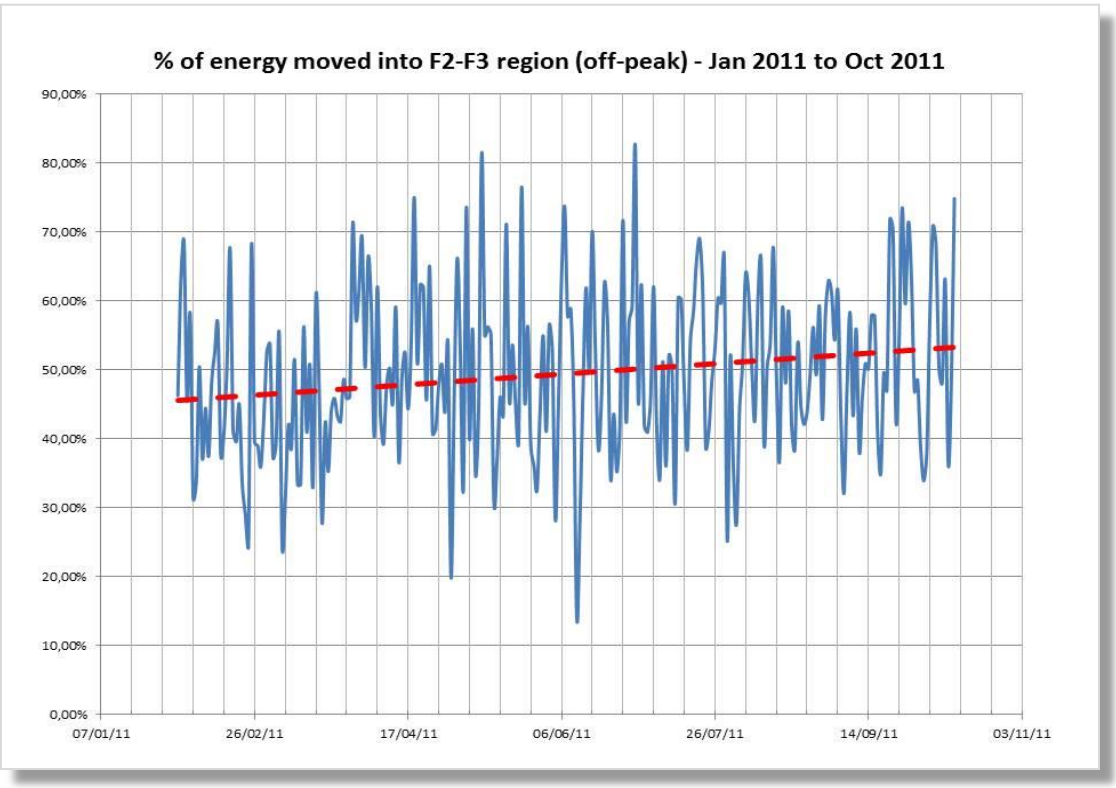


Figure 40: Percentage of load shifted in cheaper time slot (F2/F3)

From calculations and data analysis it result that a small amount of the involved citizen, less than 30%, do no interact in any way with our notification system and do not vary a lot their behaviour. All the other citizen, more than 70%, modify their consumption behaviour according to notification and keep this variation also when notification were stopped. Loads in cheaper band increase from 45,3% to 53,9% obtaining a loads shift of approximately 8,6% from F1 to F2/F3 band, showing a great result considering the type of notification used and the test conditions that occur in a small village like Saint Denis.

5.2. The ESS1.0

Last step of the research activity focus on the realization of a domestic storage system able to adapt residential absorption profile to the VPS need without the interaction of the final user.
Through the study of logged data, design of the ESS, the Energy Storage System, started; some constrain limits the degree of freedom of the system, first of all:

- The reduced amount of money available for all the system
- All the internal component used for energy conversion need the European certification

Local storage should be able to provide energy in a private building for a time estimated into the range of few minutes to no more than one hour in standard condition, 50% of the load for one hour; so this system isn’t seen as an unlimited supply of energy, but as a support that gives the time to complete some actions, maybe important, before falling in a hypothetical situation of increasing of the kWh price or in a detachment from the distribution grid by the VPS manager in case off direct load control from local DNO, as already happens when absorption exceed more the 30% of the maximum amount of power imposed by the smart meter.
The Storage System is capable to store previously an amount of energy that can be used to handle peak absorption when peaks consumption happen or to provide the energy in case of blackout.

System must be invisible both to the network or load:

- On the grid side it behaves as a resistive load with cosϕ greater than 0,9;
- On the other side it has to behave as a pure sinusoidal voltage generator with same characteristics of the grid (230V_{AC} 50Hz)

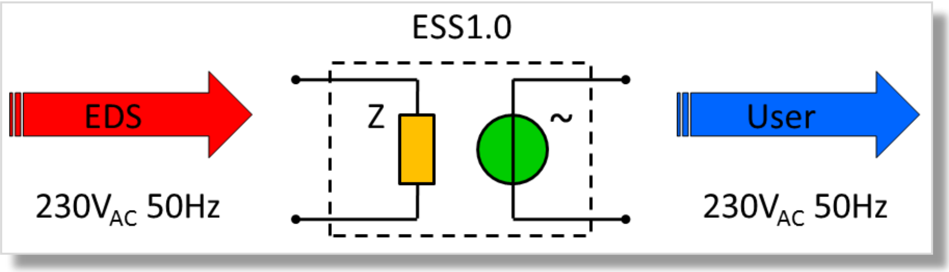


Figure 41: ESS1.0 capabilities

As said before the two main role of this system are the UPS mode and Peak Shaving functionality. In UPS mode system, using the energy previously stored into the accumulators, supply loads in the same way as the distribution grid (230V_{AC} 50Hz). When a blackout happens and the system feels that there isn't any input supply, it starts to use its energy to permit an uninterruptible supply for a short period.

