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The road to the diffusion of the Smart Grids: theoretical development and experimental management of a Smart User power plant

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Declaration

I hereby declare that this submission is my own work and, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at University of Florence or any other educational institution, except where due references are provided in the thesis itself.

Any contribution made to the research by others, with whom I have been working at the University of Florence or elsewhere, is explicitly acknowledged in the Thesis.

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Sandro Magnani
December 2013

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Publications

The papers listed below were published or submitted for publication during the candidature.

1. Chesi A., Ferrara G., Ferrari L., **Magnani S.**, Tarani F., Influence of the heat storage size on the plant performance of a Smart User case study, *Applied Energy 112* (pp. 1454-1465), December 2013.

2. Barsali S., Poli D., Scalari S., Petretto G., Pentolini M., Ferrari L., **Magnani S.**, Experience on energy management in an industrial district, *Proceedings of the 22nd International Conference and Exhibition on Electricity Distribution*, Stockholm (Sweden), June 2013.

3. Bianchini A., Ferrara G., Ferrari L., **Magnani S.**, An improved model for the performance estimation of an H-Darrieus wind turbine in skewed flow, *Wind Engineering 36-6* (pp. 667-686), January 2013.

4. Chesi A., Ferrara G., Ferrari L., **Magnani S.**, Tarani F., Thermal storage and CHP coupling in a Smart User case study, *Proceedings of the International Conference on Applied Energy (ICAE) 2012*, Suzhou (China), July 2012.

5. Bianchini A., Ferrari L., **Magnani S.**, On the effects of a skewed flow on the performance of a three-bladed H-Darrieus turbine: experimental and theoretical analyses, *Proceedings of the International Conference on Applied Energy (ICAE) 2012*, Suzhou (China), July 2012.

6. Bianchini A., Ferrari L., **Magnani S.**, Energy-yield-based optimization of an H-Darrieus wind turbine, *Proceedings of the ASME Turbo Expo 2012*, Copenhagen (Denmark), June 2012.

7. Balduzzi F., Bianchini A., Ferrari L., **Magnani S.**, Feasibility analysis of a Darrieus vertical-axis wind turbine installation in the rooftop of a building, *Applied Energy 97* (pp. 921-929), September 2012.

8. Bianchini A., Ferrari L., **Magnani S.**, Start-up behavior of a three-bladed H-Darrieus VAWT: experimental and numerical analysis, *Proceedings of the ASME Turbo Expo 2011*, Vancouver (Canada), June 2011.

9. Bianchini A., Carnevale E.A., Ferrari L., **Magnani S.**, Analisi delle Condizioni di Avvio di una Turbina Eolica Darrieus-H, *Proceedings of the 65° ATI Congress 2010*, Cagliari (Italy), September 2010.

10. Bianchini A., Ferrari L., **Magnani S.**, Analysis of the Influence of Blade Design on the Performance of an H-Darrieus Wind Turbine, *Proceedings of the ASME-ATI-UIT 2010 Conference on Thermal and Environmental Issues in Energy Systems*, Sorrento (Italy), May 2010.

Synopsis

The increasing energy production from unpredictable renewable sources, combined with the uprising need to meet the growing world energy demand with a decrease in the greenhouse gases emissions and lower energy supply costs, are pushing the research efforts towards the development of smart energy management tools and systems. Starting from the Smart Grids at the largest spatial scale to the small Virtual Power Plants, passing through the Micro Grids, several case studies are conducted onto these results.

Within this context, the Japanese Yanmar Holding group, embodied in its Italian research center Yanmar R&D Europe, in partnership with Enel Ingegneria e Ricerca, s.d.i. automazione industriale, and Pontlab, decided to develop an system based on a Yanmar micro-cogeneration engine able to smartly manage different types of energy from several production devices to some categories of loads, with the final objective to reduce the energy costs and, consequently, the CO_2 emissions, ready to fulfill the requirements of the next energy scenario in terms of communication with the DSO and of incentives, with the fundamental purpose of presenting to the external grid a predictable energy exchange profile.

To this purpose, a preliminary analysis on the existing technology was undertaken, with the main purpose to understand the future trends for the energy market and to set in mind the most important goals which had to be achieved with the developing management system.

A so called Smart User was thus defined, both in terms of hardware equipment needed and of plant layout: starting from this latter point, a dedicated optimization tool, based on the Genetic Algorithms, was developed, with the fundamental assumption that it could be also applicable to different systems, all characterized by the same layout but with different constraints of the particular energy scenario and with a modified size of the installed pieces of equipment.

The algorithm was firstly verified by several off-line simulations, in order to verify its robustness and reliability, and to understand the most influencing parameters for the selected experimental case study.

Only after this necessary activity it was implemented into a SCADA system in the experimental test bench, which helped to understand the effective behavior of the system on the field, concerning several test involving the three different operation options of the system: the optimization schedule of all the devices and of the deferrable loads for the next day, the correction performed by the system on the present day based on the most recently update load and weather forecasts, and the real time management of the plant with the objective of ensuring a pre-determined energy exchange profile with the external power grid.

In order to provide an organic discussion of the research activity, the main results of the work have been divided into six chapters, on the basis of a logical sequence which could be able to move the analysis from a general overview of the present challenges in the energy management to the specific outcomes of this work.

To this purpose, in Chapter 1 is presented a background of the world energy matter which led to the beginning of the thesis activity.

The main solutions in the research field dealing with the presented problems are presented in Chapter 2, considering both large and small spatial scale solutions.

In Chapter 3 the energy management system concept proposed within the thesis work is described, with particular attention on the hardware matters, in terms of the selected plant layout and of the sizing of the different pieces of equipment.

The “core” of the system is presented in Chapter 4, describing the optimization algorithm purposefully developed, its operations and the computational system which necessarily should be implemented in.

In Chapter 5 all the simulated and experimental results are presented, with particular reference to the obtained results in terms of the energy price reduction, the electric exchange profile with the grid, and the influence of the errors on the forecasts to the final result.

Finally, some conclusive remarks are provided in Chapter 6.

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Subscripts

c	cooling
e	electric
th	thermal

Acronyms

AEEG	Autorità per l’Energia Elettrica e il Gas
BPR	Balancing Responsible Party
CAISO	California Independent System Operator
CAMC	Central Autonomous Management Controller
CAR	Cogenerazione ad Alto Rendimento
CCHP	Combined Heat, Cooling and Power
CCS	Central Control System
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CERTS	Consortium for Electric Reliability Technology Solution
CHP	Combined Heat and Power
COP	Coefficient Of Performance
CSV	Comma Separated Values
DCS	Distributed Control System
DER	Distributed Energy Resources
DG	Distributed Generation
DoE	United States Department of Energy
DOE	Design On Experiment
DSO	Distribution System Operator
EEGI	European Electricity Grid Initiative
EMS	Energy Management System
ESO	European Standardization Organization
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
GA	Genetic Algorithm

GHG	Green-House Gas
HAWT	Horizontal Axis Wind Turbine
HMI	Human Machine Interface
HV	High Voltage
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
I/O	Input/Output
LHV	Lower Heating Value
LV	Low Voltage
MEDA	Maharashtra Energy Development Agency
MG	Micro Grid
MGCC	Micro Grid Central Controller
MGP	Mercato del Giorno Prima
MILP	Multiple Integer Linear Programming
MINLP	Multiple Integer Non-Linear Programming
MV	Medium Voltage
NEDO	New Energy and industrial technology Development Organization
OEM	Original Equipment Manufacturer
PC	Personal Computer
PEM	Proton Exchange Membrane fuel cell
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Programmable Logic Controller
PM	Prime Mover
PQR	Power Quality and Reliability
PSO	Particle Swarm Optimization
PV	Photo Voltaic
RES	Renewable Energy Sources
RI	Regional Initiative
ROI	Return Of Investment
RTU	Remote Terminal Unit
R&D	Research and Development
SA	Stand Alone
SCADA	Supervisory Control And Data Acquisition
SET	Strategic Energy Technology
SG	Smart Grid
SMS	Short Message System
STAR	Station for data Acquisition and Regulation

SU	Smart User
TCP/IP	Transmission Control Protocol/Internet Protocol
TEE	Titolo di Efficienza Energetica
TOE	Tons of Oil Equivalent
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
UK	United Kingdom
USA	United States of America
VPP	Virtual Power Plant
VSA	Virtual Stand Alone
V2G	Vehicle-To-Grid
ZNE	Zero-Net Energy

1. Introduction

1.1 Background

The world energy supply was since now dominated by large-scale power plants fed by fossil fuels (coal, oil, natural gas), nuclear and hydro-power, with the electricity delivered over long distances to consumers by means of the High Voltage (HV) transmission grids (Figure 1), but now this layout is presenting some critical drawbacks.

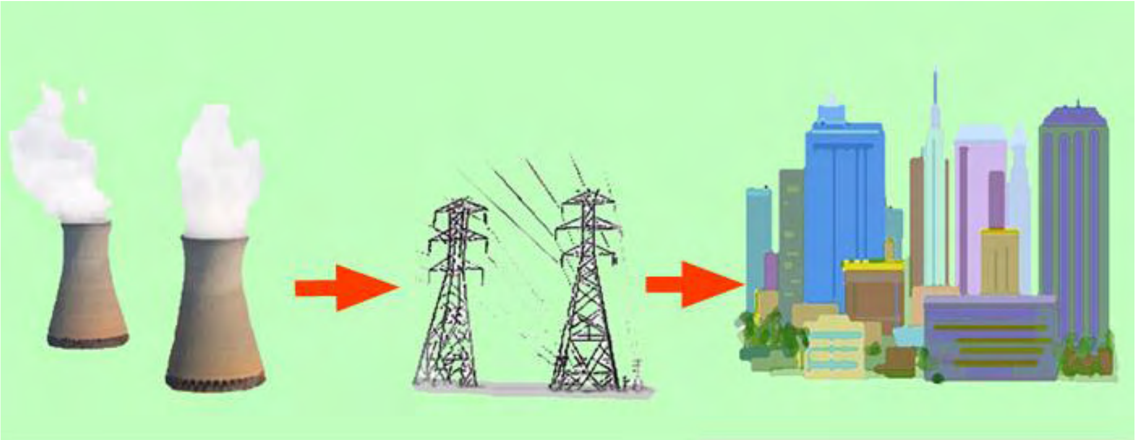


Figure 1 - "Traditional" power supply

On one hand, a significant amount of generation plants, in particular coal- and nuclear-powered ones, is approaching the commercial end-life, even if procedures for the operations extension are attempted; in addition, the power grid infrastructure (both transmission and distribution) is old, thus requiring large investments in a short-term period for its enhancement. On the other hand, the continuous increasing demand for energy, whose growth was only recently lowered due to the economic crisis (Figure 2), has stressed a number of shortcomings:

- The dependency on imported fuels for most of the industrial Countries, leading to potential price rises and supply disruptions;
- The environmental impact of the Green-House Gases (GHGs) produced by the combustion of fossil fuels, in addition to the other pollutants;
- The large transmission losses, due to the transportation of the electricity over long distances;
- The reduction in the Power Quality and Reliability (PQR), with frequency and voltage fluctuations in very short-time periods, leading to an increase in the energy consumptions;
- The need for the upgrading of the transmission and distribution networks;
- The congestion of some grid lines, due to the increasing diffusion of both small- and large-size unpredictable Renewable Energy Sources (RESs).

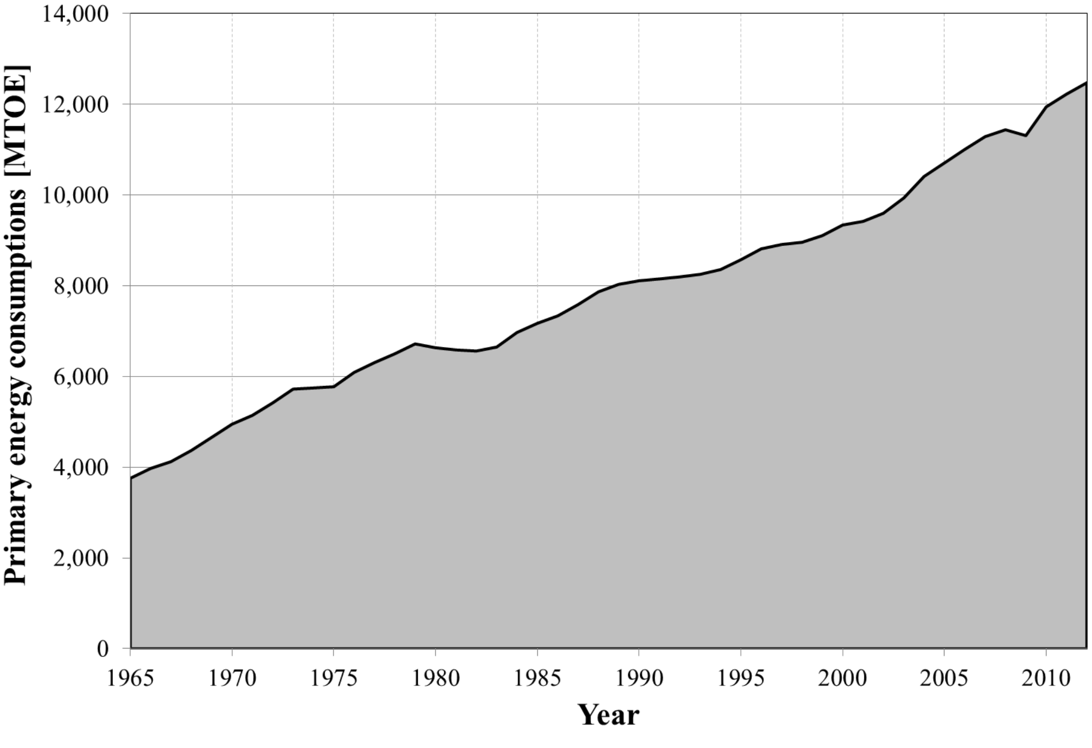


Figure 2 - World primary energy consumption trend [1]

Remaining the energy one of the major component of the economic growth (e.g. in recent years the increase in the Gross Domestic Product (GDP) of China was limited by the insufficient supply of energy sources), such deficiencies have a direct impact on the world economic development, on the stability (concerning the security of energy supply), and on the environmental protection: these issues provide the main drivers for the energy industry towards a different paradigm of the energy system.

Indeed, the current grid is a relic of the past, designed to meet the needs of an industry in an era with outdated technologies incapable of meeting the modern requirements: the existing grid was designed essentially as a one-way conduit. The original thinking behind that, from generation to transmission and distribution, was based on the premise that customers load is given, and the generation have to be managed in order to match it. The balancing between production and demand in real time was accomplished by the adjustments on the only supply side.

Until recent times, customer demand was not subjected to any control or manipulation, with virtually no means or incentives for the loads to play an active role. In this “dumb” grid the active management, with the aim of influencing or controlling customer demand, was problematic or impossible, mostly due to the limitations of the technology, particularly in two areas:

- The energy meters used for the measurement of the consumptions for all but the largest customers were only capable of registering the energy flows, not differentiated by time of use, voltage, current, or anything else;
- The limitations in the communications between the suppliers and the end-users.

The suppliers, as well as the grid operators, need much more robust means of communication to both send price signals and receive feedback from consumers in real time, if there is any will of influencing the demand. The metering limitations place severe restrictions on how electricity could be priced (resulting in flat rates, undifferentiated by time or location, application, or anything else). Moreover, the limitations on communications mean that the revenue collection could only be rough. Until recent times, most consumer bills were calculated on the basis of limited data (a monthly energy consumption) and in some cases even that could not be achieved, resulting in a largely approximated estimations. Even now some of the consumers, including cases in developed Countries, are billed on a flat multiplier times the volumetric consumption for the enquired period. These technological limitations combined to the low per-unit costs of the power generation mean that the consumers would be billed on simple tariffs that remained flat for all the hours of the day, also not varying across wide geographic areas.

In addition to the technology limitations, also the political and economic issues avoided the development of a more advanced power system. Indeed, for much of its history the electric power industry was favored by enormous economies of scale. As the industry grew and expanded, the electricity could be generated and supplied to the consumers at decreasing costs. The industry was worried about its rapid expansion, needed by a rapid rise in the demand which the falling prices further encouraged. Thus the suppliers benefited from more investments on which they could earn a regulated rate of return, and the same regulation gave them every financial incentive to encourage more consumption: the consumers were encouraged to use more energy, in some cases with falling tariffs, which meant the more they used the lower the per-unit cost. With the introduction of the commercial nuclear power, the electricity would simply seem to be “too cheap to meter”, with the implication that consumers may simply be billed with a flat and low monthly fee.

But in recent years, as the consumer loads have grown, the flat undifferentiated tariffs have turned into something no longer convenient. E.g. with the growth of the air conditioning globally over the past 30 years, the flat and undifferentiated tariffs resulted in highly pronounced peaks of the energy cost. The air conditioning load has become a noticeable nuisance due to its spiky and highly unpredictable nature. For serving these loads, significant investment in peaking generation are required, with the result of price spikes in the market, and with a new interest in how they can be effectively and efficiently managed.

There are several other reasons suggesting that the existing grid is out of line for the current needs and, above all, the future requirements. Among the most compelling reasons is the increasing significance, as said, of RESs. While some of these, such as geothermal or biomass-based, may operate as base-load or can easily be controlled, such as hydro, others, particularly wind and solar energy, are intermittent by nature and largely non-dispatchable. Our existing grid is badly equipped to deal with a large diffusion of these types of sources [2-5].

Transmission and Distribution System Operators (TSOs and DSOs) dislike non-dispatchable resources that are not under their direct command and control. Moreover, the intermittency and variability play a detrimental role in the traditional means of balancing supply and demand, which is based on scheduling generation to meet variable but highly predictable loads [6-8]. This matter does not allow going forward in many parts of the world, where intermittent renewables are projected to make up a third or more of the resource base [9,10]. As an example, in the European Union (EU), the target is to meet 20 % of the energy requirements by 2020 from RESs [11], as schematically shown in Figure 3.

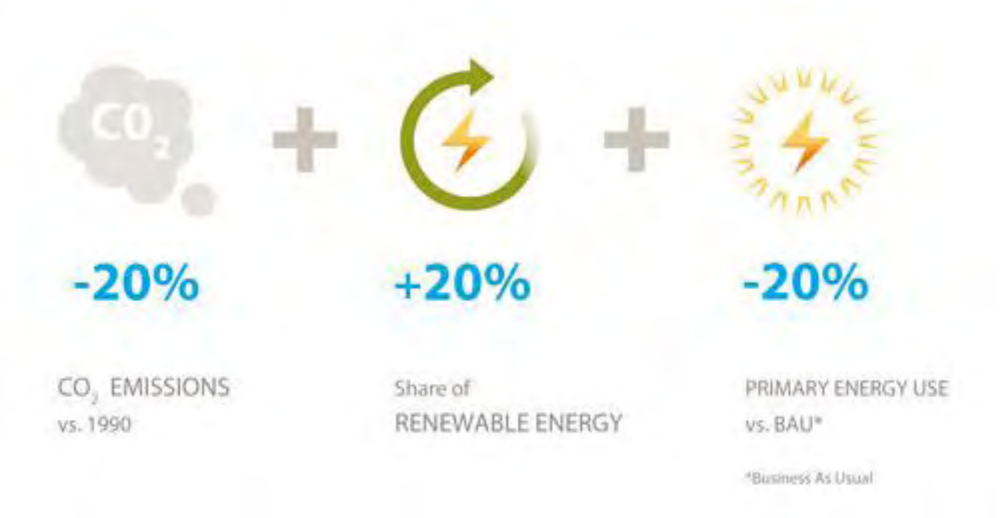


Figure 3 - EU energy policy target at 2020

Germany, following the Fukushima accident in Japan in March 2011, is considering a total phase-out of its existing nuclear fleet, mostly to be replaced by renewable energy (as much as 80 % of the generation needs by 2050) [12].

Another major phenomenon affecting the electric power sector is the emergence of Distributed Generation (DG) (Figure 4).