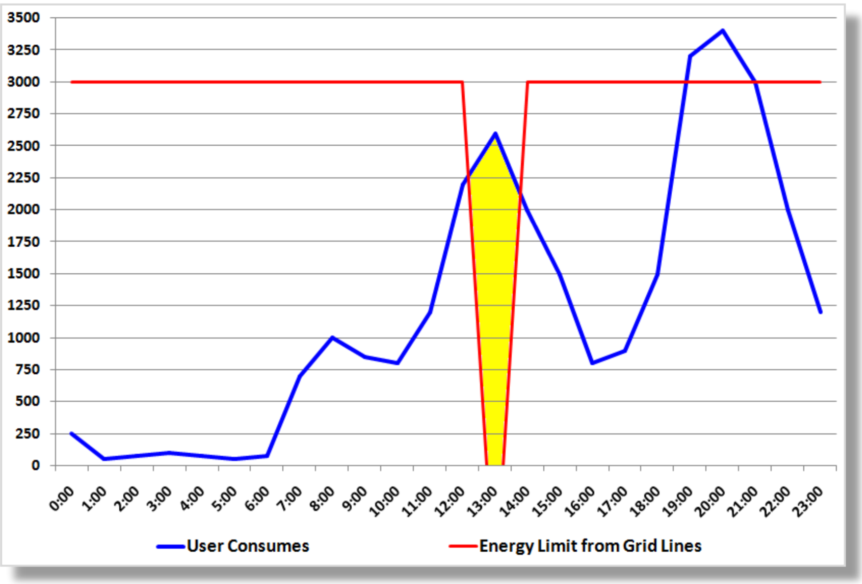


Figure 42: ESS1.0 UPS functionality

Peak Shaving Functionality is a new to manage peak absorption; systems manage the consumption peaks to not overload the national grid. Along the day normal house consumption aren't characterized by a continuous energy absorption but by consumption peaks in an impulsive way, like in the lunch period and in the evening. All the rest of the day there is a low absorption from the distribution grid. Indeed the average power requested to grid normally is equal to less than 20% of the maximum power available. This kind of consumptions aren't good both for the net and for the user: on the net side there is an overload consumption only during specific periods and this requires to size the energy grid on the supposed maximum absorption value that can happens in this periods. On the user side there's a limitation on the use of the household appliances due to a power limitation imposed by the smart meter that disconnect the energy if a specific threshold is exceeded. I.e. user can't switch on the washing machine and the electric water heater or the ovens together.
In this case the storage system can be set to manage the absorption peaks over a specific threshold; that means that all the consumption under this limit are managed by the distribution grid and all the absorption peaks are managed using the energy stored into the accumulators. In this way there isn't an overload of the net and the user can increase power absorption for short period.

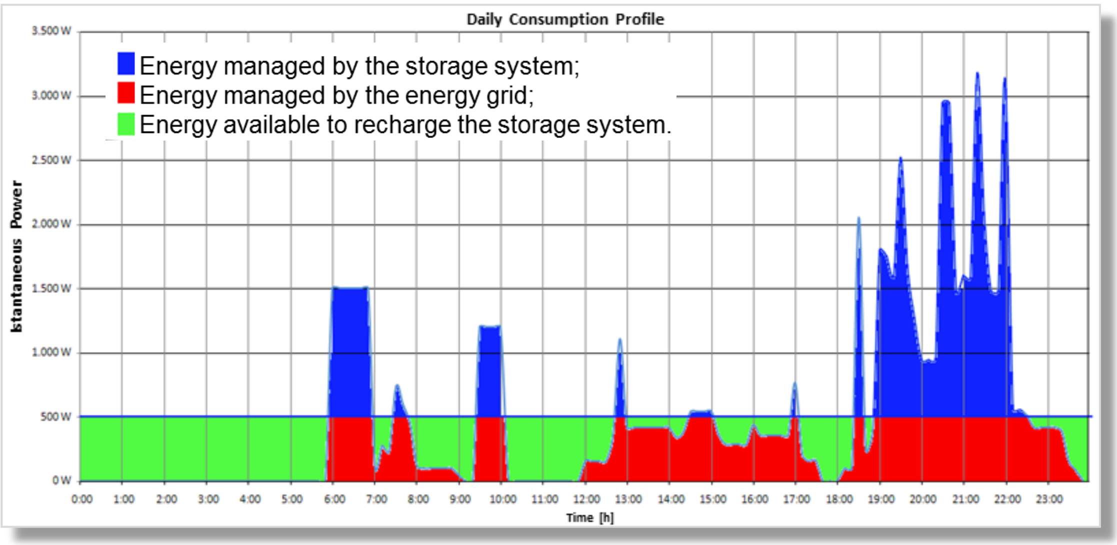


Figure 43: ESS1.0 Peak shaving functionality

Then the storage system can recharge itself either when the power supply is restored, in case of blackout, or during low consumption periods, like in the night, or also from renewable sources to increase self-consumption.
So this system can transform a discontinuous load of a house into a continuous, power limited and predictable load. In the same way this system can be used with a RES plant, to transform a discontinuous production, photovoltaic and wind, into a constant power supply.

5.2.1. ESS1.0 Design

Design started with the definition of main parameters and structure. The main element necessary to realize our purpose can be grouped into four subsystem:

- Accumulators to store the angry
- DC/AC inverter to supply loads
- AC/DC rectifier for storage recharge from EDS
- Communication and control system to perform peak shaving and UPS functionality

Design started analysing absorption profile data; a small group of users was selected according to their interest in the activity and considering mainly who during the monitoring and feedback activity show an interest in the research and also was available to test our system. A simple SW developed during mechatronics master thesis was adapted and used to calculate the main parameters of the ESS: the storage capacity. The main role of the system is to manage only the peak absorption, so capacity need to be sized according to that functionality that is the more critical and not on the autonomy in case of UPS functionality, that is intrinsically included in the system and was always possible to supply loads for 15 minutes in standard conditions (3kW power absorption). Capacity calculation was done with the following steps:

1) Loading of the customer’s monthly data and definition of main system parameters (efficiency of storage and conversion system).

2) Profile analysis and calculation of starting parameters: these parameters like the min/max/average power absorption are used to start the next simulation. It's obvious that the minimum power required from the grid can't be equal or less than the average power normally requested.

- Simulation of minimum Power Cut needed to keep constantly supplied all the loads assuming to have available a storage system oversized for the application.
- Calculation of the Minimum Capacity of the storage system related to the previous Power Cut imposed.
- Simulation of all the storage capacity necessary increasing step by step the power cut threshold and exporting it on a graphical way.

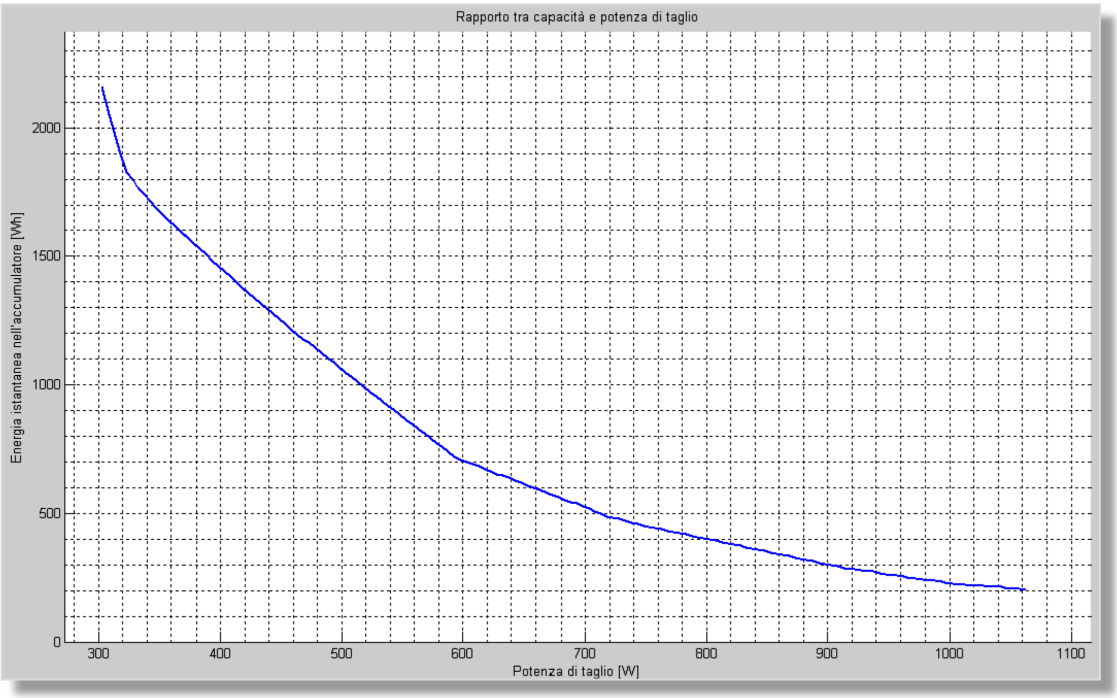


Figure 44: Storage capacity simulation example for small family

According to simulation, was found that users have different behaviour, mainly according on the family composition and age: small (≤ 3 persons) or families composed by older people (>70 years) required an average power smaller than 450W, medium and bigger families required an average power around 550W.

Another aspect to keep in mind is the overall efficiency of all the elements inside the ESS; the main problem was related to the storage system, batteries. At beginning the ideal solution was to adopt a lithium polymer storage but due to the fact that this system required to be installed in various environment where sometimes temperature can reach critical values like more than 55°C if the system was exposed to sun or -10°C if position in shadow location. It's important to remember that the implementation was done in location with heights greater than 1500m a.s.l. so temperature can become critical during winter time. For these reasons and also due to the very low amount of money available for the ESS realization, each system had to cost less than 1500€, the accumulator was realized using lead acid storage for photovoltaic application.
In the end ESS have to satisfy three main parameters:

- Guarantee a correct supply with an overall load of at least 5kW of power peak, 50% more power respect to the standard contract with the DNO in order to permit overconsumption for short period.
- Do not absorb more than 600W from distribution grid during recharge phase (a little bit more respect on how much calculated to compensate low storage efficiency)
- Keep continuously supplied the load in standard condition for 15min in case of blackout.

In order to demonstrate the advantages reported before and to achieve a reduced cost for the prototype realization, the ESS is not supplying the load in parallel with the distribution grid using a grid tie inverter, but it's interposed between the grid and the load. With this configuration the ESS draws energy from the grid and directly supply the load in case of overconsumption. This decision was over imposed due to some limitations, like the ban to modify electric plants inside houses and the prohibition to connect any "not certified" system, like prototypes, to the distribution grid and also due to the fact that grid tie inverter are more expensive than standard inverter used in island plants. Accordingly with this limitations the only way to test the ESS on field is to interpose the system between the distributor smart meter and the residential building, the real loads.

Using this configuration, the building is supplied from the internal inverter while the distribution grid supply only the battery charger, limiting the amount of power requested to the imposed value. The energy coming from the battery charger flow into an interconnection, the DC bus, that connect together rectifier, batteries and the inverter; with this central distribution node the energy flow according to these rules:

- if $P_{out} = P_{in}$ from AC/DC rectifier directly to the inverter;
- if $P_{out} > P_{in}$ from AC/DC rectifier and batteries (discharge) to the inverter;
- if $P_{out} < P_{in}$ from charger to inverter and batteries (charge).