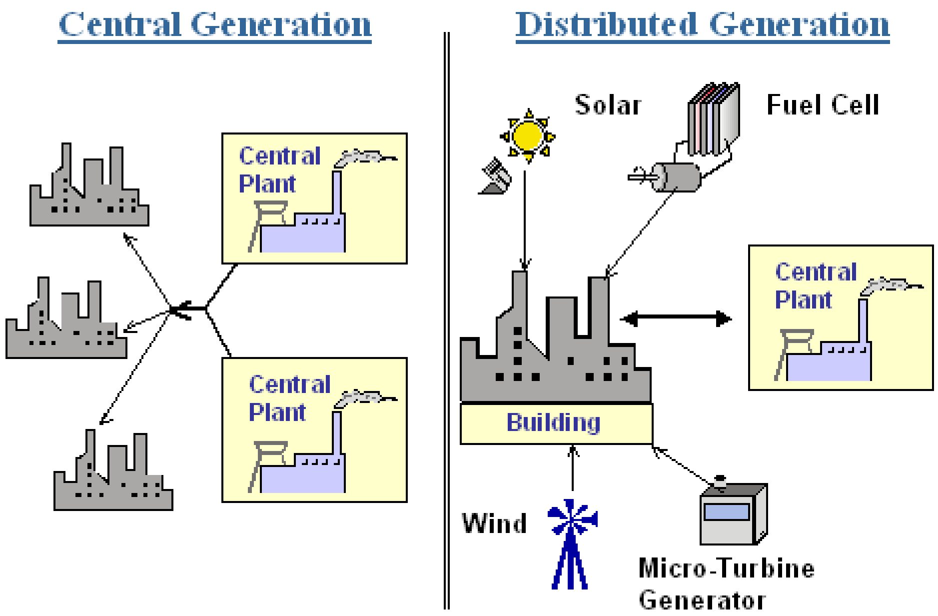


Figure 4 - Centralized vs. distributed generation

With rapid technological development and an equally rapid drop in prices, many DG technologies already are commercially viable [13-16]. Many industrial, commercial, and even residential customers can generate a growing percentage of their internal needs from localized or on-site DG resources. Rooftop-mounted solar PV panels, solar hot-water collectors, ground-source geothermal heat pumps, Fuel Cells (FCs), micro-Combined Heat and Power (CHP) systems, and a number of other emerging technologies mean that consumers can become self-sufficient or, in some cases, be in a position to sell their exceeding generation to the grid. This created not only technical challenges for the utilities, but also raised a number of issues such as how much they should pay for the electricity when it is fed into the grid. Moreover, the fact that an increasing number of customers may conveniently become small producers (the so-called *prosumers*, from the fusion of the words *producers* and *consumer*s), poses challenges to the utilities and the network operators on who must maintain the network even in the face of flat or falling consumption. Making matters more complicated, there is the growing interest in energy efficiency promoted in a large number of jurisdictions. Since in many cases the cheapest energy purchase may be that not consumed, utilities with high and rising rates may be facing something totally unprecedented: demand elasticity. As they raise retail rates, consumers may find it attractive to cut back consumption, either through investing in energy efficiency and/or self-generation. The utilities can no longer assume that the consumers will consume what they always have. For better understand this tendency, within the EU the concept of Zero-Net Energy (ZNE) or passive homes has been proposed [17]. At its core, ZNE requirements will result in a strong decline in the customer energy consumption (Figure 5) from outside as an increasing number of households meet the new standards.

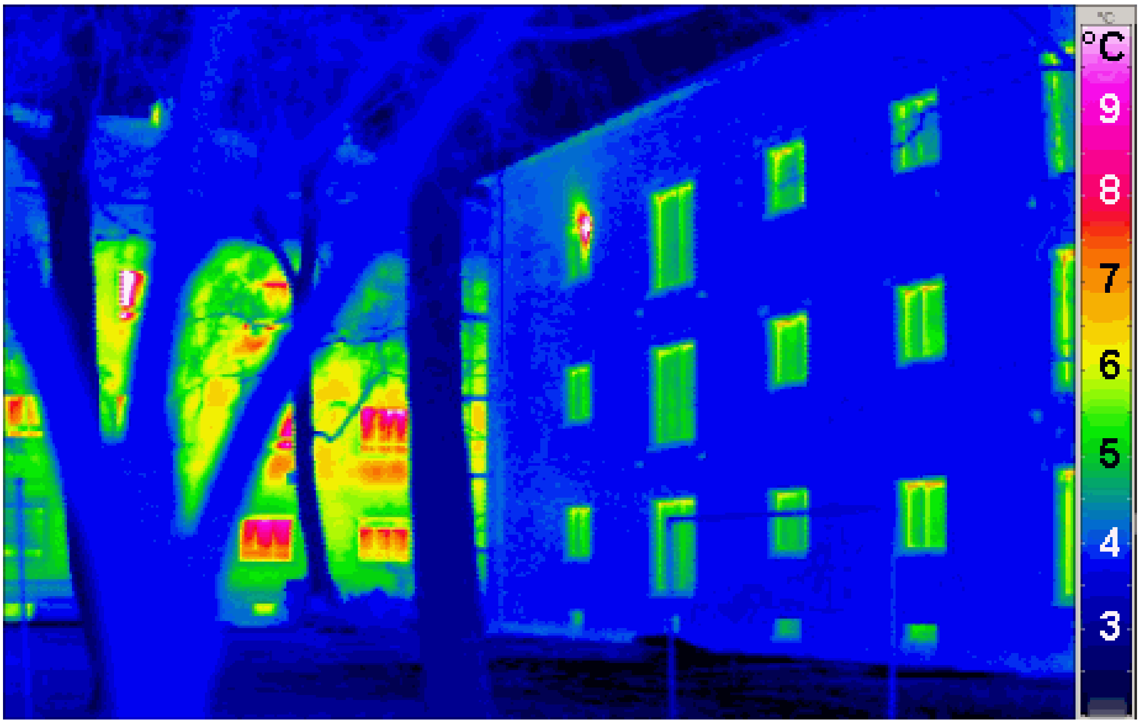


Figure 5 - Thermographic picture comparison between a passive home (right) and a "conventional" home (left)

Since an average home or office cannot generate a lot of power, the only conceivable way to meet the ZNE requirement is to decrease the consumption by increasing the efficiency of the energy use. This means higher efficiency appliances, improved lighting, better shell insulation, and improved and more sparing use of the energy. Moreover, because the on-site power generation is unlikely to be correlated with on-site consumption, the average consumer will be feeding its excess generation into the grid for a part of the generation time, while taking power from the grid at other times.

The grid of the future will therefore be required to work much harder than today. This has important implications on tariffs, which must not only be dynamic, but reflect the two-way nature of transactions. In case of nearly-zero or null consumptions from the grid, with the connection still standing for back-up reasons, traditional tariffs based on a multiplier times volumetric consumption could no longer be applied. The definition of service must change from what it used to be. The time has arrived for utilities to consider alternatives to billing customers based on flat rates and volumetric consumption.

Still, other technical developments are likely to further complicate the traditional grid and the traditional utility service paradigm. The next generations of Plug-in Hybrid and full Electric Vehicles (PHEVs and EVs), for example, not only promises to serve as a potentially huge storage medium for grid operators to "dump" vast amounts of unneeded intermittent energy when network demand is low, but also offers the possibility that some of the stored energy may be fed back into the grid during high demand periods, the so-called Vehicle-To-Grid (V2G) [18-20] technology (Figure 6).

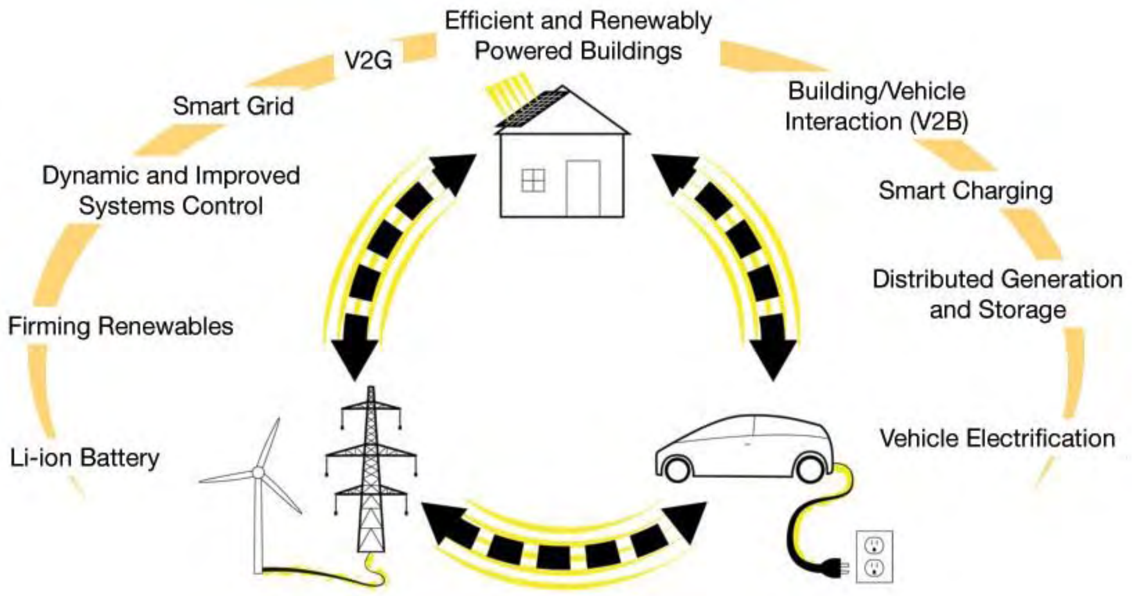


Figure 6 - V2G concept schematic

Energy storage, whether in EVs or in centralized plants or in the form of energy stored in other media is recognized as a central requirement of any Smart Grid (SG) of the future [21-24].

2. The next energy scenario

2.1 The Smart Grid

2.1.1 Definition

Despite the widespread diffusion of the Smart Grid concept, there is no universal definition of what it practically means. There are as many definitions of SG as there are Smart Grid projects, experts, or technicians. This poses a challenge consisting of contributions from a diverse number of experts, scholars, academics, and practitioners from different sectors, representing different disciplines and perspectives. For these reasons, it is helpful to provide a definition and scope for the SG at the outset.

The Smart Grid can be defined as any combination of technologies (both hardware and software) or practices that make the infrastructure or the grid more reliable, secure, efficient, and, last but not least, useful and cheaper for the consumers. For the achievement of all these aims, the Smart Grid must consider a number of key features and characteristics including (Figure 7):

- The easy integration of different supply-side resources, including an increasing level of intermittent and non-dispatchable RESs;
- The easy support to the integration of distributed and on-site generation on the customer side;
- The opportunity to promote more active engagement of demand-side resources and the participation of the customer loads to the effective grid operations;

- The opportunity to facilitate the widespread of the dynamic pricing of the energy, enabling intelligent devices to adjust the customers non-privileged loads on the basis of the energy price variations and other signals and/or incentives (e.g. the availability from the customer to supply ancillary services to the grid);
- Turning the grid from a one-way conduit delivering electricity from large centralized plants to users load, to a two-way, intelligent system, allowing power flows in different directions, at different times, from different sources to different sinks;
- The presence of both small-size energy storage devices on customers' premises and large-size centralized devices to store energy when it is plentiful and inexpensive to be utilized during times when the reverse is true, in an intelligent and efficient way;
- Allowing the diffusion of the DG as well as the distributed storage to actively participate in balancing generation (especially by RESs) and loads;
- Encouraging a more efficient use of the supply-side and delivery network through efficient and cost-effective implementation of dynamic pricing;
- The easing of any attempt for diffusing a greater participation of the customers in balancing supply and demand in real time through the concept defined as "demand-response";
- Making the grid more robust, reliable, and secure;
- Accomplish all the mentioned aspects while reducing the costs of the operation and maintenance of the network.

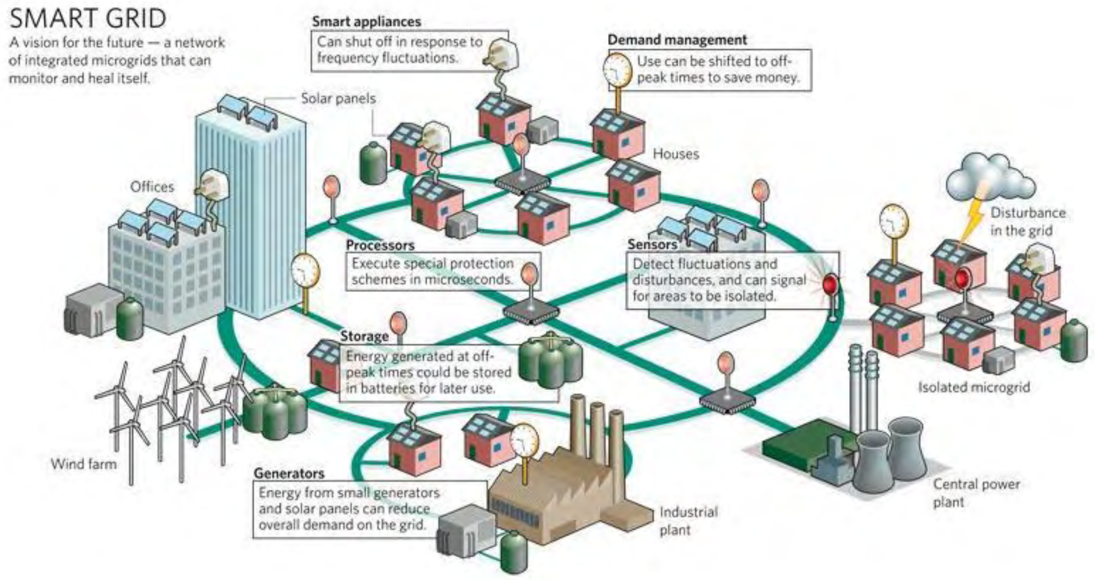


Figure 7 - Smart Grid conceptual schematic

In addition, the SGs offer the possibility to address the challenges posed by climate change, something that may not be immediately obvious or generally acknowledged. As mentioned, the Smart Grid allows to integrate an increasing percentage of RESs as well as a better balancing of generation and loads, both of which address concerns about climate change.

The implementation of dynamic pricing in conjunction with the introduction of the enabling technologies is expected to lead to the “prices-to-devices” concept [25], which in turn, promises to unleash the full potential of smart prices delivered to smart devices through smart meters resulting in more efficient utilization of electricity.

There are already indications that electricity markets and grid operators are beginning to take appropriate steps in response to concerns about climate change. E.g. the rules of conduct in the electricity market in the UK are being modified in response to Government's desire to meet future low carbon emission targets [26]. In the case of California, the CAISO has developed a future Smart Grid vision in response to the State's ambitious climate Law as well as the 33 % renewable target mandated by 2020 [27].

While the concept of energy efficiency is understood by many consumers, their use of energy tends to be driven more by their desire for comfort and convenience than by the effect on system costs or emissions reductions. Smarter technologies and a smarter grid are critical to achieve this potential: the Smart Grid should actively identify energy efficiency opportunities throughout the entire system, using better information for better decisions. Smart homes and buildings will be able to monitor equipment performance, optimize comfort and efficiency, and convey environmental performance [28-30]. In the Smart Grid, energy efficiency will become intrinsic to how buildings are operated. Modernizing equipment and automating operations can significantly improve the performance, reduce losses, and reduce the operating cost of the grid. Most of the cost and benefits of the Smart Grid occur in the distribution network (Figure 8).

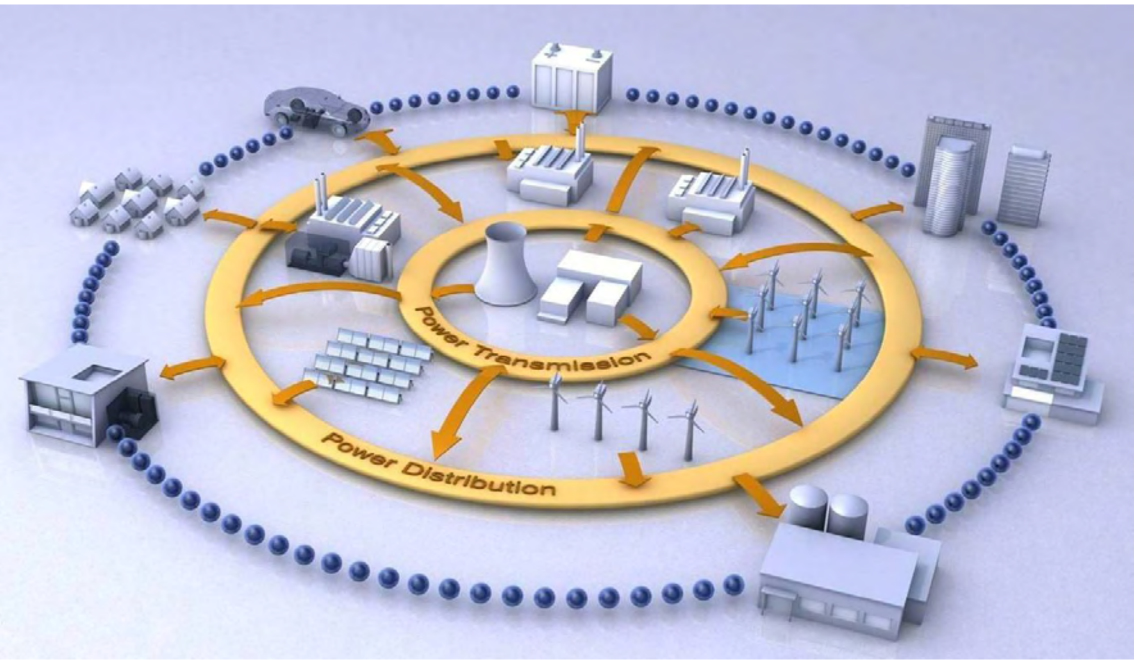


Figure 8 - Central role of the distribution network in the Smart Grid [31]

New technologies and systems are needed to implement active maintenance and repairs, reducing failures and increasing the life of aging equipment. Significant energy savings are possible through techniques such as voltage optimization and dynamic line rating. Many utilities have begun to address this issue by installing sensors, communications, and controls at critical points. The knowledge of the status of various devices in real-time can enhance the ability of operators to optimize power flow and quality. Digital meters equipped with the ability to communicate at each account location can reduce the cost of reading the meters, automatically report local outages, allow operators to remotely connect and disconnect accounts, monitor voltage levels, and provide other benefits. More progressive utilities have installed automated systems with dynamic digital maps and sophisticated management tools. These features not only improve the efficiency of utility operations, but also open up new levels of service. Given their different starting points and driving motivations, the full benefit of automating operations will vary substantially from one utility to another, with highly customized applications. Eventually, the Smart Grid may provide ancillary services like frequency regulation by automatically adjusting demand with storage devices or by varying certain dedicated loads [32-34].

In designing and building the Smart Grid, it is important not only to optimize the performance, but also to optimize the cost of the grid operations. When consumers decide to buy more electric devices, they expect their electric utility to make sure that electricity is available to power them. This is true whether it's the hottest day of summer or in the middle of a winter storm. Consumers do not perceive the grid-related consequences or costs of their decisions. The industry essentially disengaged the consumers from the activities up-stream of the meter. The easiest way to please the most consumers in the past has been to build the system big enough and robust enough to meet all of their needs anytime. The utilities are asked to estimate the future consumer demand for electricity and build the production and delivery infrastructure (power plants, transmission and distribution systems) to accommodate the increasing loads. Since we cannot store electricity (or, at least, not too much), the production has to match consumer demand at any instant. Moreover, the utilities are asked to build the system 10-20 % larger than the anticipated demand to make sure they can accommodate unexpected increase or loss of critical generation or transmission lines. There are at least two reasons why production capacity is expected to increase more than twice as fast as electricity demand:

- The first is that more than 50 % of the expected capacity increase is attributed to renewable sources [35-38], the availability of which is rarely coincident with peak demand (typically less than 25 % of the time) [39-41], whereas base-load plants are typically available during peak demand;
- The second reason is that the electricity use has been increasingly weather-dependent and peaky.

Business tend to use more electricity in the mid-to-late afternoon, while residences use more electricity in mornings and evenings. More than 10 % of the total production capacity is required less than 100 hours each year [42]. The net result is that in many areas the peak demand is increasing faster than the average demand, a trend that is unhelpful if costs must be kept low and the utilization factors of the large plants high enough. This explains why reducing consumer electricity use during peak times (commonly referred to as *demand-response* or *peak shaving*, Figure 9) has become a high priority [43-49].