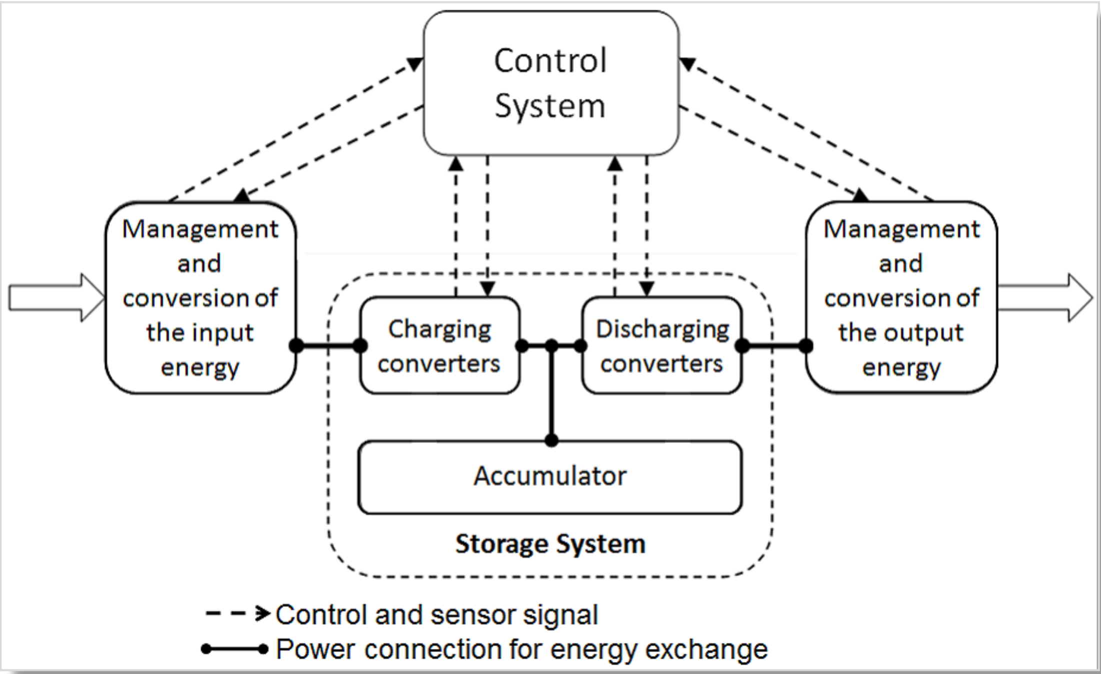


Figure 45: ESS1.0 subsystem interconnection

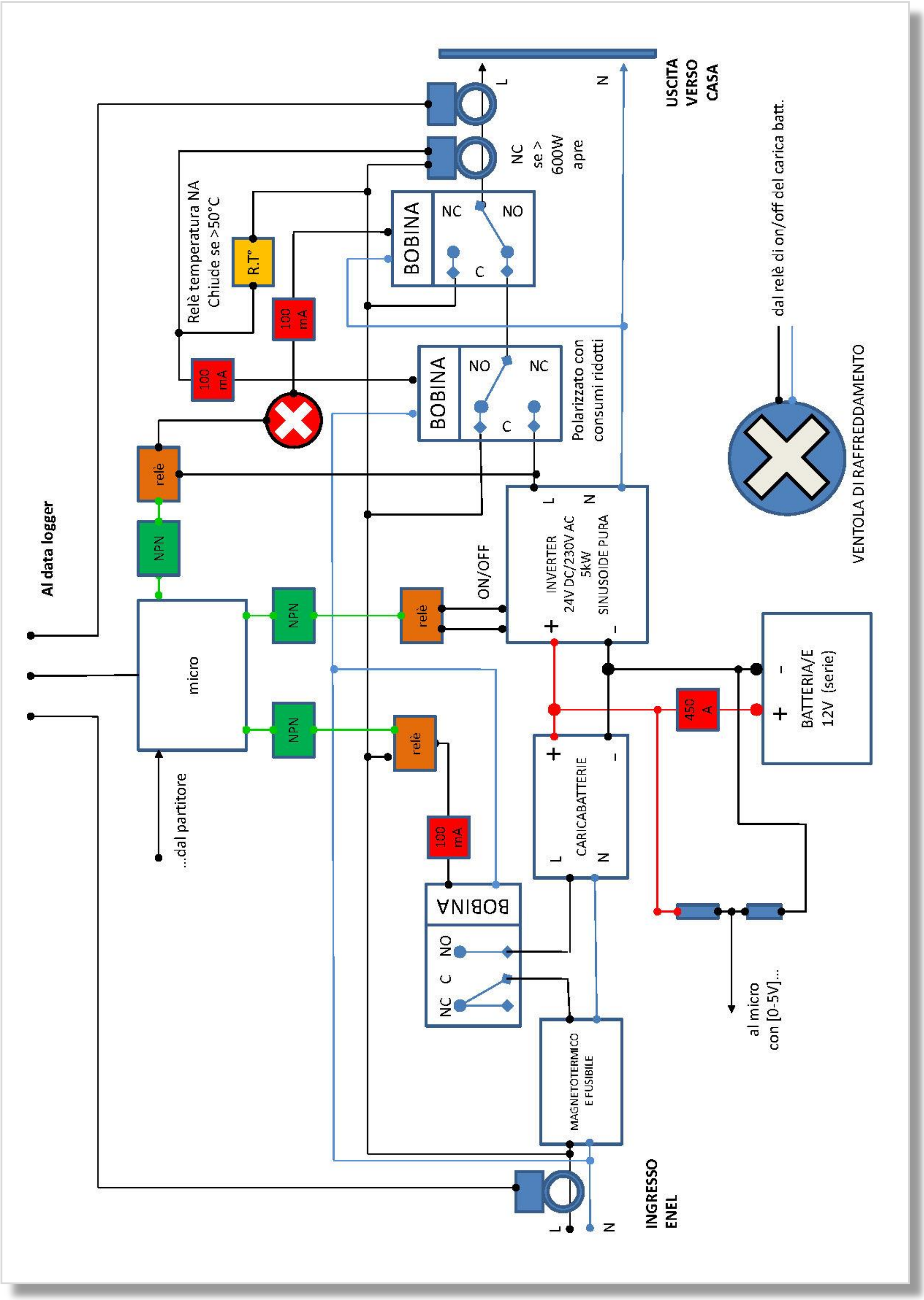


Figure 46: : ESS logic scheme

5.2.1. ESS 1.0 Prototype

Component selection was done according to the simulation specification and according to implementation restriction, like insulation, environment and mobility.