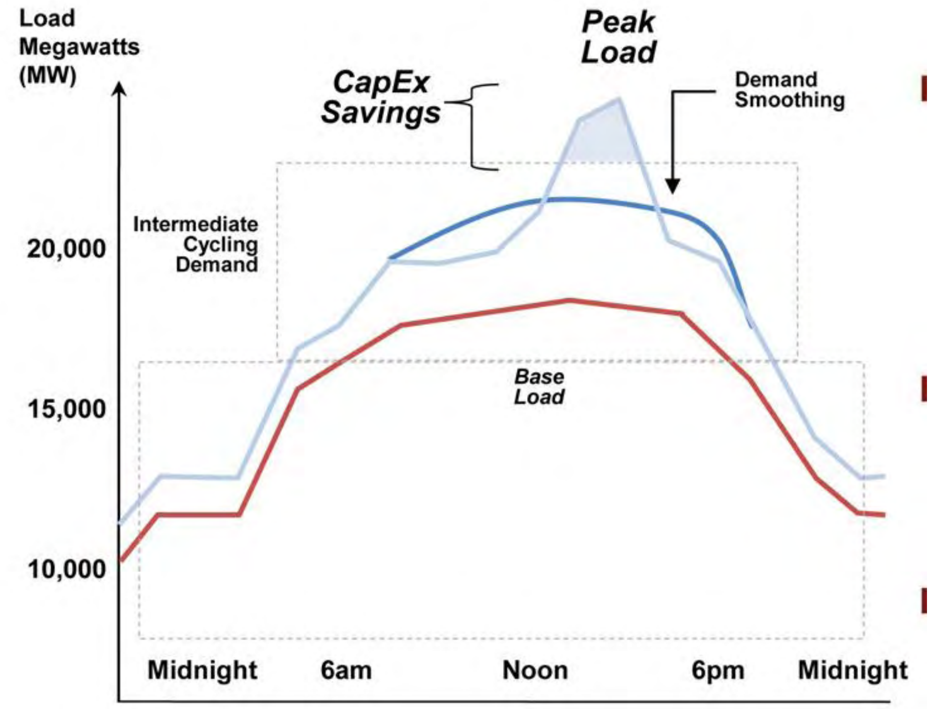


Figure 9 - *Demand-response* concept schematic

There are several technologies and programs that can make demand-response relatively easy and cost effective for consumers. The Smart Grid development requires the utilities to be more consistent in looking for the improvements in the load factor and that consumers to be induced to participate to peak-shaving programs. In the Smart Grid, the exact amount of *demand-response* is less important than the concept of creating a grid that allows the electricity system to reduce loads readily, when necessary, diverting electricity from deferrable to critical and privileged loads. This should be performed automatically and with enhanced consumer participation. Such an energy management system should involve consumers to set their load preferences and to vary them when prices or conditions are more favorable. New technologies and systems might provide ways to induce demand to follow changes in production (and production costs) instead of production responding to changes in load, with the customers no longer being passive subjects but participating to the operations in a more active way. This approach should logically incorporate dynamic rates so that the consumer behavior is linked to the cost of delivering energy at any particular time. One of the important benefits of this change to the grid would be to sharply reduce the reserve margin requirements for utilities and grid operators. This requirement, absolutely critical with the current grid structure and management, could eventually become obsolete, with huge savings in capital investments.

The power industry is beginning to carefully analyze the barriers to rapid scale-up of wind, solar, PHEVs, and other clean technologies and the barriers to managing distributed power sources. Parallel impacts on transmission and distribution operations must be accurately estimated to determine their real value in reducing CO_2 emissions [50-53]. Many studies indicate that when the percentage of renewable sources on the grid reaches 20 % or more (of course, the percentage is strictly dependent from the grid structure), substantial operational changes become necessary [54-56]. Higher penetrations of RESs are possible with additional transmission infrastructure and various operational changes [57,58]. In short time, the drive toward consumer-centric energy systems, as well as expected cost reductions in RESs to the grid parity, will accelerate the installation of such kind of generation systems. This may also drive toward “miniaturized grids” that, combined with local network storages, give the consumers the opportunity for clean critical power systems.

For the Smart Grid the ability to store electricity may be as significant as the availability of information [59-62]. Recent breakthroughs in materials and materials processing have shown promise in reaching this challenging goal. With the investments currently being made globally [63-65], storage, both mechanical and thermal, will likely be a foundational component of the Smart Grid. Storage devices that are networked and flexibly dispatched for a variety of applications have the potential both to drive down costs and increase value. This is one of the main reasons why plug-in vehicles have received so much attention: they eventually should be able to provide electricity storage for their own use, as well as the grid, providing opportunities to create other markets and applications [18-20,66-68]. Historically, storages have been focused on individual applications such as vehicles or bulk storage to increase the efficient utilization of renewable resources. The economic value has always been difficult to demonstrate, even when the projections in the costs of the technology were forecasted to consistently go down. The real value of the storages is much broader to grid operations: it may lead to improved asset utilization for generation, improved provision of ancillary services, better integration of renewable resources, and congestion relief for transmission and distribution.

Depending on the design of the charging stations, a typical PHEV or EV could require almost as much power as a typical home, meaning that neighborhoods that have several electric vehicles may require upgraded infrastructure, especially in densely populated urban and suburban areas with older infrastructure. New, smarter infrastructure will give utility operators more freedom to manage these new loads optimally and minimize negative impacts. In this scenario, the Smart Grid will allow utilities to use primarily off-peak power for battery charging, increasing asset utilization, and absorbing the exceeding energy production from renewables (Figure 10).

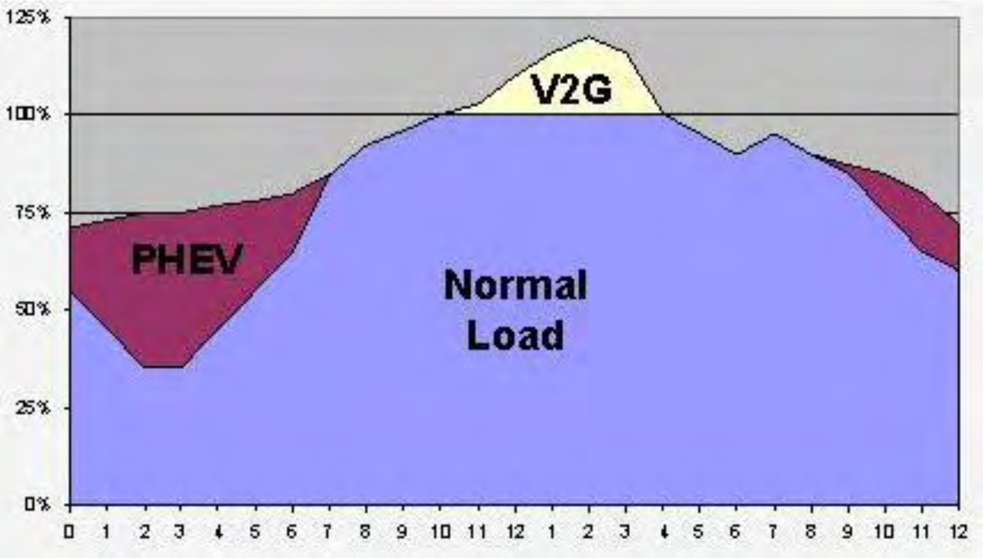


Figure 10 - Plug-in electric vehicle efficient charge-discharge management in a Smart Grid

In the Smart Grid reliability represents the attempt to highly differentiated services to consumers, which are classified on the basis of the different use of the energy. This heterogeneous grid can provide highly differentiated service to consumers, with value and costs better aligned. Power quality and reliability could even vary by location, with each utility finding the appropriate level for its varied groups of customers. Of course, electricity prices would need to be structured to correspond to the various levels of power quality and reliability that consumers desire. It is also expected that a basic level of power quality could be provided. By doing so, the consumers would pay for these services as now it's done in the telecommunications industry. Some entities are also beginning to drive more serious efforts to increase the reliability of loads that are critical to the National security. Certain communications systems, for example, require essentially 100 % reliability, which is impossible to guarantee with the current grid infrastructure. A grid that operates with heterogeneous reliability might ensure that traffic lights and emergency facilities would still function during a typical power outage or a natural disaster.

The Smart Grid must enable every consumer (both large and small) to participate in optimizing the cost and performance of their own use and of the entire grid. As with other industry transformations, a fundamental challenge is engaging the consumer in the transformation. Therein lays one of the basic paradoxes that plague the power industry: no single consumer, except for a few large industrial consumers, has much impact on how the system operates, but consumers collectively dominate the system design and operation. In other words, a utility cannot afford to pay much to affect one consumer's behavior, yet it is only by affecting each consumer that the system can be changed. As the power requirements evolve with the economy, the simple distinction between residential, commercial, and industrial consumers becomes both less accurate and less convenient. Business can be run from home with increasingly sophisticated electronics and associated power needs. Health care occurs in homes demanding higher reliability. Commercial buildings become more sophisticated in their design and operation, demanding more customized power supply and often including their own local power supplies. The result is the emergence of new markets for electricity technologies, solutions, and services, and economic opportunities for innovative companies ready to meet these diverse requirements. Technologies that already engage consumers in other aspects of their lives can easily be adapted to manage their electricity use. Availability of information on consumer use will allow utilities to analyze users to better frame service and price offerings. No longer would residential consumers be viewed as one generic and homogeneous market. Rather, one can imagine consumers being differentiated, for example, by whether one has a preponderance of energy-efficient appliances; whether one conducts business at home; or whether one has critical medical devices in the home. The line between commercial consumers and residential consumers may become blurred as homes become more differentiable, like businesses. In the transition to the Smart Grid, consumers will have the opportunity to move from being passive participants to active, interactive, and even trans-active customers, as their level of sophistication increases. This does not mean that they will be forced to make numerous decisions about energy use, but that they will possess intelligent software that understands their preferences and acts on their behalf. With richer information that is easy to interpret, consumers will be able to tailor their energy use to their needs and save money.

2.1.2 Experimental projects

At now, in EU are active 219 projects concerning Smart Grids, with about 90 % of the projects in the 15-EU, and with few projects in the new-entry Countries (27-EU). The overall budget for all the project is about € 5 billion, a little part of the previsions within 2020 objective, which is about € 56 billion [69,70].

Italy has about 5.5 % of the projects, the third largest one, with the leading Country being Germany (5.8 %) followed by Finland (5.6 %).

The 56 % of the European investment in the Smart Grid sector is inherent the smart meters, with the Italian project *Telegestione* [71] that in the past was financed by EU with about € 1 billion, regarding the installation of electronic meters in the distribution application field.

The 35 % of the projects (corresponding to 15 % of the investments) regards the integration between existing technologies and the development of integrated smart management systems. Real projects of R&D in new smart grids constitute a little part of the projects, about 9 % of the overall amount, with the 5 % of the investments.

The Smart Grids can give an important contribution to the new strategy for smart, sustainable and inclusive growth, including the objectives proposed under the flagship initiative for a resource-efficient Europe and Europe's energy and climate goals, which are at the heart of the internal market for energy. The Third Package provisions and especially Annex I.2 of the Electricity Directive (2009/72/EC) [72] explicitly oblige Member States to assess the roll-out of intelligent metering systems as a key step towards the implementation of Smart Grids and to roll out 80 % of those that have been positively assessed. Smart Grids are also identified as a way for Member States to meet their obligations to promote energy efficiency [73].

In addition, the Energy End-Use Efficiency and Energy Services Directive (2006/32/EC) [74] calls for metering that accurately reflects the final customer's actual energy consumption and provides information on actual time of use. The European Council of February 2011 recognized the important role of Smart Grids and invited the Member States, in liaison with European standardization bodies and industry, "to accelerate work with a view to adopting technical standards for Electric Vehicle charging systems by mid-2011 and for Smart Grids and meters by the end of 2012" [75].

Over the long term, the Commission's Communication on a Roadmap for moving to a competitive low-carbon economy in 2050 identifies Smart Grids as a key enabler for a future low-carbon electricity system [76], facilitating demand-side efficiency, increasing the shares of renewables and distributed generation, and enabling electrification of transport.

In Europe, over € 5.5 billion has been invested in about 300 Smart Grid projects during the last decade (Figure 11), with about € 300 million coming from EU budget.

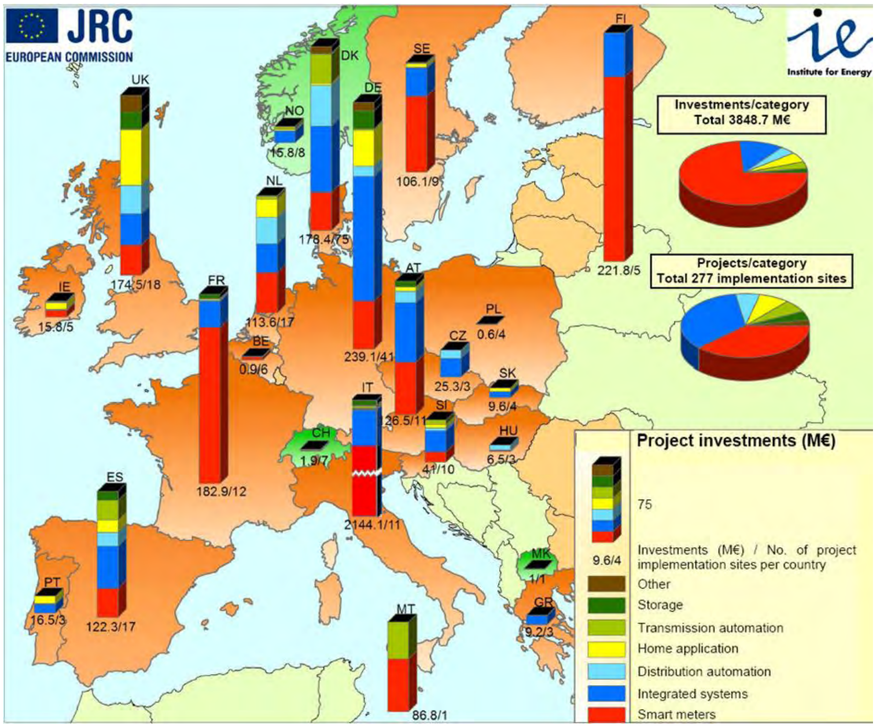


Figure 11 - European investments in SG distribution, per sector [77]

At present, there is a considerable gap between current and optimal investment in Europe, which can only partly be explained by the current economic downturn. Grid operators and suppliers are expected to carry the main investment burden. However, unless a fair cost sharing model is developed and the right balance is struck between short-term investment costs and long-term profits, the willingness of grid operators to undertake any substantial investment might be limited.

The conclusions of the European Council of February 4th, 2011 stated the urgent need to adopt European standards for Smart Grids [78]. The work already started in March 2009, when, based on the Measuring Instruments Directive (2004/22/EC) [79] and the Energy Service Directive [74], the Commission issued a mandate to the European Standardization Organizations CEN, CENELEC and ETSI (ESOs) to establish European standards for the interoperability of smart utility meters (electricity, gas, water and heat), involving communication protocols and additional functionalities, such as assuring interoperability between systems to provide secure communication with consumer's interfaces and improve the consumer's awareness to adapt its actual consumption. The ESOs were to provide European standards for communication in March 2010 and complete harmonized solutions for additional functions by December 2011, but the deliverables accumulating almost two years of delay. The Commission has since intervened to clarify the scope of the mandate in line with intermediate findings by the Smart Grid Task Force and to avoid further delays. The first deliverables for European standards for smart meters are expected by the end of 2013.

In June 2010, the Commission issued a mandate to ESOs to review existing standards and develop new standards so that a European harmonized approach could be adopted in 18 months for the interoperability of chargers for electric vehicles with all types of electric vehicles and with electricity supply points. This harmonization will allow users to use the same charger for a range of EVs and ensure that such chargers can be connected and operated throughout the EU.

On March 1st 2011, the Commission issued a mandate to ESOs for Smart Grids to develop standards facilitating the implementation of high-level Smart Grid services and functionalities by the end of 2012. As the mandate builds on the consensus achieved among the stakeholders participating in the Task Force and the ESO Joint Working Group on Smart Grids, this should ensure a smooth and fast process. To ensure that the 2012 deadline set by the European Council of February 2011 is met, a monitoring system was set up. But progress in the course of 2011 was not sufficient, so the Commission intervened to ensure that the goal is met and the necessary standards are set in an acceptable time period.

In addition, the Commission continues reviewing the European standardization policy by following up its White Paper *Modernizing ICT standardization in the EU* [80].

There is wide agreement among investors that the regulatory framework needs to be conducive to investment in Smart Grids. The Electricity Directive and the Energy Services Directive provide a mix of obligations and incentives to Member States to establish such a framework. Regulatory incentives should encourage a network operator to earn revenue in ways that are not linked to additional sales, but are rather based on efficiency gains and lower peak investment needs, i.e. moving from a "volume-based" business model to a quality and efficiency-based model. Article 10 of the Energy Services Directive obliges Member States to remove such volume-based incentives. If evaluation of the implementation of the Directive shows that this provision is insufficient or inadequate, the Commission will consider whether to amend it in the upcoming revision of the Directive or to complement it by a Network Code on Tariffs, to be drafted as part of the Third Package.

The Annex I.2 of the Electricity Directive requires Member States to define an implementation plan and timetable for the roll-out of smart metering systems. Given the relationship between the Smart Grids and the smart meters, such implementation plans would also need the development of Smart Grids, and should thus address the required regulatory incentives for the implementation of Smart Grids. The European

Commission will actively monitor Member States’ progress, and provide guidelines on key performance indicators.

In designing national incentive regimes, it is important to ensure that they do not diverge to an extent where trade and cooperation across national borders becomes difficult. For the same reasons, Smart Grids deployment in the Member States should also proceed at a similar pace. Large differences between national energy infrastructures would prevent businesses and consumers from reaping the full benefits of Smart Grids. Permitting procedures for the construction and renewal of energy grids have to be streamlined and optimized, and regional regulatory barriers and resistances must be tackled. In this context, the EU-wide Ten-Year Network Development Plans (TYNDP) [81] as well as the Regional Initiatives (RI) can play a major role.

The Commission has launched several initiatives for the modernization of energy networks. These have shaped the Smart Grids vision, established the needs for technology R&D and prompted small-scale pilot projects to verify and demonstrate the functioning and benefits of Smart Grids. Over the last decade, about € 300 million has been spent on these projects, financed mainly through Framework Programmes 5, 6 and 7 [82-84]. In May 2005 the Commission launched the European Technology Platform for Smart Grids [85] with the aim of creating a joint EU vision and research agenda for Smart Grids. A continued R&D effort towards advanced electricity network technology is necessary, and the Platform is expected to provide inputs for its agenda. Recently, the European Electricity Grids Initiative (EEGI) was established under the Strategic Energy Technology (SET) Plan to accelerate the deployment of SG technologies in view of the 2020 targets. Its main emphasis is on innovation at system level, and it will clarify technology integration and business cases through large-scale demonstrations and R&D projects for Smart Grids. It also aims to prevent duplication of efforts through a wide-ranging knowledge sharing approach. In May 2010, the EEGI adopted a detailed implementation plan, setting priorities for the period 2010-2018 and indicating financing needs of about € 2 billion [86]. The plan identifies the need for major upgrades to networks, particularly at distribution level, and the need for tight collaboration between distribution and transmission operators to ensure end-to-end delivery of electricity. This work is complemented by the necessary R&D investment in new Information and Communication Technology (ICT) components, systems and services supported by public-private partnerships.

In parallel to this industry-driven initiative, action has been taken at regional and local level in the form of the Covenant of Mayors initiative and the SET Plan initiative Smart Cities and Communities [87-89]. The EEGI contribute its results on Smart Grids to the Smart Cities and Communities initiative, which focus on the integration of various energy supplies and uses (electricity, gas, heat and transport) to maximize energy efficiency.

These EU initiatives are expected to accelerate the deployment of Smart Grids in Europe, starting from a modest level. Government-level support for deployment has so far been limited, even when compared with other parts of the world. The SET Plan complements research actions with deployment-oriented actions, fully in line with the Energy 2020 strategy. Projects and investments must now aim for ‘real life’ demonstration and validation, solving system integration issues and demonstrating the business cases. They must also demonstrate how consumers can benefit most from the introduction of these systems. The EEGI and Smart Cities and Communities initiatives are a step in that direction.

The roll-out of SG technologies is identified as a European infrastructure priority requiring particular attention in the Energy Infrastructure Package. It outlines the necessary toolbox for the planning and delivery of the energy infrastructure, including through an instrument for EU financial support to leverage private and public funds. The Commission will also examine the possible use of other EU funding instruments, including the Structural Funds, to offer tailored financing solutions involving both grant support and repayable assistance, such as loans and guarantees, as well as support to innovative actions and technologies.

In Italy, the promotion of Smart Grid pilot projects begin with the *Autorità per l’Energia Elettrica e il GAS* (AEEG) Deliberation ARG/ELT 39/10 of March 25th 2010 [90], providing incentives to distributors or other subjects promoting investments for the widespread diffusion of DER technologies and the modernization of the existent HV/MV power grid, with innovative solutions for the automation of the transformer kiosks and grid management.

The fundamental background for the project financing was the high repeatability of the proposed solutions, in order to make them valuable for other similar applications. Within this context, 8 pilot projects were selected for the period 2011-2013 (Table 1), for a total amount of € 16.5 million.

Title	**Distributor**
A2A - CP Lambrate	A2A Reti Elettriche S.p.A.
A.S.SE.M. San Severino Marche	A.S.SE.M. S.p.A.
ACEA Distribuzione	Acea Distribuzione S.p.A.
ASSM Tolentino	ASSM S.p.A.
ASM Terni	ASM Terni S.p.A.
A2A - CP Gavardo	A2A Reti Elettriche S.p.A.
Deval - CP Villeneuve	Deval S.p.A.

ENEL Distribuzione - CP Carpinone	ENEL Distribuzione S.p.A.

Table 1 - Italian SG approved projects [91]

2.2 The Micro Grid

The penetration of Distributed Generation at Medium and Low Voltages, both in utility networks and downstream of the meter, is increasing in all the developed Countries. One key economic potential of DG application lies in the opportunity to locally recover and use the heat discharge during the conversion of the primary fuel into electricity by means of reciprocating engine generators, gas turbines, micro-turbines, or FCs using small-scale CHP equipment. As a consequence, there has been significant progress toward developing small CHP applications.

These systems, together with solar PV modules, small wind turbines, and other small renewables (e.g. biogas digesters), thermal and electric storage, and controllable loads are expected to play a significant role in future electricity supply. These technologies are collectively called DERs. They can substantially reduce CO_2 emissions, thereby contributing to the commitments of the most developed Countries (or in some cases regional Governments, such as California) to meet their greenhouse gas emissions reduction targets, or otherwise substantially reduce their carbon footprints. Also, the presence of generation close to demand can increase the Power Quality and Reliability of the electricity delivered to sensitive end-uses.

Indeed, DERs can be used to actively enhance PQR. In general, these three perceived benefits (increased energy efficiency through CHP, reduced carbon emissions, and improved PQR) are the key drivers for DER deployment, although many other benefits, such as reduced line losses and grid expansion deferral, could be also considered.

While the application of DERs can potentially reduce the need for traditional system expansion, the control of a potentially huge number of small generators and resources in general creates a new challenging matter for operating and controlling the network safely and efficiently. This challenge can be partially addressed by Micro Grids, which are entities capable to coordinate DERs in a consistently more decentralized way, thereby reducing the control burden on the grid and permitting them to provide their full benefits (Figure 12).

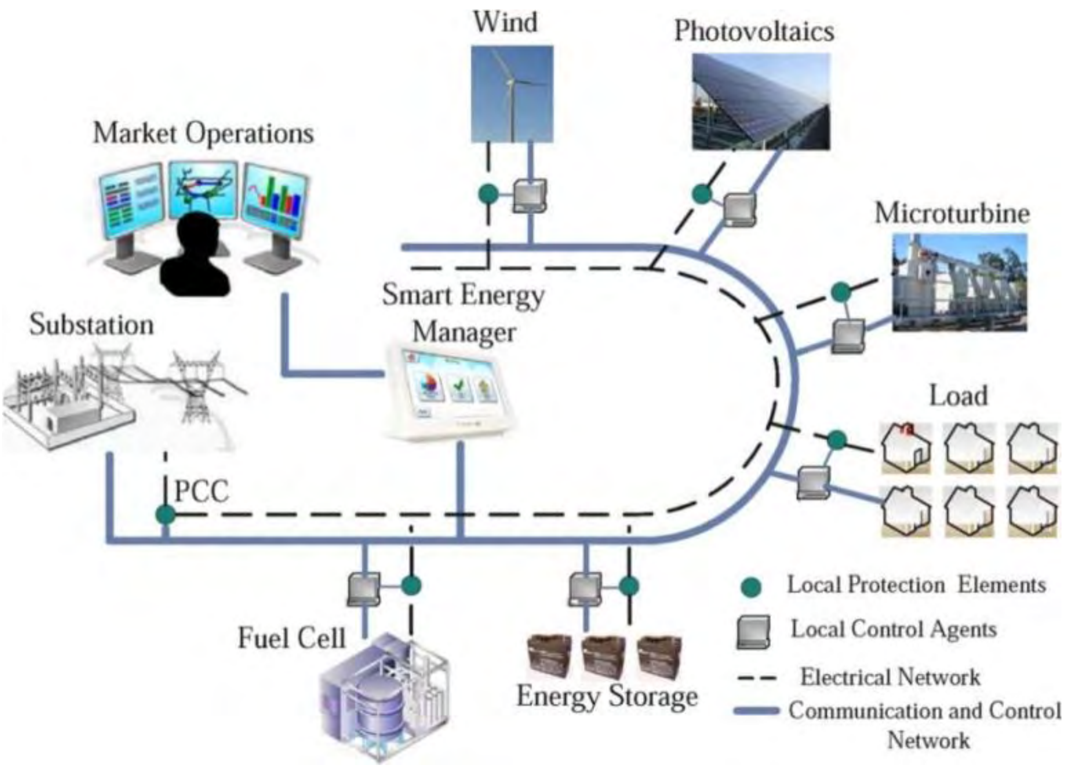


Figure 12 - Micro Grid concept schematic

In general, a Micro Grid comprises a LV (≤ 1 kV) or MV (usually ≈ 1-69 kV) locally-controlled cluster of DERs that behaves, from the grid's perspective, as a single producer or load both electrically and in energy markets. A Micro Grid operates safely and efficiently within its local distribution network, but it is also capable of islanding. MG design and operation demand new skills and technology, while distribution systems containing high DER penetration may require considerable operational control capabilities. While not strictly compliant with the above definition, small isolated power systems are included here as Micro Grids. They apply similar technology and provide added insights into how power systems may evolve differently where they are currently rudimentary or non-existent.

2.2.1 Definition

As previously mentioned, the MG concept is a logical evolution of simple distribution networks with high penetration of DG, also constituting a necessary Smart Grid sub-level system. Micro Grids comprise LV distribution systems, in which small and modular generation units, in the range of a few tens of kW or even less, are connected together with loads and storage devices. Furthermore, a MG is an extremely flexible cell of the electrical power system if properly controlled and managed (Figure 13). Advanced control strategies allow two different operation modes [92-97]:

- Normal interconnected mode, when the MG is connected to the MV network, being either supplied from it or injecting some amount of power into it;
- Emergency mode, when the disconnection from the MV network occurs following a fault in the upstream system.

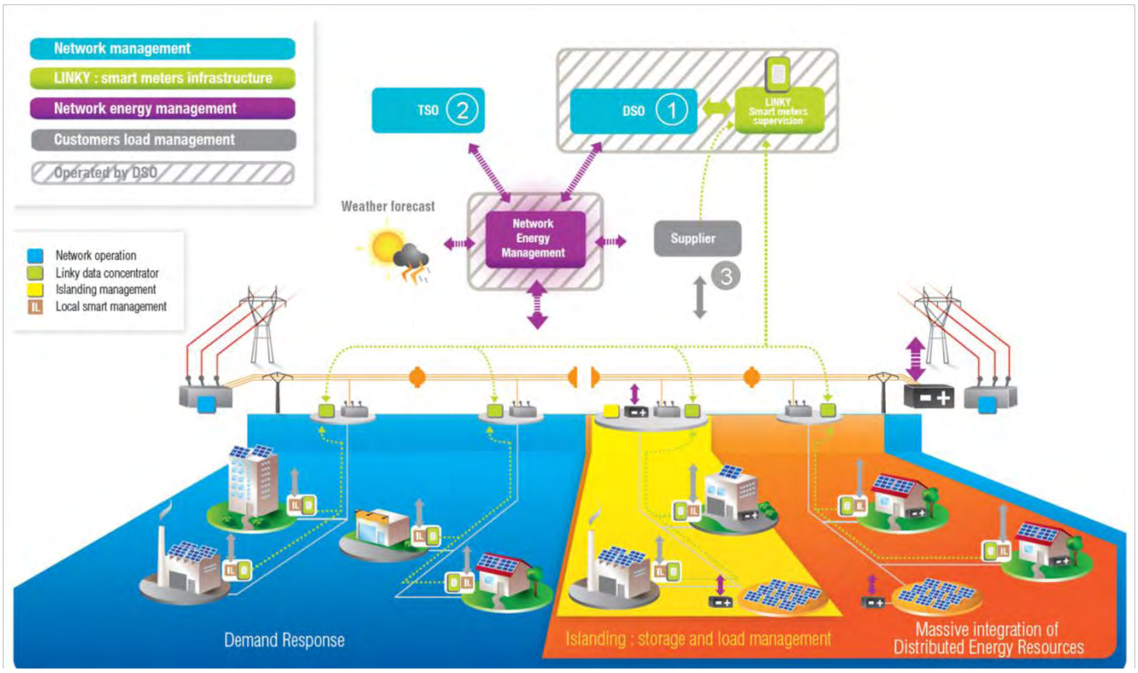


Figure 13 - Micro Grid management issues

Therefore, the MGs offer considerable advantages to the network operation both from the utility and the customers point of view. Thus, DG placed close to loads will reduce flows in both transmission and distribution systems with, at least, two important effects: the loss reduction and the deferral of the investments related to the future grid reinforcements and expansion, since the branch congestion can be controlled in a simpler way from the "hardware" point of view. On the other hand, the MGs can provide both thermal and electric needs to the consumers and, at the same time, enhance the reliability and improve the power quality by supporting reducing voltage and frequency dips [98-100]. In addition, MG potentially lower costs of energy supply.

The increase of penetration of micro-generation in electrical networks through the exploitation and extension of the MG concept leads with the More-Micro Grid concept, which is being developed within the framework of the EU More-Micro Grids Project [101], as previously mentioned.

The MG concept involves an operational architecture, developed within the EU R&D Micro Grids project. This MG example includes:

- Several feeders supplying electrical loads;
- Micro-generation systems;
- Storage devices;
- A hierarchical-type management and control scheme supported by a communication infrastructure.

In terms of current available technologies, the micro-generation systems can include several types of devices, like FCs, small wind turbines, PV systems, micro-turbines, and Internal Combustion Engines (ICEs), typically in the range of 10 -100 kW_e powered by natural gas or bio-fuels. CHP is one of the most promising applications, leading to an increase of the overall energy effectiveness of the whole system.

A special issue related to MG operation concerns the slow response to the control signals in order to change the output power. When the MG is operated autonomously, the absence of the LV network supply requires that the power balance during very fast transients have to be provided by energy storage devices, either flywheels or batteries and super-capacitors, which are continuously charged by the primary energy sources. Although MG are dominated by inverter interfaced systems that are inertia-less, they offer the possibility of a very flexible operation allowing the MG ability to behave as a coordinated entity in both interconnected and islanded operation. The storage technologies become important components with the duty of helping on MG stabilization during transient phenomena and in the moments following the beginning of the islanded operations. In order to achieve the full benefits from the MG operation, a hierarchical control and management systems have been envisaged, which comprises three important control levels:

- Local micro-source controllers and load controllers. The MG take advantage of the micro-source power electronic interface and can be enhanced with various degrees of intelligence in order to control both voltage and frequency during transient conditions based on only local information;
- Micro Grid Central Controller (MGCC). The MGCC functions can vary from monitoring the active and reactive power of the generators to

optimizing the MG operation by sending set points to control micro-generators and controllable loads;

- Distribution Management System (DMS), which can be used to manage the integration and operation of the MG and the upstream distribution network.

The Multi-Micro Grid (MMG) concept being developed under the framework of the Multi-Micro Grid project [102] is related to a higher level structure at the MV level, consisting of DG units and LV Micro Grids connected on several MV feeders. Micro Grids, DG units and MV loads under DMS control can be considered as active cells for control and management purposes. The technical operations of such systems require the adoption of a control structure, where all these active cells, as well as MV/LV passive substations, should be controlled by the Central Autonomous Management Controller (CAMC) to be installed at the MV bus level of a HV/MV substation, under the responsibility of the DSO [103]. The increase in dimension and complexity that the management of such a distribution system presents requires the use of a flexible decentralized control and management architecture, due to the large amount of data to be processed and treated, and to ensure an autonomous management during islanding operation mode. The CAMC must play a key role and must be the responsible for the data acquisition process, for enabling the dialogue with the DMS upstream, for running specific network functionalities, and for scheduling the different active cells in the downstream network [103]. The need to operate in both a islanded and interconnected state requires the management system to achieve the following targets:

- The state estimation of the whole system, including the operation charge of each device (generators, storages, and loads), including the diagnostic of all the elements;
- The coordinated voltage support and flow control, to ensure the predetermined level of the power quality within the MG;
- The coordinated frequency support and emergency functions, to allow the operation of the system in both islanded and interconnected mode, without affecting the behavior of the higher-level network or the reliability of the loads.

The effect of such a combined interaction and new global operation strategy is expected to enable an increase of the global penetration of both the micro-generation and the renewable sources.

2.2.2 Experimental projects

In the EU, the promotion and deployment of DERs are expected to benefit the energy consumers, the European energy system, and the environment, through the optimization of the value chain from the energy suppliers to the end users. Micro Grids are considered a basic feature of future active distribution networks, able to take full advantage of DERs, if coordinated and operated efficiently. They have been studied in a number of R&D projects, and they represent a key component in the *Strategic Research Agenda for Europe's Electricity Networks of the Future* [104].

At the EU international level, two major research efforts have been devoted exclusively to Micro Grids. Within the 5th Framework Programme, the *Micro Grids: Large Scale Integration of Micro-Generation to Low Voltage Grids* [105] activity was funded with € 4.5 million. The Consortium, led by the National Technical University of Athens (NTUA), included 14 partners from seven EU countries, including utilities such as EdF (France), PPC (Greece), and EdP (Portugal), manufacturers, such as EmForce, SMA, GERMANOS, and URENCO, in addition to research institutions and universities such as Labein, INESC Porto, the University of Manchester, ISET Kassel, and Ecole de Mines. The R&D objectives were to:

- Study the operation of the Micro Grids to increase the penetration of renewable and other DERs while reducing CO_2 emissions;
- Study the operation of the MGs in parallel with the grid and in islanded mode;
- Define and develop effective control strategies to ensure efficient, reliable, and economic operation and management;
- Define the appropriate protection and grounding policies to ensure safety, fault detection, separation, and islanded operation;
- Identify and develop the required ICT infrastructures and protocols;
- Determine the economic benefits of the MGs operation, contemporarily proposing reliable and effective methods to quantify them;
- Simulate and demonstrate MG operations on laboratory scales.

The project was completed, providing several innovative technical solutions, with the highlights including the development of:

- DER models plus steady-state and dynamic analysis tools enabling simulation of LV asymmetrical, inverter-dominated MG performance;
- Islanded and interconnected operations;
- Control algorithms, both hierarchical and distributed;

- Local black-start strategies;
- Definitions of DER interface response and requirements;
- Methods for quantification the reliability benefits;
- Laboratory Micro Grids of various complexities and functionalities.

Several levels of centralized and decentralized control were explored at the participating laboratories of ISET (Germany), the University of Manchester (UK), Ecole de Mines (France), and NTUA (Greece), and relative benefits were identified.

A follow-up project titled *More Micro Grids: Advanced Architectures and Control Concepts for More Micro-Grids* [106] within the 6th Framework Programme was funded with € 8.5 million. This second consortium, again led by NTUA, comprises manufacturers, including Siemens, ABB, SMA, ZIV, I-Power, Anco, Germanos, and EmForce, power utilities from Denmark, Germany, Portugal, the Netherlands, and Poland, and research teams from Greece, the UK, France, Spain, Portugal, and Germany. The new objectives included:

- The investigation of new DER controllers to provide effective and efficient operation of the Micro Grids;
- The development of alternative control strategies using next generation ICTs;
- The creation of alternative network designs, including the application of modern protection methods, interfaces, and operations;
- Technical and commercial integration of multiple MGs, including their interface with upstream distribution management systems, and the operation of decentralized markets for the energy and the grid ancillary services;
- The standardization of technical and commercial protocols and hardware to allow easy installation of DERs with plug-and-play capabilities;
- The analysis of their impact on the power system operation, including benefits quantification at regional, national, and EU levels of reliability improvements, reduction of network losses, and environmental benefits;
- Exploring the impact on the development of the electric network infrastructures to the overall network, and to the reinforcement and replacement strategy of the aging EU electricity infrastructure;
- Executing extensive field trials of alternative control strategies in actual installations, with the experimental validation of different Micro Grid architectures in interconnected and islanded modes, and during transition.

The pilot installations include the following demonstration sites:

- Greece: the Kythnos island Micro Grid.
    - This system electrifies 12 houses in a small valley on Kythnos, an island in the Cyclades Archipelago of the Aegean Sea. The generation system comprises 10 kW_e of PV, a 53 kWh_e capacity battery bank, and a 5 kW_e diesel ICE. A second PV array of about 2 kW_e, mounted on the roof of the control system building, is connected to an SMA inverter and a 32 kWh_e electric storage to provide power for the monitoring and communication system. Residential service is powered by 3 SMA battery inverters. They can operate in frequency droop mode, allowing information flow to switching load controllers if the battery State-Of-Charge (SOC) is low, and limiting the power output of the PV inverters when the batteries are at their full capacity.
- Netherlands: Continuon MV/LV facility.
    - Continuon operates a holiday camp with more than 200 cottages, equipped with grid-tied PV for a total rated power of 315 kW_e. The cottages are connected to an MV/LV transformer. Daytime loads are low, so most of the PV power is injected into the MV grid. During the evening and night, the support from the grid is needed. High voltages at the end of the feeder and a high level of voltage distortion during high PV output have been noted. With the Micro Grid in islanded operation, the improvements in the power quality are carried out by using power electronic flexible AC distribution systems and storage.
- Germany: MVV Residential Demonstration at Mannheim-Wallstadt.
    - The 1,200 inhabitant in Mannheim-Wallstadt has been prepared for a continuous long-term field test site for the MMGs project. A total of 30 kW_e of PV has already been installed by private investors, and further DERs are planned. The first goal of the experiment has been to involve customers in the load management. During the summer of 2006 2-month trial, more than 20 families and one municipal center participated in the *Washing with the Sun* program [107]. Based on PV output availability information in their neighborhood, customers shifted their loads to times when they could use directly the power from PV. As a result, participating families shifted their loads significantly from the typical residential evening peak toward hours with higher solar insolation, and from cloudy toward sunny days.

Over the described activities, other demonstrations are taking place in Denmark, Italy, Portugal, and Spain. In addition to EU-funded R&D projects, there are several activities supported by national or regional governments in Germany, Spain, the United Kingdom, the Netherlands. Out of the EU, similar projects were developed in North-America and in Japan.

The R&D activities in the USA on Micro Grids research program was supported both by the US DoE and the California Energy Commission. The most well-known US Micro Grid R&D effort has been pursued under the Consortium for Electric Reliability Technology Solution (CERTS). The CERTS Micro Grid [108,109] is intended to separate from the normal utility service during a disruption and continue to serve its critical internal loads until acceptable utility service is restored. Actually, the function provided by the CERTS Micro Grid is purposely to save cost and no single device is essential for operation, creating a robust system. The reliability of the CERTS Micro Grid has been well demonstrated in terms of simulation and the bench testing of a laboratory scale test system at the University of Wisconsin, Madison. Full-scale testing on the CERTS Micro Grid concept has been installed at the Dolan Technology Center in Columbus (Ohio), which is operated by American Electric Power [110].