5.2.1.1. Accumulators

Accumulators were the first component selected: worst case simulation of families' absorption profile report that for a 550W constantly requested to the grid, a storage capacity greater than 1200Wh is necessary. AS said before was not possible to implement a LiPO accumulator, so the only solution was to move on lead acid batteries. Including safety values about conversion efficiency, it was possible to calculate the real capacity of the ESS:

$\eta_{CHARGE/DISCHARGE}$ = depend on internal recombination efficiency (~88%)

$\eta_{AVAILABLE\ CAPACITY\ RANGE}$ = depend on how much is possible to discharge battery without capacity reduction in the next cycles (~not under 20%)

$\eta_{BATTERY} = \eta_{CHARGE/DISCHARGE} \cdot \eta_{AVAILABLE\ CAPACITY\ RANGE} = 88\% \cdot 80\% = 70\%$

Assuming that inverter and rectifier have a whole efficiency greater than 95% the total amount of capacity to guarantee a min value of 1200Wh is:

$\eta_{BATTERY} \cdot \eta_{CONVERTER} = 70\% \cdot (95\%)^2 = 63\%$

Total Capacity = 1200Wh / 63% = 1904Wh

A reduced capacity of 80% is considered due to safety rules: is important to not exceed the minimum threshold equal to 20% of the capacity in order to avoid degradation of internal cells with deep discharge. In this way battery voltage remains constant during discharge allowing an optimum inverter supply also with low charge levels.

Chosen accumulators are designed to store the whole amount of energy necessary for peak shaving functionality and also to supply 3kW loads for 15 min and also to deliver more power if necessary (<5kW), even in unfavourable weather conditions, as during winter period when low temperatures reduce the chemical recombination, or during summer where high temperatures degrade and reduce the total capacity.

Figure 47: FIAMM 12FLB350 batteries

Selected batteries were two lead-gel acid accumulators optimized for deep discharge and with low affection to capacity reduction due to incomplete charge and discharge cycles (memory effect). Accumulator is so composed of two FIAMM 12FLB350 12VDC batteries connected in series, in order to obtain the necessary 24VDC bus to properly supply the output inverter; the size of each battery is 90Ah, obtaining a whole capacity of 2160Wh, more than how much calculated. Batteries can perform quick discharge reaching a rate of 4C÷5C equal to an ideal instantaneous output power of 8640W. Considering the whole efficiency of the batteries (~70%) and a reduced capacity equal to the 80%, the useful energy is about 1,2kWh equal to 4,8kW for 15 min.

5.2.1.2. DC/AC inverter

To correctly supply the residential building it was necessary to use a pure sine inverter because modified sine wave inverter can generate a lot of stresses and problems to the electronic systems included into standard household appliances.

The continuous maximum output power was set to 5kW with a 100% overload capacity, reaching 10kW for short periods. It requires an input voltage equal to 24VDC ± 20% to properly generate a 50Hz 230V ± 10% sinusoidal waveform with a conversion efficiency greater than 85%. Maximum inductive and capacitive cosϕ of 0,7 permit also a correct drive of appliances like motor or DCDC converter. Multiple safety algorithms are integrated in the internal controller like the input monitoring for under and over voltage protection, the output overload protection and the over temperature protection.

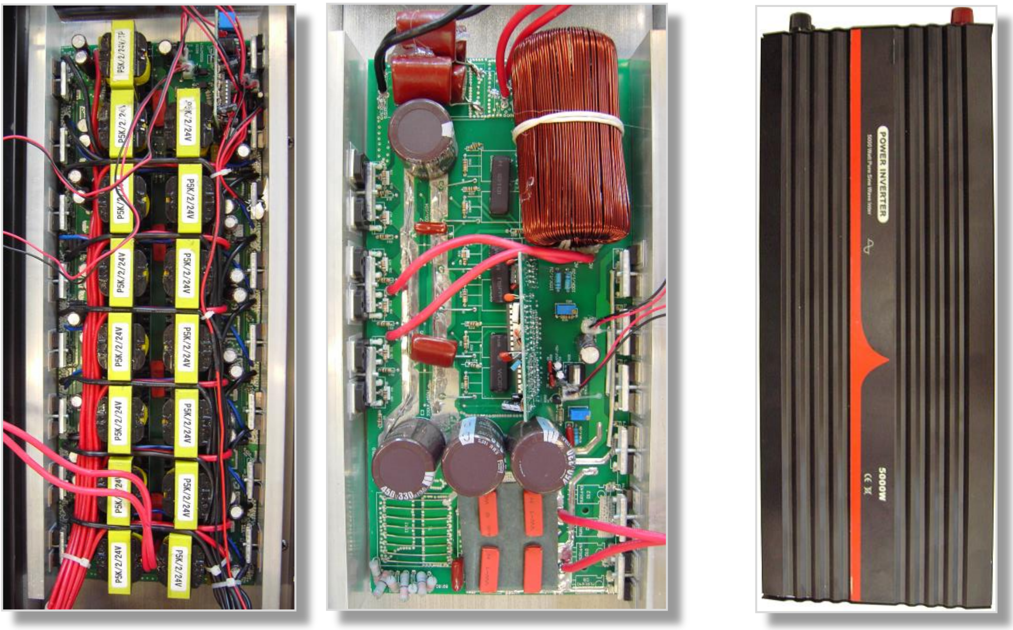


Figure 48: Internal view of 5kW pure sine wave inverter: from right to left, DC/DC boost converter, AC inverter and general view.

Inverter is composed by two main elements:

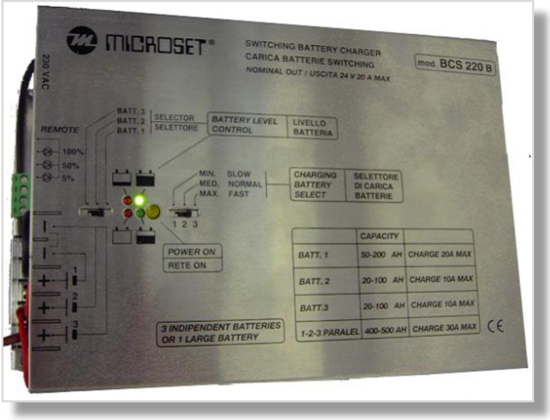
- A DC/DC boost converter to increase input voltage of 24VDC to 450VDC. Boost use fifteen single converter equipped with coupled inductance driven in push pull configuration; all the stages are driven in parallel permitting a unique feedback referred to the current on the internal high voltage DC bus.

- A DC/AC converter realized using IGBT H bridge equipped internally with an inductive filter and a capacitive filter connected in series to remove any eventual DC component.

5.2.1.3. AC/DC rectifier

The easiest way to recharge storage system was using a BCS220B from Microset, an AC/DC battery charger equipped with an internal current output control to limit the power absorption from grid.