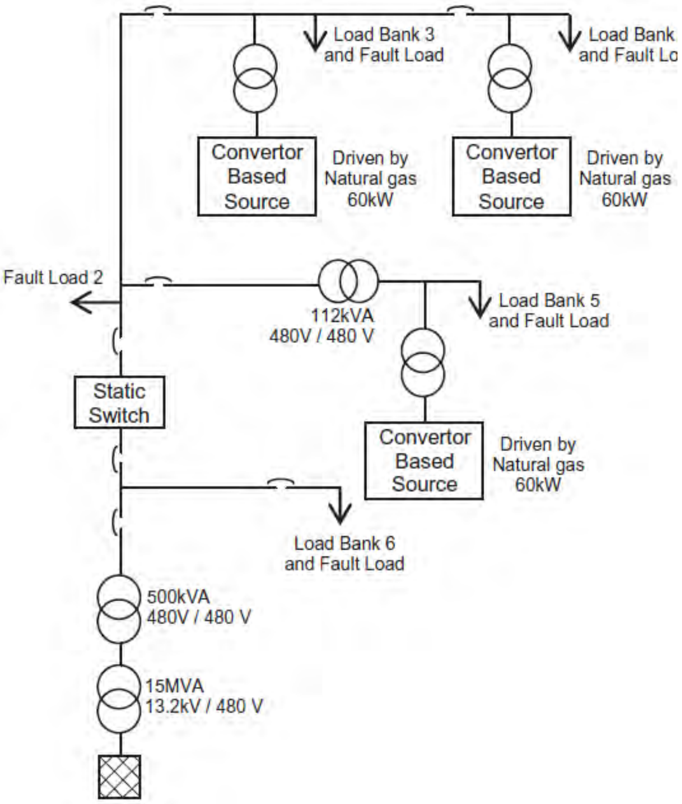


Figure 14 - CERTS Micro Grid design

Figure 14 illustrates the CERTS Micro Grid design with protected critical load circuits and unprotected traditional load circuits. The CERTS Micro Grid has presents unique electrical analysis challenges such as contain three phase, single phase and variety of sources interconnected by power electronic devices employing different control approaches. The modeling approach enables analysis of a variety of issue such as prediction and evaluation of imbalance, asymmetries, generation-load control and dynamic voltage.

In Japan the New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Economy, Trade and Industry started three demonstrations under its regional power grid with renewable energy resources project in 2003. Field tests were carried out by integrating new energy sources into a local distribution network [111]. The Micro Grid projects were done in Hachinohe, Aomori, Aichi, and Kyoto. The main achievement is the development of an optimum operation and control system. Even though multiple field-test of Micro Grids are demonstrating the technical feasibility of the MG, evident economic and environmental benefits have not yet been demonstrated. Some methods for the economic design and the optimal operation of the Micro Grids with RES were proposed. The Hachinohe project (Figure 15) features a Micro Grid system constructed using a private distribution line measuring more than 5 km.

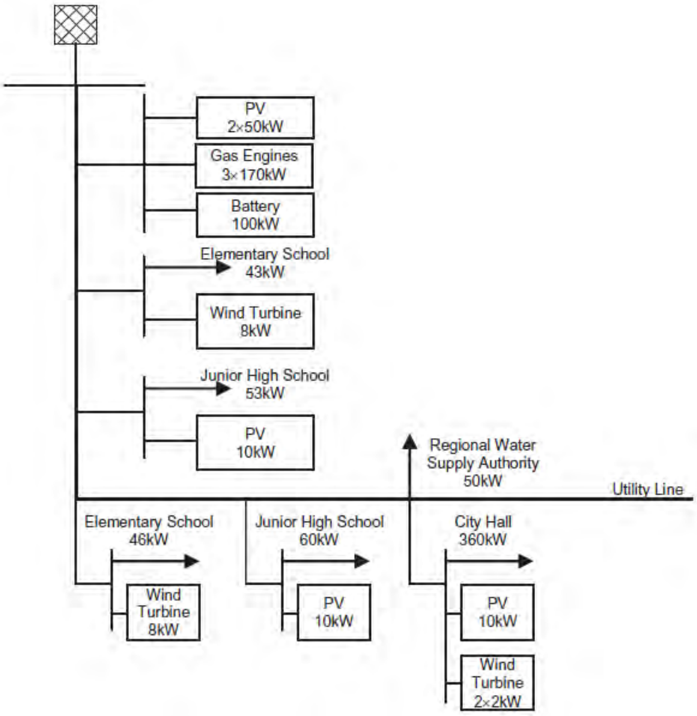


Figure 15 - Hachinohe Micro Grid design

The private distribution line was realized for the transmission of the electricity primarily generated by the gas engine system. Several PV systems and small wind turbines are also connected to the MG. At the sewage plant, three 170 kW_e natural gas-fed engines and a 50 kW_e PV system have been installed. To support the creation of digestion gas by the sewage plant, a wood-waste steam boiler was also installed due to a shortage of heat to safeguard the bacteria.

In India for the execution of the Micro Grid project one of the sites selected is Alamprabhu Pathar [112], a hill area in Kolhapur district in the state of Maharashtra. The site is rich of energy resources, and is characterized by an adequate load growth. Maharashtra Energy Development Agency (MEDA) has declared Alamprabhu Pathar as one of the windy sites, where good amount of wind power can be tapped off. The presence of the sugar industries close to Alamprabhu Pathar has made it possible to include biogas-based generators as one of the constituent sources of the MG. The 11 kV transmission and distribution main network around the Micro Grid in Maharashtra is shown in Figure 16.

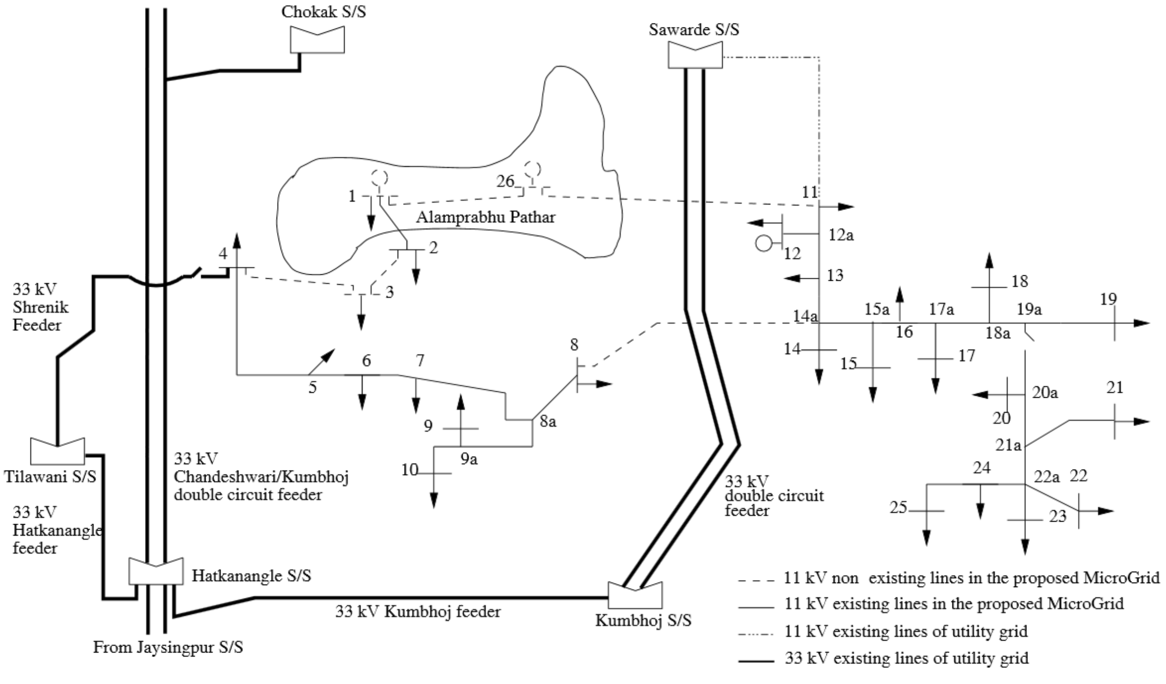


Figure 16 - Alamprabhu Pathar Micro Grid design

Around the Alamprabhu Pathar area, there exist a good amount of residential, agricultural, commercial, and industrial consumers. Analysis shows that 2,400 kW_e of natural gas-based generators, 500 kW_e of biomass-based generators and 14,250 kW_e of gas turbines are to be installed to supply all the loads.

2.3 The Virtual Power Plant

2.3.1 Definition

The definition of the Virtual Power Plant (VPP) concept can be traced back to 1997 when Dr. Awerbuch defined the Virtual Utility as "*a flexible collaboration of independent, market-driven entities that provide efficient energy service demanded by consumers without necessarily owning the corresponding assets*" [113]. Just like the Virtual Utility, which aims to take advantage of the emerging technologies and provide customer-oriented energy service, the idea of VPP is to aggregate different types of DERs through an advanced ICT infrastructure for the better use of those available resources. With properly designed aggregation methods, potential benefits could be easily achieved. These benefits can be:

- Offering considerable savings of primary energy and the contemporary reduction in pollutants emission;
- Reducing the energy losses at transmission and distribution levels, resulting in an additional energy saving;
- Facilitating the integration of the intermittent generation technologies based on RESs like wind power or PV, by stabilizing the stochastic power output;
- Enabling the delay of investment on enforcing the electrical infrastructure, thanks to the characteristic that the VPP requires relatively little modification to the existing infrastructure;
- Providing value-added services like ancillary services to power system operation through centralized/coordinated control strategies to both maintain the reliability and the security, and to increase the flexibility of the electricity supply;
- Increasing the participation of the end users in both the electricity market transactions and the power system operations with improved degrees of freedom;
- Representing a wide range of options towards the future Smart Grid.

Using aggregation to achieve a better use of the available generation/consumption resources is not a new technology. Many energy trading companies have already been aggregating small-size (from hundreds of kW_e to several MW_e) power plants for years. Normally, the intention of such aggregation is to break the capacity threshold for the electricity market entry and the benefits for the owners of small generators and the energy traders. Besides, load aggregation is also very common to see by which individual energy users are banded together in an alliance to achieve more competitive prices or to provide demand-response services.

However, there is no consensus on the definition of the VPP. Literally, the VPP can be interpreted as a power plant with geographically located generation assets which are interconnected through the “virtually” existing communication channels. This literal interpretation happens to provide the three most basic features of the VPP: a power plant like entity/system, managing a cluster of generation assets and using advanced ICT technologies. The first feature, power plant like entity/system describes the obligations that a VPP has to fulfill and its role in the power system operation. The second feature, managing a cluster of generation assets, distinguishes the VPP from a conventional power plant by highlighting the control needs of the VPP. The third feature, “virtual”, emphasizes the importance of communication in the VPP applications. As a result, the author would like to say any system having all of the three features can be regarded as a VPP.

The VPP can thus be defined as an entity/Energy Management System (EMS) that aggregates multi-fuel, multi-location and possibly multi-owned DER units via advanced ICT infrastructure either for the purpose of energy trading or to provide system support services. Differing from other aggregations, VPP exploits the technical and economic synergies between diversified DER technologies. In the case of being an independent entity, the VPP can either function as an independent power producer (based on DER aggregation) or an energy supplier (based on prosumer aggregation).

2.3.2 Experimental projects

One of the first VPP experimental project is realized under the EU 5th Framework Programme [114]. The aim is to develop the VPP concept, to implement and test it and show the results. 31 stand-alone residential CHPs, based on FCs, were installed, each unit with 4.6 kW_e and 9 kW_{th} rated power. An energy manager was set up to control the whole system and was responsible for benefits for end-users and grid operators. A Central Control System (CCS) was created to manage all the fuel cell systems. CCS communicates with the on-site energy manager and allows the utilities to control the micro CHPs in terms of peak demand and defined load profiles. Wireless transmission standards, GSM and radio ripple control receivers are used for communication purposes. The whole system resulted stable and there were no emergency cases involving units being turned off. Fuel efficiencies of up to 90 % are achieved, with 30 % electrical efficiencies. The low temperature PEM fuel cell system worked for 138,000 hours and during that period about 400 MWh_e have been produced. The system is tested to check how VPP delivers electricity supplies. The results demonstrate that there are no latency time in delivery, but some problems have to be solved before developing this type of system for the mass market:

- Costs must be reduced significantly to increase their economic viability;
- The system must be simplified to improve reliability;
- The temperature of the heat output must be increased to become compatible with the existing heating systems, and to give opportunities for the tri-generation.

The total cost of the project was € 8.3 million. The FC system comprised a fuel cell battery (fed by natural gas), peak heat boiler, hot water tank and control module. An energy manager controlled the whole system, whose primary aim is to supply the heating to meet heat demand in the buildings. To do this, it communicates with the CHP system in household sites and controls the FC, the boiler and the hydraulic system. Of course, the heat is consumed on site and the electricity first is sent to the inverter, where DC current is transformed into AC current, and then the it is supplied to the buildings internal grid.

The EDISON Project [115] aims to integrate an electric vehicle fleet with the power system, realized by means of a VPP. RES cause problems with balancing in the power system, and to this end a comprehensive solution must be developed. Electric vehicles can be treated as energy storage units, with the first issue being the drawn up of a schedule for charging them, minimizing the costs. To solve this problem a special platform must be developed, which will be coordinated with the power system and the energy market to gain all the needed information, with the RESs being taken into account as well. The comprehensive system must supply the required energy to all the electric vehicles immediately and, contemporarily, all the boundary constraints of the electric distribution network must be taken into consideration. The platform is located on the island of Bornholm, and every electric vehicle in every location on the island can be linked with the power system via the VPP. One aspect differentiating the EDISON Project VPP from other ones is the common usage of the electric vehicles as active energy storage units, whilst most of the VPPs concentrate only on the intelligent management of the generation units. To this purpose, two possible ways of implementation are considered: in the first one, the VPP can be integrated as a part of the power system, while in the second one the VPP is a completely new system cooperating with the existing power system. In this latter approach, the VPP is a new subject on the market and if it is introduced with the power system as is being considered, then it can be considered as a part of the power company. The VPP provides balancing tasks as Balancing Responsible Party (BPR). The VPP might be a perfect tool to smooth the boundary between the demand and the supply, with the stand-alone VPP architecture representing an alternative. In that case, the VPP is a BRP too, but it is independent and works as any other member of the market, buying and selling energy on the basis of the collected data and the status of each generation unit. The VPP of the EDISON project contains three main modules:

- The control module for each DER;
- The data collecting module;
- The connection, cooperation and communication module.

Each of the modules contains other modules. For the stand-alone VPP architecture the whole system is more complicated than in the case of the VPP being integrated in the existing power system structure as a part of a power company. 52 DER units are located around the island and 35 of them are wind turbines, with 27,000 consumers of electricity being present on the island. The total generation capacity is 135 MW_e and the maximum experienced load is 55 MW_e. The project checks how electric vehicles can cope with wind farm generation. The potential exists to have active management of the electric cars without any disruption to the car owners. A simulation is performed on the basis of a purposefully developed model of the power network of the island, which simulates and analyzes the transmission and the distribution networks, the power sources and the consumers. The model is used for the data management, the prediction and the optimization of the operation of the whole system, being also possible to simulate the energy flow in the power network on the basis of the electric vehicle movement. All the calculations are made with 15-minute intervals and are used to make an energy flow map for the determination of where the network and the transformers are overloaded. The generated energy and the consumption are balanced by regulating the wind turbines and the power plants. Further work is dedicated to two problems:

- <u>Prediction</u>: the electricity demands must be predicted in order to create a schedule of the power source generators. In addition, the charging of the electric vehicles represents another issue. The wind conditions must be predicted using weather forecasts and historic data, with all these tasks requiring solutions and better models for improved results;
- <u>Optimization</u>: various objective functions can be optimized (i.e. costs, power balancing in the case of intermittent operation of RES units and

power supply for electric vehicles). The optimization must be developed to achieve a better global optimum based on local optimums.

The basic requirements and the experience regarding the VPP are set out in [116]. The increasing penetration of the RESs causes remarkable problems in terms of power balancing, and the CHPs operations are generally driven on the basis of the heat demands, largely determined by the weather conditions. Liquidating the reserve power of the central power sources is justified from an economic point of view, with this reserve used to compensate for a lack of power in the power network resulting from the unpredictable RESs generation. It is more sensible to transfer a balancing task to a different level of structure: this structure should contain different types of DERs, energy storage units and demand-control facilities, and it could all be clustered into the VPP structure, which can perform as a system power plant. The operations of each unit can be scheduled in advance, with a DEMS supervising the whole system, after taking into account all the boundary constraints and conditions. All these tasks can be performed thanks to the innovative data transfer methods, communication and remote control which together can monitor a large number of distributed energy sources. The VPP controls all the energy flows in the system and the factors in the weather forecast. The management process has to adapt to the presence of distributed generators and their unique method of operation, with the power system which has to cope with the unpredictable conditions of DG operations: therefore, an innovative approach to the management of the power system is demanded. The new approach to the management must be cost-effective, economic and provide a stable operating system. The balancing process in some areas can be taken over by the VPP. The VPP will operate on the basis of schedules made in offline mode and it supervises the schedule realization of each DER in online mode. The VPP can be integrated vertically or horizontally. One VPP system can be a part of another, bigger VPP system. It is possible to connect many VPPs to the existing power system, resulting in a very flexible structure, which represents one of the VPP biggest advantages. The basic functionality of the VPP is provided by DEMS, performing generation, storage and load management. The main goal of the DEMS is to achieve a “win-win” situation in the power system, meaning that it will benefit both the power system and the customers.

3. The Smart User

3.1 Definition

There is no accepted definition for the Smart User (SU) concept. In principle, a SU is a local small-size total power system, presenting both loads and generators, whose peculiar characteristics are the ICT and an Energy Management System (EMS) allowing the plant to operate in a different and more optimized way than a traditional energy system. Respect to the MG or VPP, the space scale is smaller, in this case limited to a small factory, but it can be also referred to a residential building, or a small tertiary activity.

In principle, a SU should be one of the fundamental steps towards the diffusion of the Smart Grids: indeed these latter ones can be only exploited for the management of large space scales (i.e. nations, continents), with relevant power flows and logics going further the matching between the loads request and the production. Such a system can be effective only if a large number of subsidiary systems is realized, and in the small space scale the Smart User can be one of them (Figure 17).

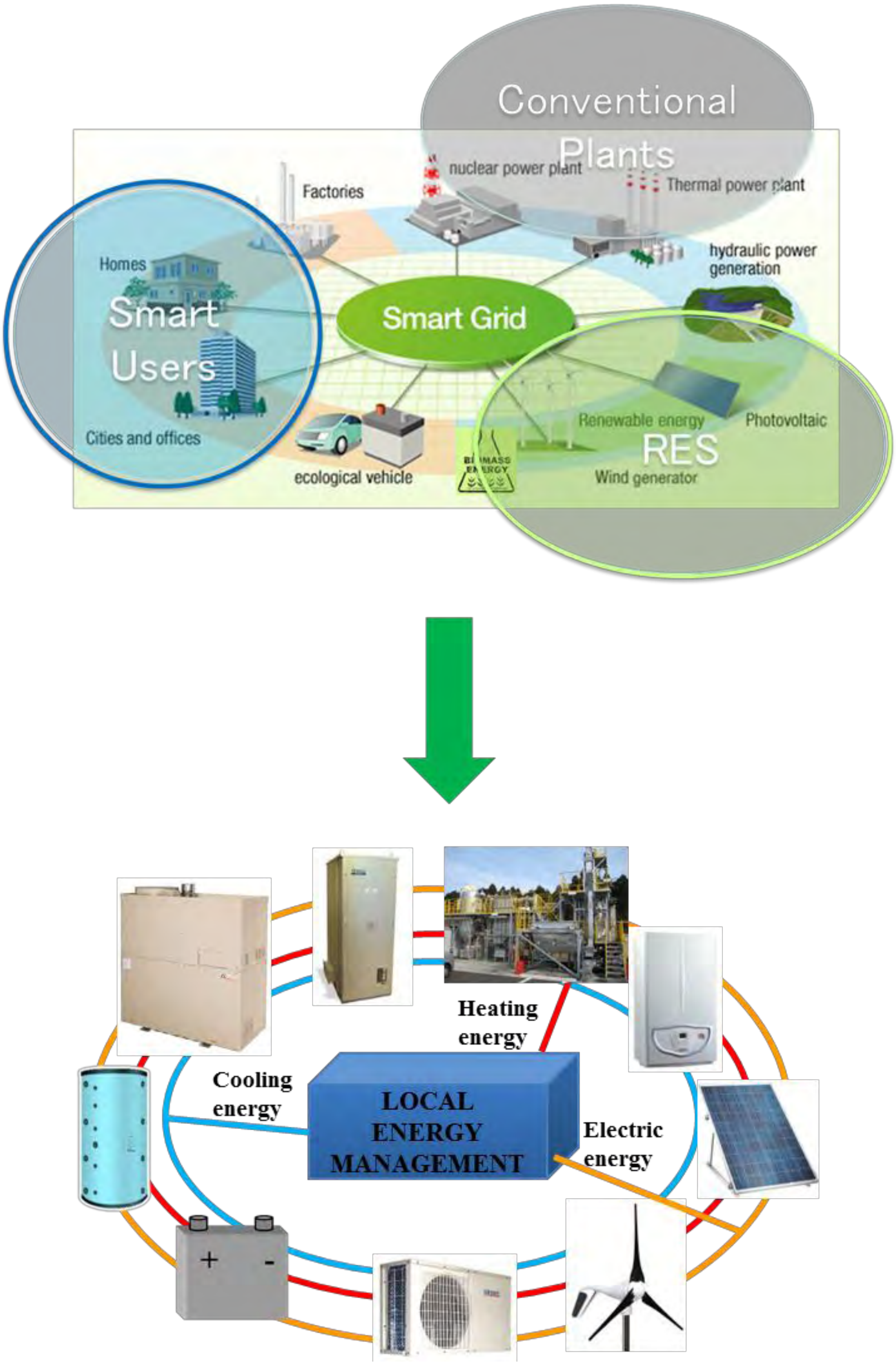


Figure 17 - Smart User concept within the Smart Grid

The SU is thought as a production/consumption system which can offer several useful services, to both the user and the DSO/TSO.