This charger can simultaneously manage from one to three distinct 24V accumulators with a maximum output current of 30A. Such a current limits the input power to the imposed threshold of 600W with an overall efficiency greater than 90%.



5.2.1.4. Control system

The main important component inside the ESS is the monitor and control system realized using a Microchip PIC16F886 microcontroller running at 20MHz equipped with an actuating power circuit, connected to each subsystem.

A conditioning circuits allow to sample every 100ms the instantaneous conditions of the whole system in order to prevent any kind of malfunction:

- Batteries voltage: system monitor constantly battery voltage in order not discharge too much internal accumulator.
- Load power absorption: output power is monitored to actuate correctly the internal switch from EDS to the ESS.

- Temperature: one of the most critical aspect was the internal temperature of the system. Control unit had the role to keep it under specific limit actuating or not internal the fan .
- Input voltage of the ESS: if a blackout occurs system immediately switch from EDS supply to the ESS internal supply.
- Output voltage from the ESS: in case of malfunction to the internal conversion system, the control unit disconnect immediately the ESS from the utilities and report to the cell controller all the anomalies.

If any of this parameters exceeds the imposed threshold, the control system starts different recovery procedures to correct the anomalies and recover the normal functionality. If, for some reasons, is not possible to correct the problem, the control system can disconnect the ESS from the electric plant, recovering the original configuration between the load and the distribution grid where the ESS is not present. This solution is performed with an internal bypass that allows on one side to recover the original supply configuration from the grid, and, on the other side, to protect the internal subsystems of the ESS.

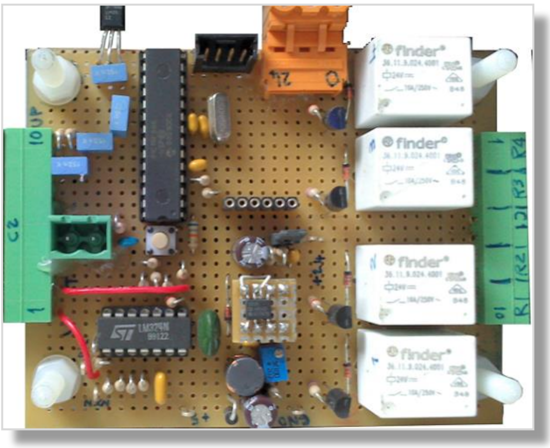


Figure 49: Internal control board

When disconnection occurs, the control system start a recovery procedure testing each internal subsystem in order to reactivate the original functionality.

The lower voltage limit is used to prevent batteries degradation due to deep discharge; monitoring system actuate an internal bypass if these conditions are reached. The bypass disconnect the load from the ESS and reconnect the system directly to the distribution grid to start the accumulator capacity recovery without output any absorption. Control system keeps the ESS disconnected from loads for not less than 20min, also if problem is fast solved, in order to evaluate functionality of each elements before reconnection and also to stabilize some parameters like temperature and internal energy of the batteries. When recovery is completed, the ESS is reconnected to the loads like in standard situation and the recharge phase continues using standard rules.

Any reconnection of the system to the house appliances is performed checking constantly the load absorption and when the power requested decrease under 250W, control system reconnect the ESS between distribution grid and the house, removing the previous bypass. This solution is adopted to reduce as much as possible any current peak during switching and also to avoid stress to internal elements.

Control system had also the main role to permit the communication and the interaction with the cell controller. The EMU previously present in the residential building was disconnected from the electric plant and inserted inside the ESS. It continue to perform the consumption monitoring but new parameter and functionality were implemented:

- Input power monitor, to check the absorption from distribution grid side
- Output power absorption, to perform the same monitor of the residential consumption as done before
- Battery SOC monitor to check the instantaneous level of energy available in the ESS
- Remote control by cell controller to permit disconnection of the residential utilities in case of grid overload (simulated). This condition sets the ESS in UPS modality in order to ensure a good supply of all the loads and at the same time light the energy absorption on the distribution grid.

5.2.1.5. Assembling an test

Before the assembling all the single components were tested to guarantee the correct functionality:

- The battery charger has proved to be an excellent choice recharging the batteries in less time than how much considered and maintains a high efficiency, always above 90%.
- Batteries for energy storage, the FIAMM 12FLB350, showed an excellent resistance to shocks like deep discharge, even with high currents, with a total capacity very close to the nominal value. The voltage tends to remain constant in the range of discharge allowing an optimum power supply to the inverter also with a low charge level.
- The power inverter was tested first with a 6kW resistive bank and then with a set of appliances to simulate a condition of use as similar as possible to the domestic environment, as in standard condition in which the system was then installed. In both cases, the output voltage remained constant even with low battery charge. This prevents excessive stress when the system switch from main grid to inverter.

When all the components were tested, a review phase of the initial design started due to a consideration of safety factors previously ignored. This forced to modify the output stage of the Energy Storage System. The final configuration has added some features in case of emergency, like a push button that can be actuated manually by the user, to disconnect the system and connect all the utility to the main grid. The system was designed to still work without the supervision of the control chip, but functionality are limited and remote control from ceil controller was not possible.

When all the tests on the single components were performed, assembling of all the ESS started to realize four complete systems, one for laboratory test and three for real implementation in the village.

All the internal element are assembled into an IP66 cabinet to guarantee good working conditions when installed in outdoor or adverse environments; it is equipped with four wheel to allow an easy transportation and installation.

All connection to the EDS or to the residential electric plant can be done through simple screw terminals.
The first four prototypes were then composed by 5kW single phase pure sinusoidal inverter, two 12V 90Ah lead acid batteries for photovoltaic applications, an 230VAC/24VDC high efficiency charger limited to 600W, a control system based on PIC16F886 Microchip controller and the EMU connected for remote supervisioning.

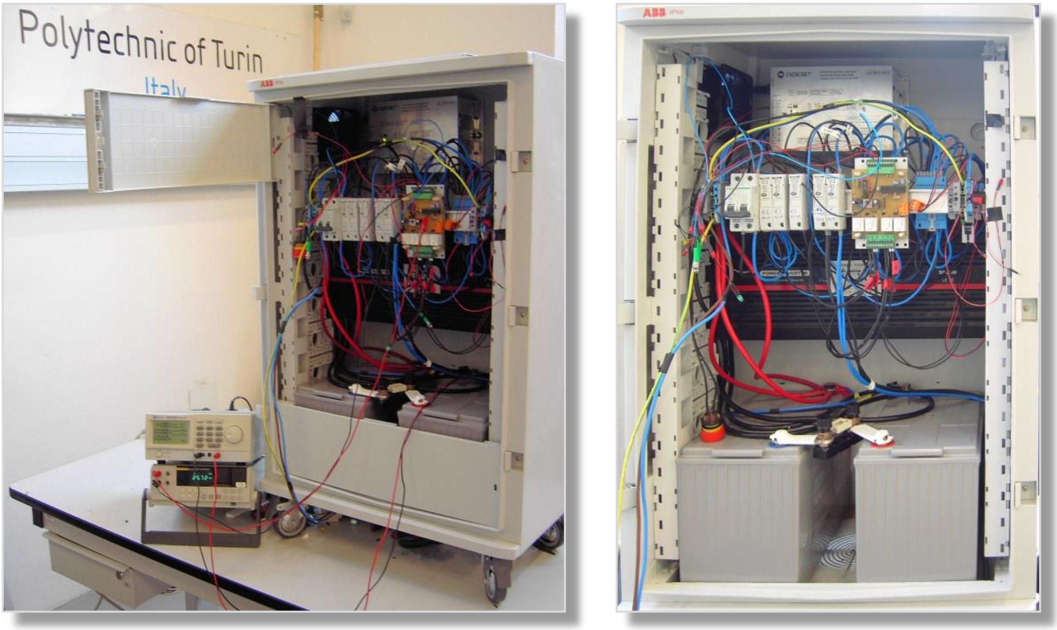


Figure 50: Assembling of Energy Storage Systems

5.2.2. ESS installation

When the assembly and test of the 4 ESSs were finished, the installation in the three localities chosen for the implementation started; three families were selected for the implementation:

- A young couple (<40 years) living in new detached house
- A family composed by four people living in a cottage
- A mature couple living in a mountain cottage

At the same time an intensive phase to control and monitor was activated to ensure that all systems work with household appliances without any problems. This monitor and data acquisition continued till the end of the project.

Figure 51: Installation of ESS in citizens houses in Saint Denis

5.2.3. ESS implementation and anomalies

After several days of use of the ESS , first anomalies were found: one of the user, the young couple, instead of a standard electric plant for the light system, it had installed in his house a domotic system for light management. These plants are characterized by a programmable control unit connected with all the light points and to all the command buttons; in this way is possible, from any position of the house, turning on or off the light according to requirements and electrical configuration can be changed easily without have to change the electrical wiring but only modifying the configurations in the control unit. The anomaly was that, using ESS for household supply, from time to time a light was turned on unintentionally. Measurement and local tests performed on the ESS show that system functioned properly and all the other appliances in the house gave no trouble. Performing additional tests has evinced that the problem was caused by the connection and detachment of appliances with high request of power; during these connections small power surges happens due to large current demands. These changes created some disturbs to the control unit that switched on lights involuntarily but without causing any damage. After a short period the system in that location was disabled as a precaution and till the end of the year only the consumptions sampling were monitored and not the ESS functionality.

One month after the implementation another ESS, installed in the family's cottage, broke down, stopping to provide power to the house. From first on site analysis it was discovered that the problem was caused by a malfunction of the inverter; returned the system in the lab and every system was checked. Damage was found on the output inverter that had all the internal fuse burned. Checking load absorption few minutes before the breakdown, an overload situation bigger than system specifications was discovered. In fact user had connected to the ESS a tool for wood working with absorption peaks during the switch on phase of more than 10kW. Since our system was calibrated to deliver 5kW continuous and 10kW for short moments, the fuses cut the energy for protection, but the inverter was damaged anyway. The user was therefore excluded from the test phase and also from monitoring network due to the long time required to fix all the system.

The last installation, the one in the mountain cottage, has never had big problems till the end of the monitoring period, only some disconnection happen due to deep discharge due to very high voltage drop of batteries especially during colder day when temperature reach a minimum of -8°C. The collected data was very useful to validate the project hypothesis.

5.2.4. Implementation results

Despite every problem found during development ad during implementation, the ESS proved what was previously assumed: the possibility to realize a low-cost systems that can handle the absorption peaks of households while ensuring an UPS function in case of blackouts. Analysing consumption profile logged during the final implementation, it's possible to see how the profile of discontinuous absorption is transformed into a constant absorption with the relative comparison with the state of charge and discharge of the internal batteries. Considering a single day and matching consumption profile of the loads and power request to the grid, is possible to see how system really work.