First of all, the user benefits are related to the decrease of the energy supply costs: in a semi-automated way, the management system should be able to reliably schedule not only the generators (both fossil-fueled and renewable), but also the loads program, both from the electric and the thermal point of view: the system must be able to manage each kind of energy request from the users. In addition to that, it must be ready-to-use to the new energy scenarios, which implies new rules from the DSOs, in particular the future requirements of achieving a prescribed energy exchange with the grid within a fixed time step. In particular this latter aspect assumes a remarkable importance, because it would imply the impossibility to connect RESs, which are intrinsically non-programmable, to the power grid. The SU system would be also capable to operate in SO or VSO conditions when required, in order to improve the energy supply reliability also in cases of distribution network blackout, or allow operations for off-grid sites in remote areas which are not served by the grid.

The global advantage of the spreading of this kind of technology would be the decrease in CO_2 emissions, for both a more efficient use of the energy and an increased penetration of DG based on renewable sources. By one other hand, the diffusion of the SU technology would allow lower primary energy consumption, because it would imply a smaller number of reserve power which should be guaranteed by the national grid operators, in addition to the exploitation of some ancillary services, such as the satisfaction of unplanned power requests from the grid or the feeding into the grid of reactive power, thus also reducing the needs of large and very expensive balancing and storage systems.

3.2 The case study selection

For the selection of the most suitable site for the installation of the Smart User experimental plant, several industrial and agricultural environments were investigated.

The selection had to be subjected to several fundamental constraints, both from the equipment and the load perspective: in addition to that, the case study to be selected have to face as many different scenario conditions as possible, in order to show that the obtained results can be extended to a plurality of different contexts.

Starting from these considerations, RESs for the electric generation are needed, in order to perform experimental analyses on the possibility to balance the intrinsic unpredictability and the fluctuations of the production from renewables, which is thought to be one of the power distribution grid constraints of the next future. In addition, the load request should be the most varied possible, for evaluating the behavior of the Smart User in different conditions: thus, a site with electric, heating, and cooling requests was looked for, with low total consumptions, to test a system with a LV grid connection and with a thermal request similar to the Yanmar micro-

CHP products, which in the intention of Yanmar R&D Europe company should represent the hardware core of the SU plant. For this reason, big companies with quite steady production cycles were not preferred, not allowing the required conditions.

3.2.1 Pontlab company

The selection fell on Pontlab facility. Pontlab is and industrial service company, located in the industrial area of Pontedera (PI), which supplies to other industries activities like 2D and 3D measuring services, testing and calibration of measurement equipment, material analyses, and durability and reliability laboratory tests.

The facility has a covered surface of about 1,100 m^2, divided into 3 floors:

- The underground floor, which is entirely assigned to the climatic chambers;
- The ground floor, presenting the workshop of the company, the durability test benches, the 3D scanner laboratory, and part of the administrative office;
- The first floor, where the laboratories and the remaining offices are placed, in addition to an external terrace with the thermal supply pieces of equipment.

Most of the installed loads is constituted by electricity needs, with only the durability test benches needing cooling power for their functioning. All the rooms of the company, included the workshop, have both air conditioning and room heating.

Before the installation of the Smart User hardware, the heating supply of the company was carried out by a Riello gas boiler of 34 kW$_{th}$ rated power, with an on/off working mode, and with an Euroklimat RAK.E-0262 compression chiller of 61.8 kW$_c$ (with a rated electric consumption of 25 kW$_e$, corresponding to a rated EER of about 2.5) and a cooling tower of 25 kW$_c$, and by the LV electric connection to the distribution grid, with a maximum power exchange of 180 kW$_e$. In addition to the LV connection, in the rooftop of the company is placed a PV plant with a rated power of 13.6 kW$_e$, contributing for about 3 % of the overall electric consumptions, and it is also present a micro-wind turbine with a rated power output of 3 kW$_e$.

There are 9 electric panels in the company:

- The general one, al the ground floor, close to the ENEL power meter;
- Panel “1”, close to the general one, where the ampere-meter of the three phases is placed;
- Panel “2”, at the ground floor, for the supply of the machinery in the workshop;

- Panel "3", with the supply of the large climatic chamber, the oil-dynamic facility, the workshop lights and air conditioning;
- Panel "4", at the underground floor, with the remaining climatic chambers, the ozone-meter, the xenon-test, and the system for the salty fog;
- Panel "5", at the ground floor, supplying the durability test benches, the compression chiller, one of the three air compressors, the air treatment units and the fire alarm system;
- Panel "6", next to panel "5", supplying the other compressors, and the pumps for the heating and cooling circuits;
- Panel "7", at the first floor, supplying all the pieces of equipment of the analysis laboratory;
- Panel "8", supplying all the offices loads.

The conceptual schematics of the floors, with the indications of the loads rated power and of the pieces of equipment, are shown from Figure 18 to Figure 25.