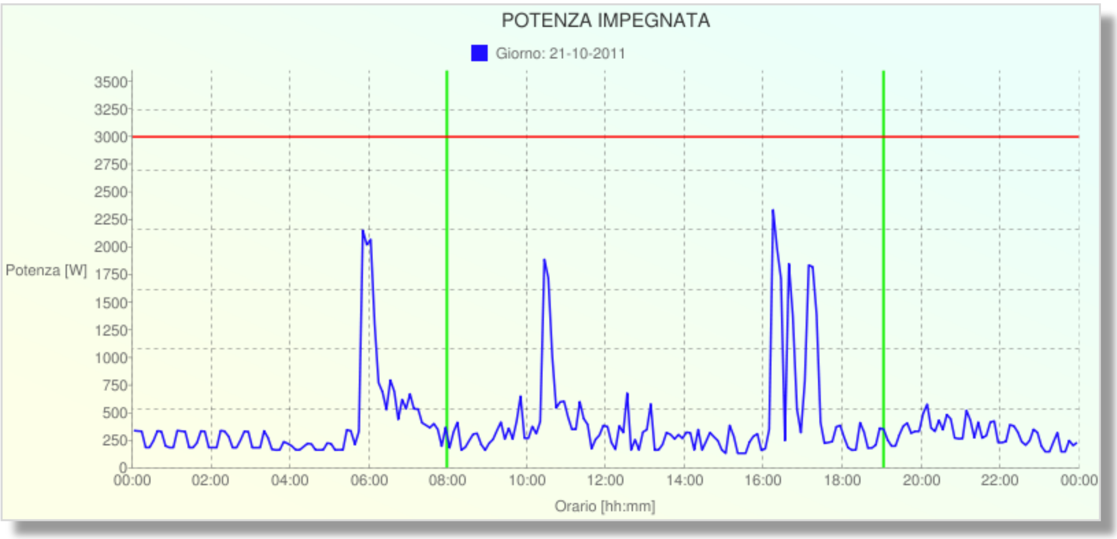


Figure 52: User's absorption profile

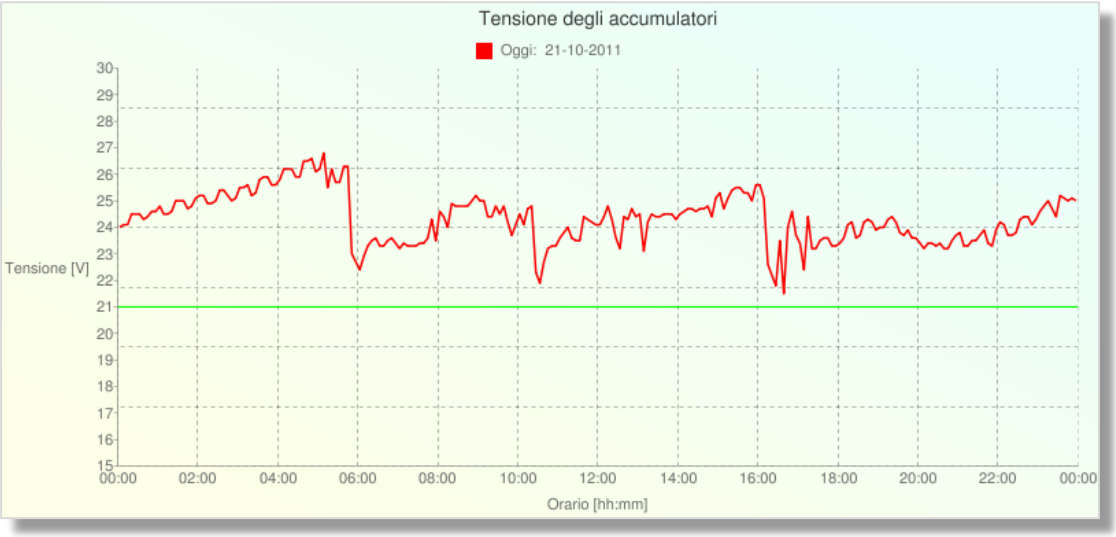


Figure 53: Charge/discharge profile of the batteries

Figure 54: User's absorption profile viewed from the National grid

Batteries' voltage vary from a maximum value of 27V when fully charged till to 20V when fully discharged. Voltage change proportionally till 20% of state of charge (SOC) and then increase the falling velocity if load keep constant.

From the above figure is possible to highlight all condition managed by the ESS: starting from midnight the state of charge of the internal accumulator is around

40%/50%. Thanks to all the night available and the low amount of load absorption of the house, ESS reach the complete charge near 05:30 and also power absorption from EDS decrease due to the reduction of the power to recharge batteries. Then at 06:00 a heavy load, like a washing machine cycle, discharge the internal storage till 30%. High load's absorption peaks correspond to deep discharge of the accumulators. Along the day same cycle were repeated, with charge and discharge phases, till the late afternoon, after 16:00, when multiple heavy absorption discharge the ESS completely. A green line is reported in the SOC graph; that represent the minimum value of SOC, equal to 21V, to not keep system into critical working conditions. When SOC continue to decrease and reach the minimum value of 20V, the system is automatically bypassed.

All the absorption profile seen by the network were completely levelled and shaped around a constant value that doesn't exceed 600W and is determined by the input stage of the ESS, the battery charger absorption, while the user absorption is similar to those registered during the monitoring phase, before the integration with the ESS, showing random and "nervous" behaviour.

This implementation aim to demonstrate that diffusion of multiple system such this, using a simple architecture, is able to bring great benefits both to the electricity grid, with a significant decrease of the load that have to be managed by the distribution network, and to the final user, that is not forced to radically change his consumption behaviour, even when in the future could be introduced a much more invasive loads management by the DNO, with short-term utilities disconnection in case of grid overload or instability. Another good feature to consider is the improving of power quality for the final user that can reduce the probability of line voltage blackouts or fluctuations.

From field tests is possible to observe that the installed capacity is adequate to satisfy all the absorption peaks over 600W in the residential application that have an average consumption along the day between 5kWh and 8kWh. A 20% capacity increment can assure a better stability to the whole system.

Chapter 6 - Conclusion

The present dissertation discussed the modelling, design and implementation of a VPS in order to realize a sort of micro Smart Grid in a real case study.
The main contribution of this work consist in:

- Development of simple solution for energy monitoring and data acquisition from main power sources and loads involved;
- Development of software algorithm to manage and perform analysis for the real time energy management;
- Find new and innovative way to involve final customer in their daily energy management to improve whole performance;
- Development of new technical solution to manage locally the energy and increase distribution grid energy management and stability.

Proposed study has shown that ESS has become an essential element for the management and the balance of the Smart Grids. Power Shaving allows reduction of peaks absorption and stresses on the distribution grid, with a more homogeneous and efficient energy deliver, reducing risk of blackouts.

A storage system, as the ESS1.0, locally distributed and interposed between the distribution grid and the house, can lighten the network in case of overload without renounce to guarantee an high quality power supply to the customer. At the same time, in a distributed reality, it allows to manage energy flows reducing risk of distribution grid overload and increasing energy efficiency. The ESS proved what was previously assumed: the possibility to implement a low-cost systems that can handle the absorption peaks of households, while ensuring an UPS function in case of blackouts.

Furthermore if final user become active and is involved into his personal energy management through a constant education and information, an improvement of his "consumer behaviour" can be obtained, and very significant results can be reached in a short time. Only incorporating him into a sort of "virtual feedback" that closes the control loop of the VPS on him, it's possible to ensure the best performance of the system. In this way the final user is not forced to change his behaviour but is naturally pushed to do that because he understand the meaning of his actions.

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