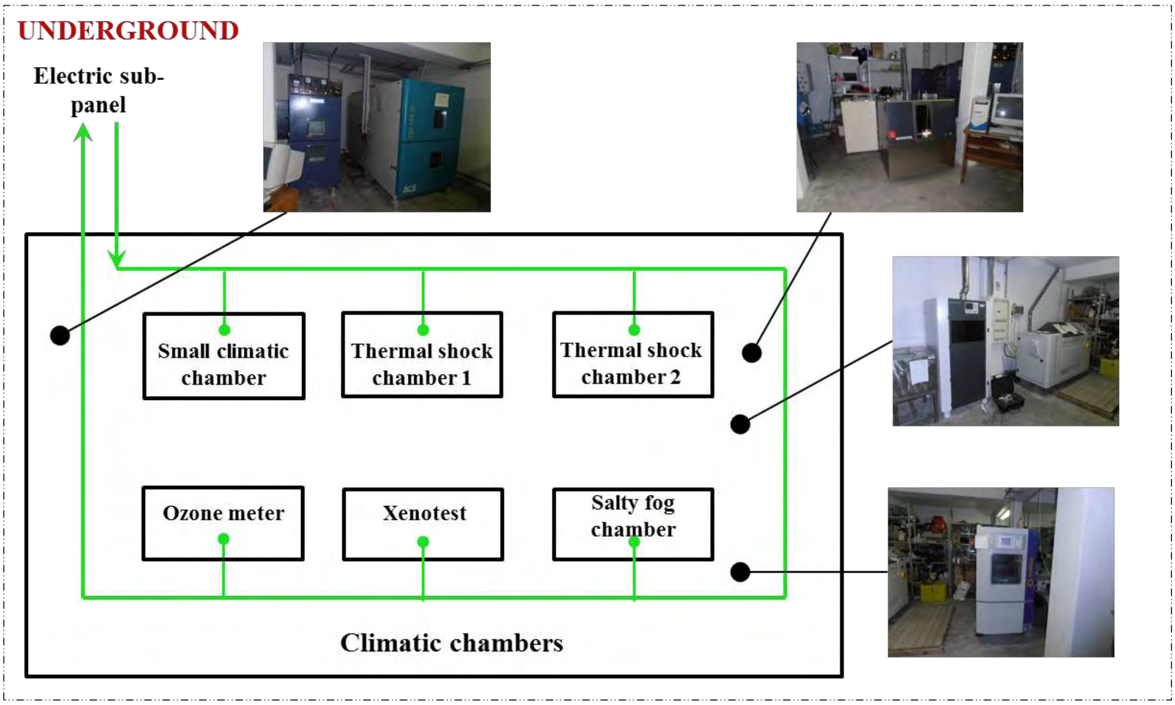


Figure 18 - Electric circuit schematic of Pontlab underground floor

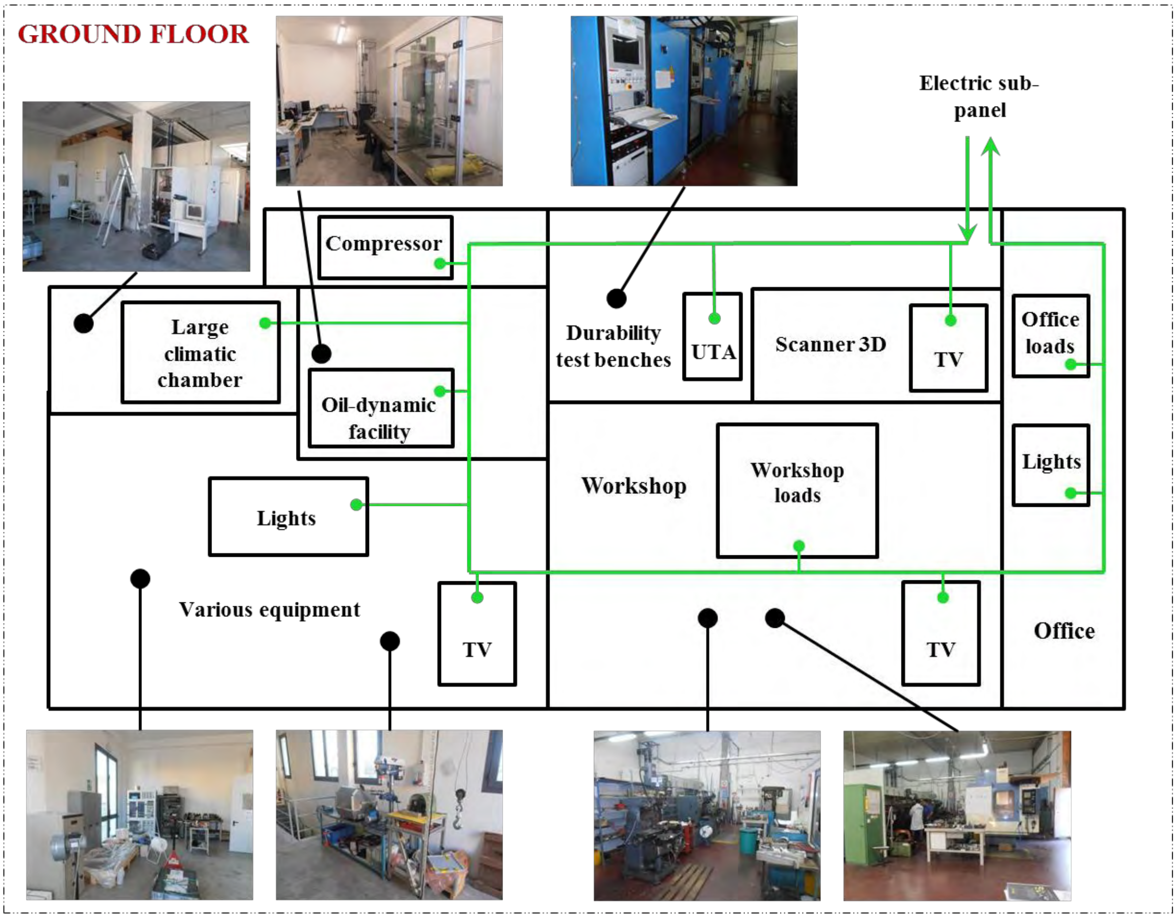


Figure 19 - Electric circuit schematic of Pontlab ground floor

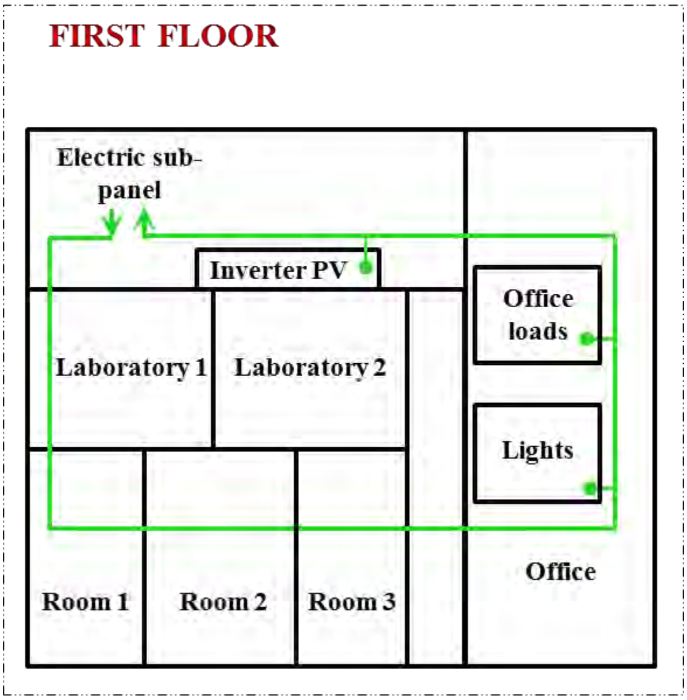


Figure 20 - Electric circuit schematic of Pontlab first floor

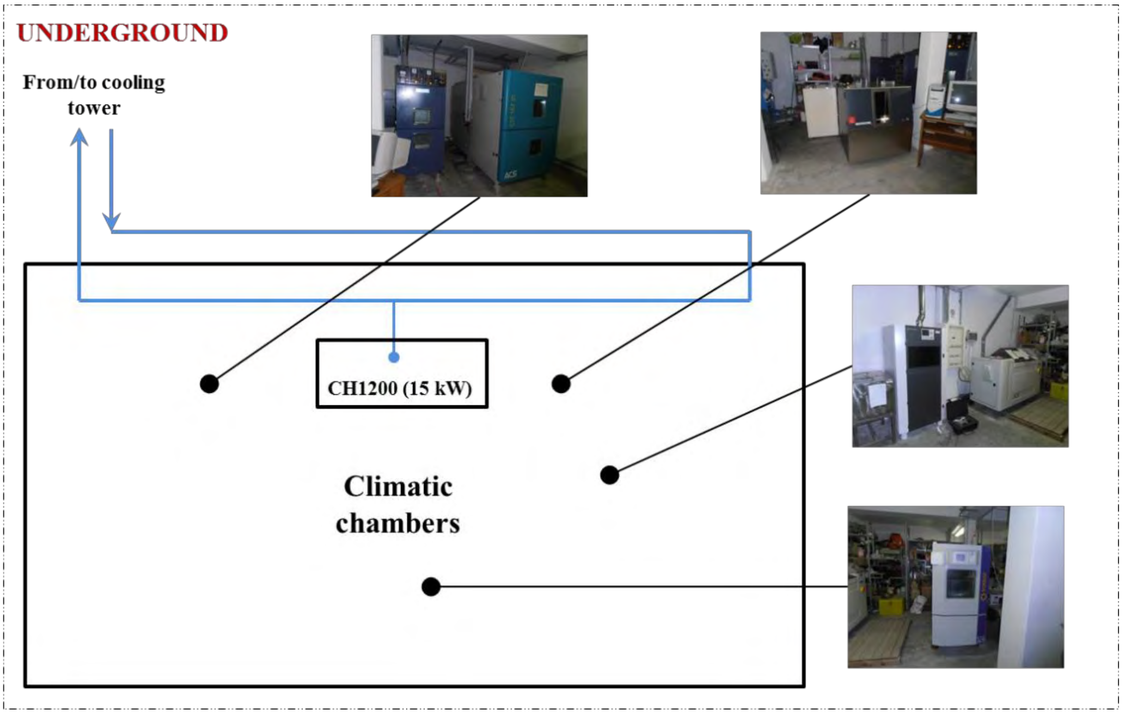


Figure 21 - Cooling circuit schematic of Pontlab underground floor

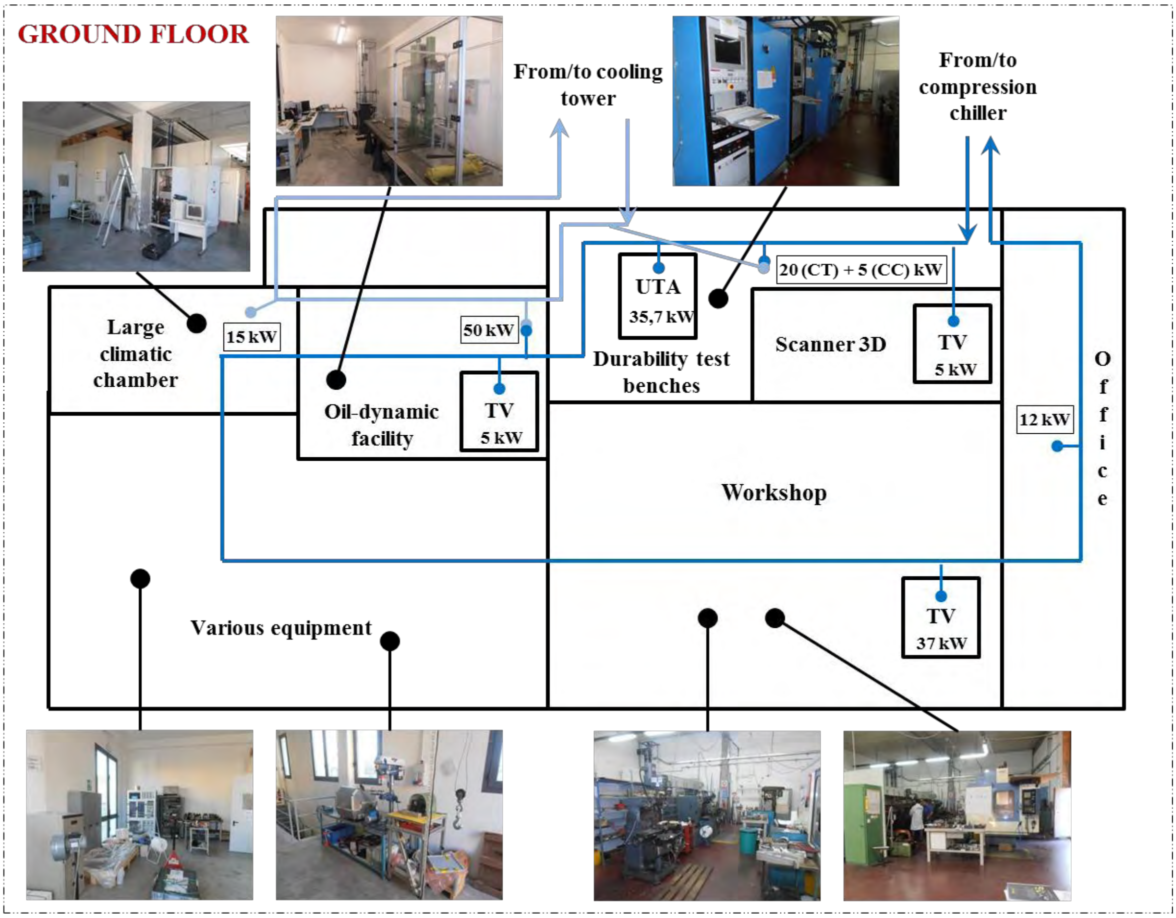


Figure 22 - Cooling circuit schematic of Pontlab ground floor

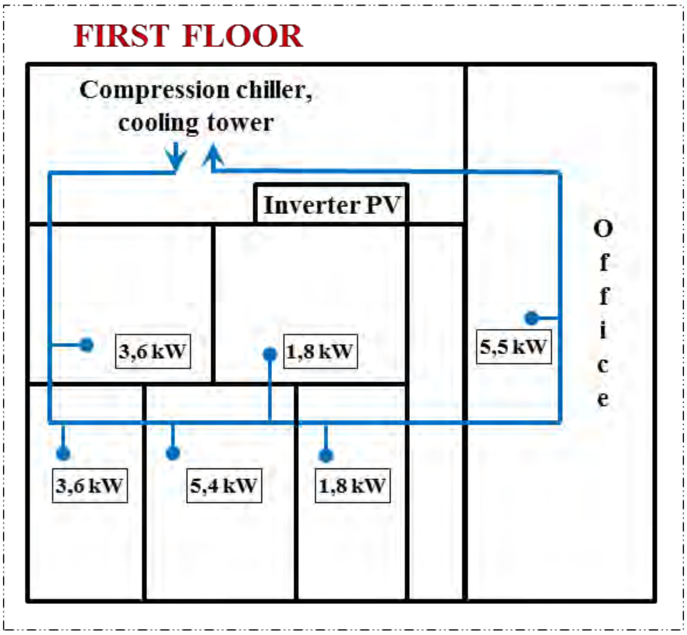


Figure 23 - Cooling circuit schematic of Pontlab first floor

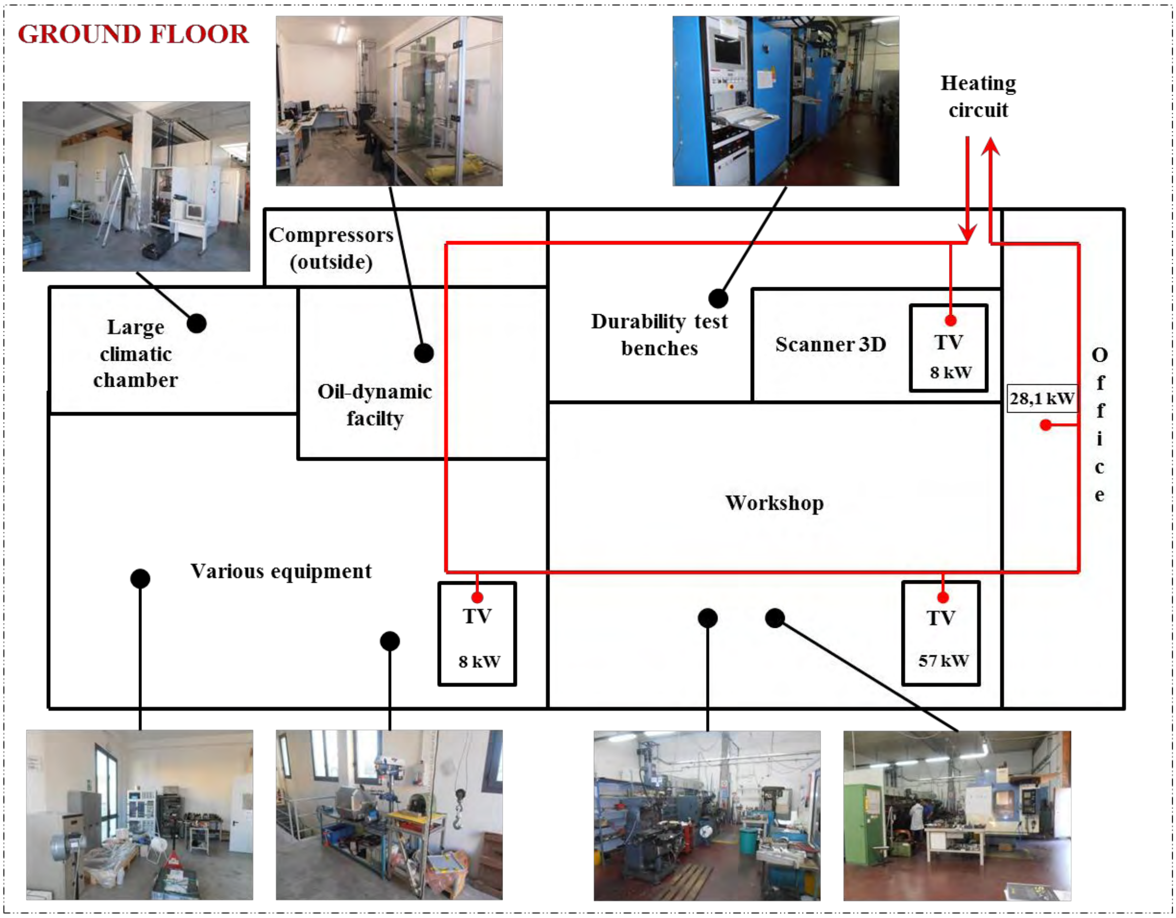


Figure 24 - Heating circuit schematic of Pontlab ground floor

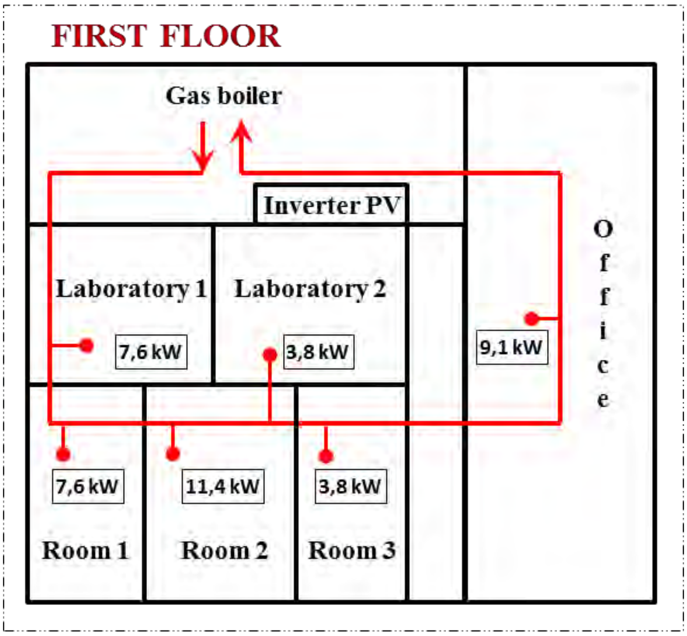


Figure 25 - Heating circuit schematic of Pontlab first floor

The list of the company equipment and of their rated power is reported in Table 2.

Device	Electric power [kW_e]	Heating power [kW_{th}]	Production mode	Cooling power [kW_c]	Production mode
Durability test benches					
Test bench DS1	4.5	0	on-board	0	-
Test bench DS2	4.5	0	on-board	0	-
Test bench DS3	4.5	0	on-board	0	-
Test bench DS4	50	0	on-board	10	Compression chiller
Test bench DS5	50	0	on-board	10	Compression chiller
Test bench DS6	150	20	on-board	25	Cooling tower + compression chiller
Test bench DS8	50	0	on-board	10	Compression chiller
Climatic chambers					

Climatic chamber CST27/2T	19	0	on-board	n.d.	Cooling tower
Climatic chamber CST157/2T	27	0	on-board	15	Cooling tower
Climatic chamber DCTC600P	2.5	0	on-board	0	
Climatic chamber CH1200	24	0	on-board	15	Cooling tower
Climatic chamber SU250	19	0	on-board	0	
Xenon-test	5	0	on-board	0	
Ozone-meter	3.6	0	on-board	0	
Workshop					
Oil-dynamic facility	50	0	-	30	Cooling tower + compression chiller
Working station	10	0	-	0	-
Milling cutter	n.d.	0	-	0	-
Lathe	n.d.	0	-	0	-
Drillers	n.d.	0	-	0	-
Laboratory					
DSC	4.5	0	-	0	-
DMA	0.6	0	-	0	-
ICP	4.75	0	-	0	-
TGA	4.5	0	-	0	-
Spectrometer IR	1	0	-	0	-
Chemical imaging	1	0	-	0	-
GC	2.6	0	-	0	-
Microwave oven	3.2	0	-	0	-
Heater	1.5	0	-	0	-

Analyzer C-S	3.45	0	-	0	-
SEM	3	0	-	0	-
Metaliser	1	0	-	0	-
Cutting machine	1.5	0	-	0	-
Polisher	0.3	0	-	0	-
Compressors					
Back-up	5.5	0	-	0	-
Back-up	5.5	0	-	0	-
Operating	17	0	-	0	-

Table 2 - List of all the machinery in Pontlab site

In Table 3 the list of the devices for air conditioning and room heating is reported.

Device	Model	Heating power [kW$_{th}$]	Cooling power [kW$_c$]	Flow rate [m^3/h]	Quantity
Workshop and laboratories					
Workshop heater	Euroklimat UTK.T L675H	57	37	8,000	1
Workshop heater	Euroklimat UTK.M 001	8	5	900	2
Air treatment unit	Euroklimat	n.d.	35.7		1
Fan coil	Ferroli FCS 4T	3.8	1.8		9
Offices					
Fan coil	Ferroli FCF VMB 15	2.4	0.98		1
Fan coil	Ferroli FCF VMB 30	4.55	1.85		6
Fan coil	Ferroli FCF VMB 40	5.45	2.45		2
Fan coil	Ferroli FCF VMB 50	6.6	3.01		2
Fan coil	Ferroli FCF VMB 60	7.9	3.55		1
Water heater		1.5	-		3

Table 3 - List of all the air conditioning and room heating devices in Pontlab site

The workshop heaters and the air treatment unit are supplied by the heating and cooling circuit of the facility, similarly to the fan coils for the laboratories and the offices.

In summary, the selected company has all the correct characteristic for the Smart User application, as previously explained in §3.1: all the kind of energy are required by the loads, and a RES is yet installed. Nevertheless, the consumptions are unbalanced towards electricity, which in principle could require an over-sizing of the CHP: considering the research project, only some electric loads will be selected to take part to the SU system.

3.3 The definition of the plant layout

Once the case study was defined and the analysis of both the electrical and thermal layouts of the facility was carried out, some proposal for the improvement of the plant hardware were performed.

In particular, the most critical choice for the system upgrade was represented by the CHP rated power: considering the electric consumptions of the company, rarely below 100 kW_e, a very large cogeneration system was required, but in this case most of the heat produced would be wasted, because the required heat would be only needed for room heating, and, also considering the installation of an absorption chiller to recovery the exceeding heat from the engine, the cooling power produced would be too large, as well. For these reasons, the decision of installing only one Yanmar CP25 CHP, with a rated electric output of 25.1 kW_e (with an electric efficiency of 31.5 %) and 38.6 kW_{th} (thermal efficiency of 53.5 %), was taken. The sizing of the engine will be better explained in §3.4.1.

The CHP is combined with a Yazaki WFC-SC5 absorption chiller, in order to extend the operating period of the engine during all the year. The tri-generation system is built on a skid (Figure 26), allowing an easier management during the installation operations and a more compact structure. Within the skid the PLC is also located, needed for the correct management of the whole system and the acquisition of the parameters from all the sensors.

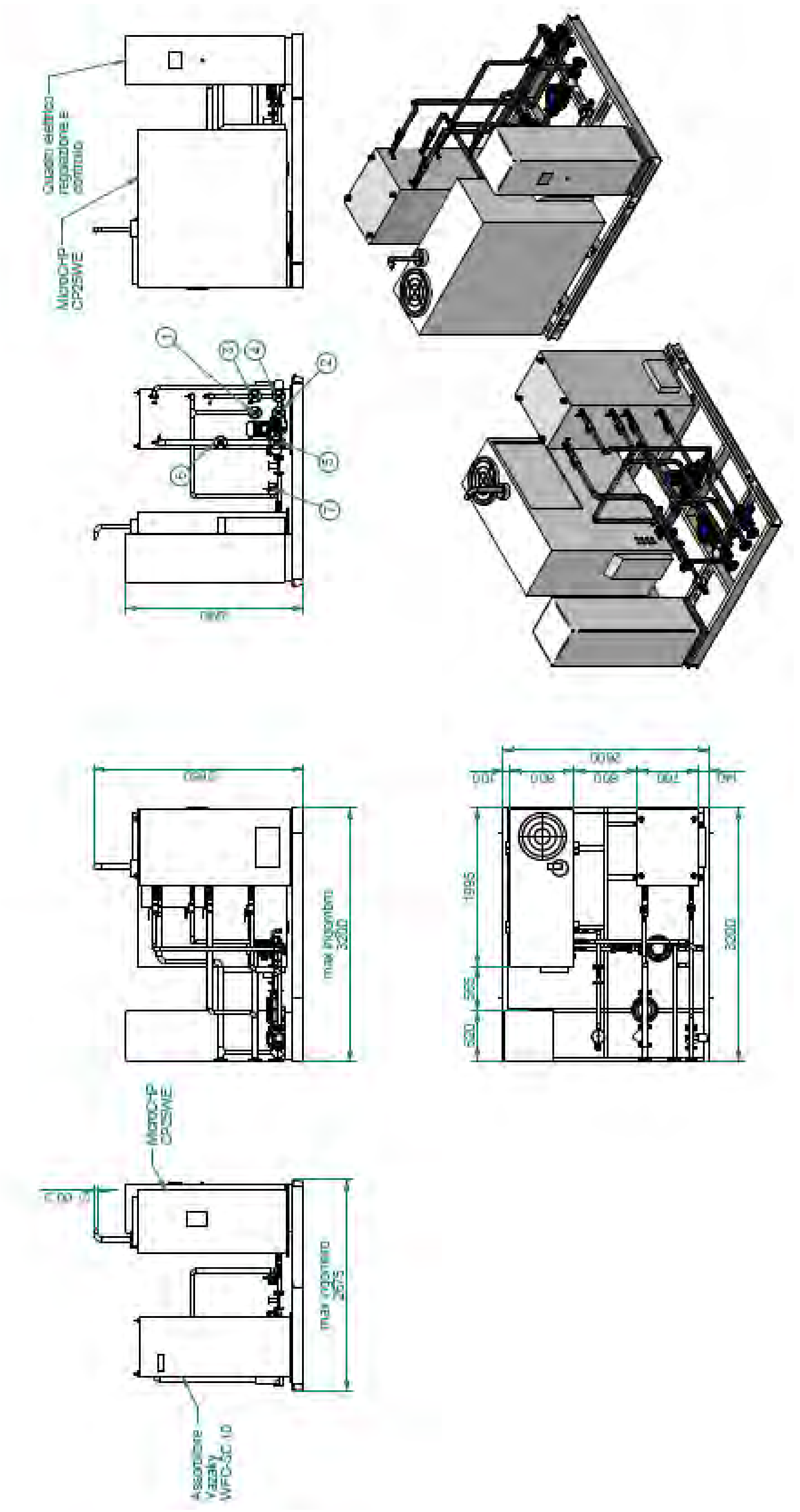


Figure 26 - Tri-generation system skid

The installation of the tri-generation system in the skid is shown in Figure 27, with the absorption chiller placed in the right, the micro-CHP in the center, and the PLC in the left part of the picture.

Figure 27 - Skid of the tri-generation system

3.3.1 Thermal layout

The thermal layout potentially allows several different solutions to be chosen, depending on the technical constraints and on the balancing between investment costs and saving benefits.

In this particular case, considering the large electric consumptions of the company compared to the thermal loads and the needs for both cooling and heating energy, two possible interventions can be taken into account: the installation of one (Figure 28) or two (Figure 29) Yanmar CP25 CHPs, in any case coupled with an absorption chiller, needed to cover the most of the thermal demand during all the year and to increase the operation time of the cogeneration system.

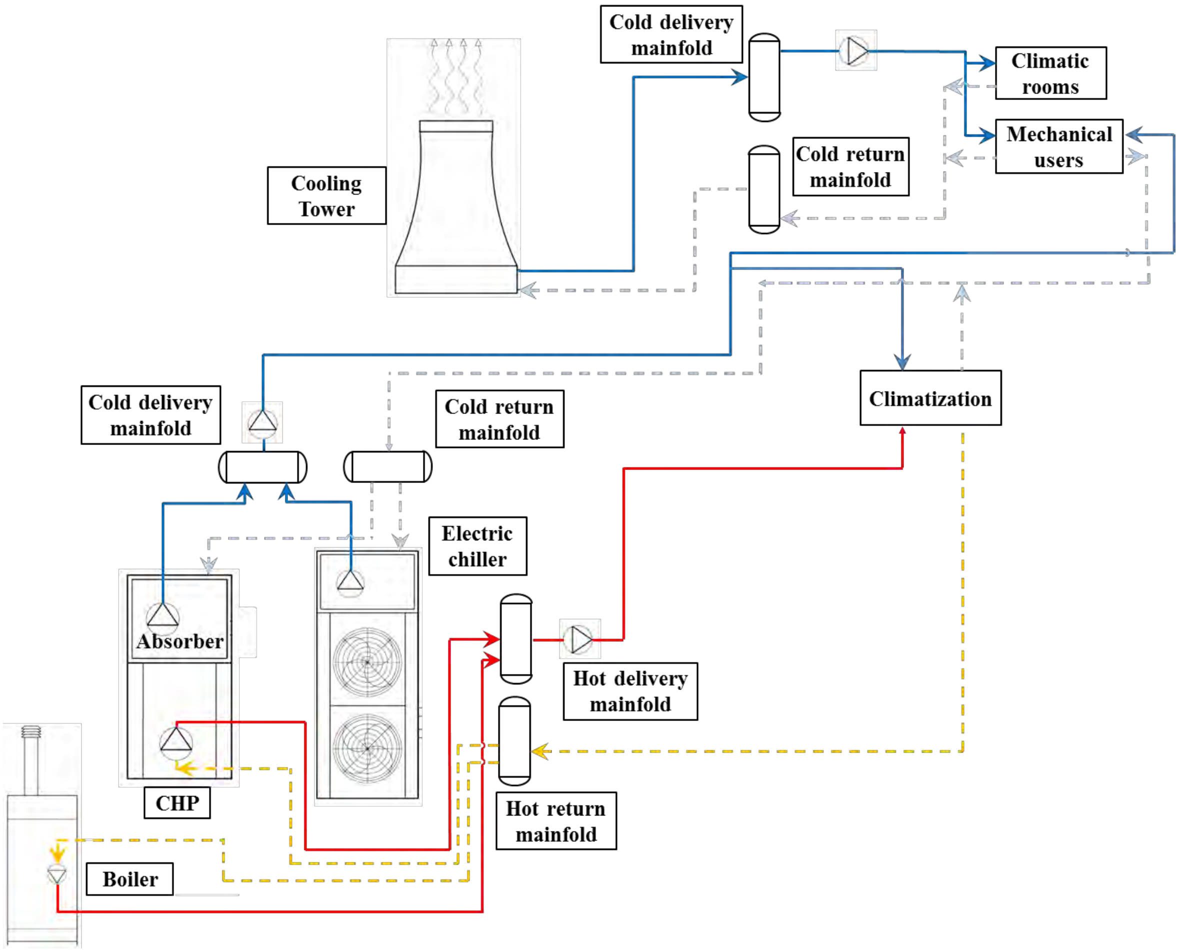


Figure 28 - Smart User thermal layout with one CHP

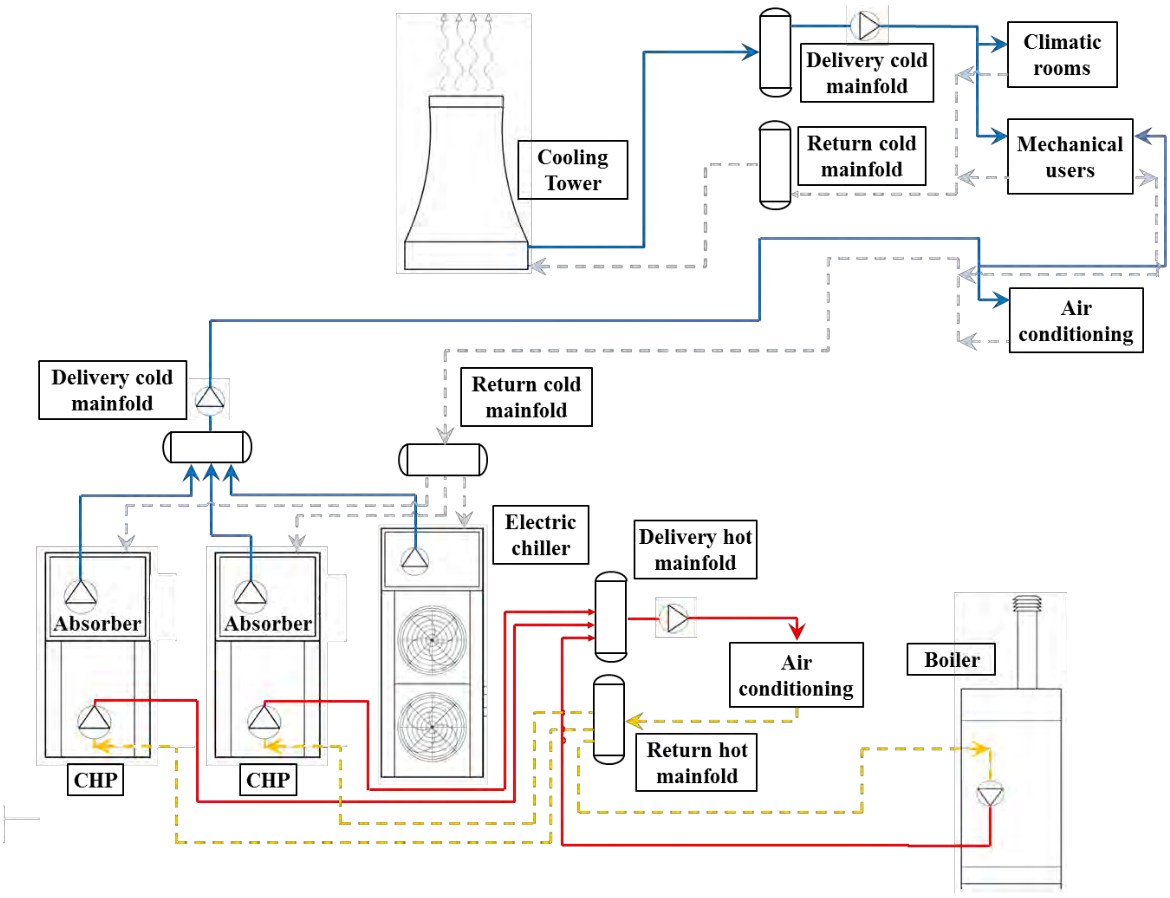


Figure 29 - Smart User thermal layout with two CHPs

This latter solution would allow a larger covering of the overall electric needs of the case study site, and would also be more suitable in the summer period, when the air conditioning request sum up to the climatic rooms and test benches cooling loads. Nevertheless during the winter period, when the heat request is limited to the room heating, the CHPs thermal production would be excessive, with a large waste of the heat recovered from the engines, balancing all the benefits during the rest of the year. The hypothesis of switching the heat from a single cogeneration unit to the absorption chiller in the winter period can be also considered, but it could be not technically effective: the absorber requirement, compared to the effective supply, could bring it to operate with poor efficiencies, or even not operating due to the too critical off-design conditions, under its lower technical limit.

On the contrary, the solution with a single CHP, even if scarcely optimized in terms of electricity production, results the optimal one from the thermal point of view during all the year: when air conditioning is switched on, the eventual small lack of cooling power could be easily covered by the electric chiller, while during the room heating period the recovered heat from the CHP is sufficient for the company needs.

Once the number of cogeneration units is established, the detailed layout has to be thought, starting from the presence of the thermal storage up to their connection with the generation devices and the loads. In principle, a Smart User plant should ensure the maximum flexibility in terms of generators management to supply the loads or charge the thermal storage, this latter piece of equipment being one of the fundamental elements especially in case of use of a CHP system for partially decoupling in time the use of the produced heat and electricity. In addition, the plant should have the lower possible capital and installation costs, in order to increase the economic benefit and minimize the Return Of Investment (ROI).

Considering all these aspects, one of the most suitable solution is represented by the use of the thermal storage as the connecting element between the generators and the loads (Figure 30).

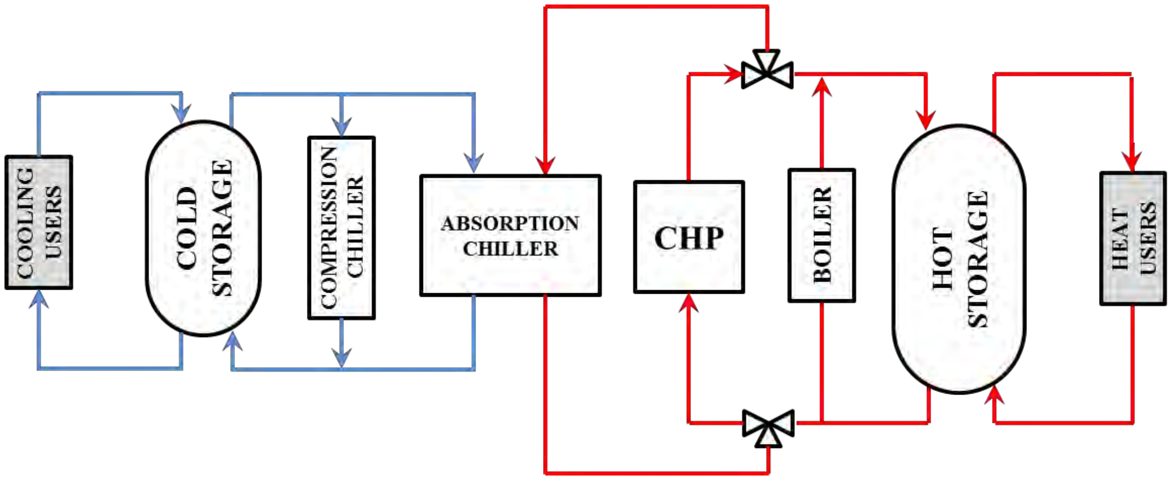


Figure 30 - Thermal layout with two storages connecting generators and users

Of course, two thermal storages are considered, because such a configuration would not allow the use of only one “hot” water tank: in that case, the storage could “feed” the absorption chiller, with the electric chiller operating like a back-up element (Figure 31).The advantage of such a layout would be that the absorption chiller could be indirectly fed also by the gas boiler, contributing to increase the temperature (and thus the energy level) of the water tank.

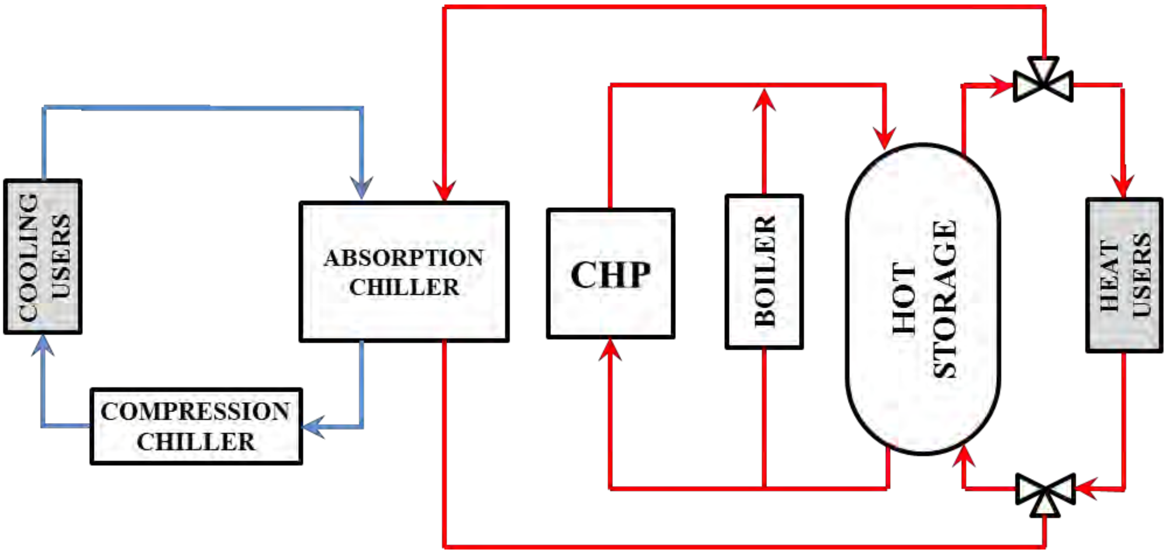


Figure 31 - Thermal layout with one "hot" storage

The solution hypothesized in Figure 30 has the advantages of allowing a real Smart User management of the generators: in this case, the storage is charged in the period it is more convenient to do it and with the most suitable generator for the situation. At now, the heating plant would not be so positively affected by this choice, because the energy market does not differentiate the gas cost with the hour of the day (even if in a not so far future it seems to be one of the possibilities). On the contrary, the cooling plant would have the most effective advantage by this solution, due to the presence of the electric chiller: in case the price of the electricity from the distribution grid is very cheap, the cold storage could be conveniently charged by the chiller, switching off or reducing the power output of the CHP, in order to use the stored cooling energy when the electricity prices are expensive and the thermal request is higher than the absorber rated power. On the other hand, such a solution has the drawbacks of a difficult management of the storage, which can be understood only considering the temperatures within the system instead of thinking in terms of energy. Indeed, the generators could operate with different temperature intervals, depending both by their technical features and by their power output, not ensuring an optimal temperature level to the loads because the stratification of the temperature cannot be kept. The resulting storage internal temperature would result no more uniformly distributed along the tank height, but there would take place a mixing of flows at different heat levels: the global effect is the increase of the "energy level" of the storage, by raising its average temperature, at the price of decreasing the maximum temperature at the top of the tank, which in some particular conditions could not be sufficient to feed the users. Some particular solutions for avoiding this kind of problem are available in the market: one of the most common is represented by the adoption of a rail with several outputs to the storage side. The output of the water flow from the generator at the correct temperature level can be carried out in two different ways:

- By adopting automatic valves, which are designed to open at a predetermined temperature;
- by adopting motorized valves, with a PLC controlling their opening and closing on the basis of a temperature sensor.

Anyway, this kind of solution is not widely adopted due to its high cost and relatively low reliability, and was definitely avoided.

For this reason, in order to ensure the loads to be always fed at the correct temperature level (particularly critical aspect especially for the duration test benches), the layout in Figure 32 is considered for the project.

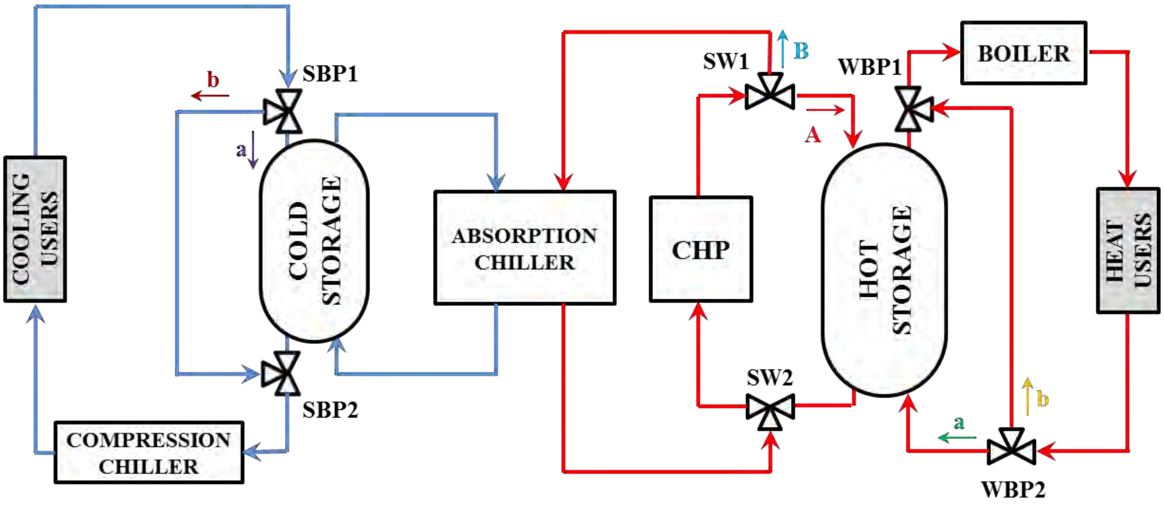


Figure 32 - Thermal layout adopted for the Smart User plant

The proposed solution allows the users to be supplied at the correct temperature in every condition: in case the temperature at the outlet of the storage is not sufficient for the loads, the compression chiller and the gas boiler operate as back-up generators, guaranteeing the correct equipment feeding. From a perusal of Figure 32, by-pass systems for the storages can be seen: their presence is considered necessary both for the correct operation of the storage and for increasing the efficiency of the system. Indeed, in some cases could happen that the temperature of the water flow at the outlet of the users is higher of the one at the top of the tank or lower than the one at the bottom of the storage, respectively for the heating and cooling part of the plant. In that case, the back-up generator would indirectly charge the storage, but increasing the energy level in the “wrong part” of the tank. E.g. if the temperature at the outlet of the cooling users is lower than the one at the bottom of the tank, within the storage would take place convective fluxes, detrimental for keeping the correct temperature gradient: on a medium term period, this would result in a higher temperature than expected at the outlet of the storage, with the consequence of an increased use of the back-up electric chiller and a decrease in the global efficiency of the plant. Similar considerations can be carried out for the heating part of the thermal plant.

For the proposed plant, different operating conditions are possible:

- **Summer period, storage used** (Figure 33): the heat from the CHP is sent through the three-way valve SW1 and SW2 (position "B") to the absorption chiller, which produces cold energy for the storage, feeding the users, with the by-pass valves SBP1 and SBP2 switched in position "a"; only in case of high temperatures from the tank, the electric chiller is automatically switched on.

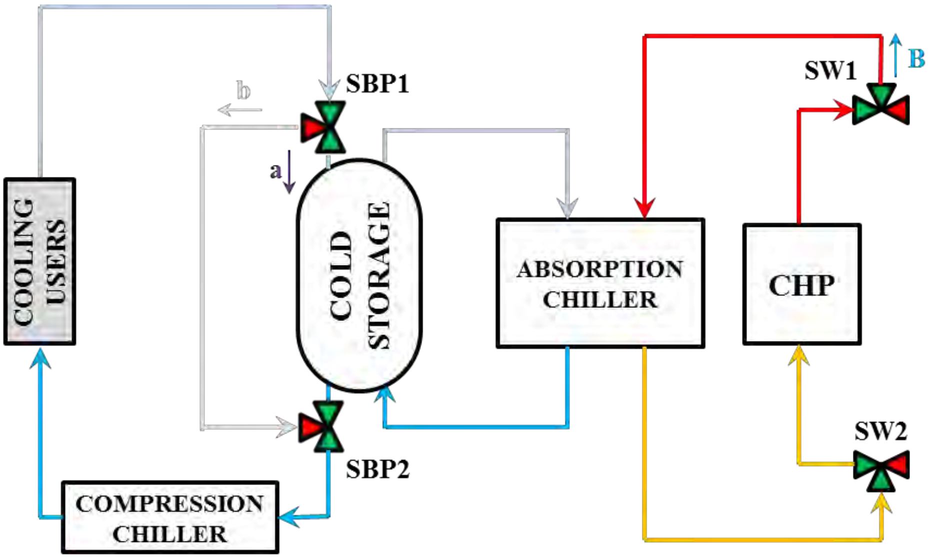


Figure 33 - Summer period, storage used

- **Summer period, storage by-passed** (Figure 34): again ,the heat from the CHP is sent to the absorber, but the by-pass is activated (SBP1 and SBP2 three-way valves position "b"), due to the temperature at its bottom being lower than the one at the outlet of the user; in the meanwhile, the absorption chiller charges the tank, restoring the correct temperature level. The by-pass system is automatically activated when the temperature from a thermocouple placed in the return manifold measures a lower temperature than at the bottom of the "cold" storage.

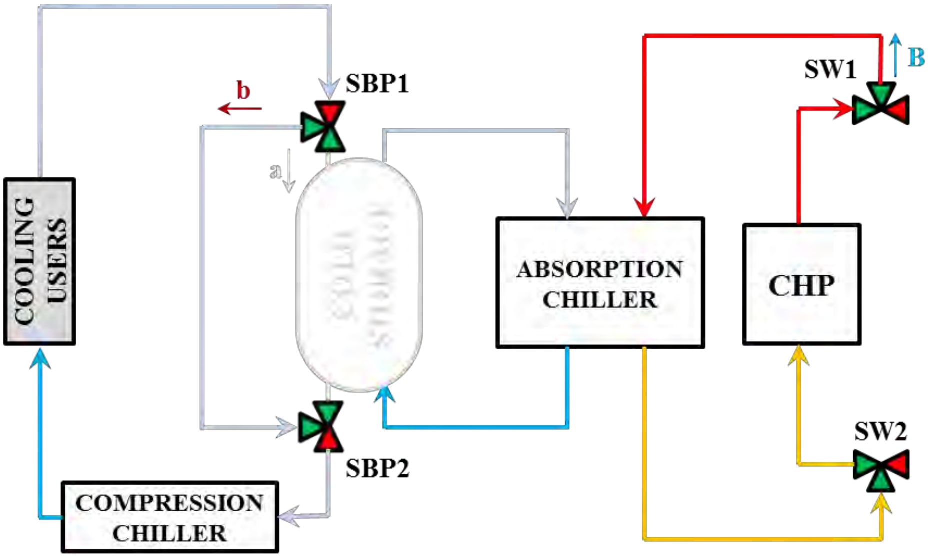


Figure 34 - Summer period, storage by-passed

- **<u>Winter period, storage used</u>** (Figure 35): the heat from the CHP is sent, through the three-way valve SW1 and SW2 (position “A”), to the “hot” storage, feeding the loads with the eventual help of the gas boiler, in case the outlet flow temperature is too low; the by-pass is deactivated, with the three-way valves WBP1 and WBP2 in position “a”.

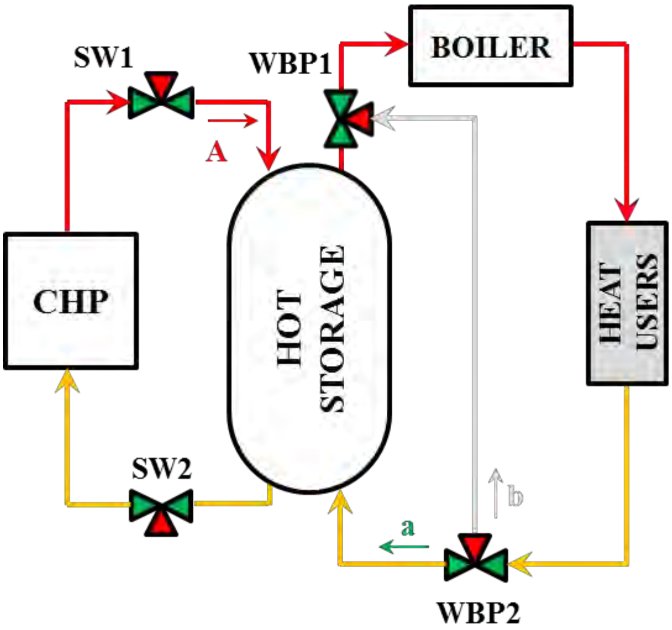


Figure 35 - Winter period, storage used

- **<u>Winter period, storage by-passed</u>** (Figure 36): again, the heat from the CHP is sent to the storage, which temperature is increased; the heat request is entirely satisfied by the gas boiler, because the temperature at the top of the tank are lower than the one at the return manifold, with the by-pass three-way valves WBP1 and WBP2 in position “b”. The by-pass system is automatically activated when the temperature from a thermocouple placed in the return manifold measures a higher temperature than at the top of the “hot” storage.

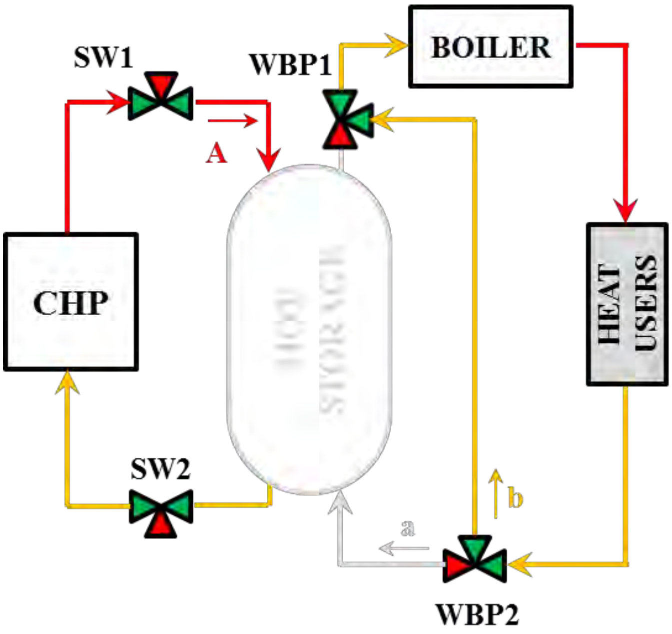


Figure 36 - Winter period, storage by-passed

In summary, the thermal plant proposed for the SU system is remarkably different to a conventional one, which commonly does not allow the presence of a thermal storage, due to the fact that the CHP is managed with thermal-led strategy, in order to exploit all the heat recovered from the engine for the local loads. The difference, also in terms of piping complexity, can be better seen by comparing Figure 37, in which the “traditional” thermal project is presented, with Figure 38, which illustrates the SU project.

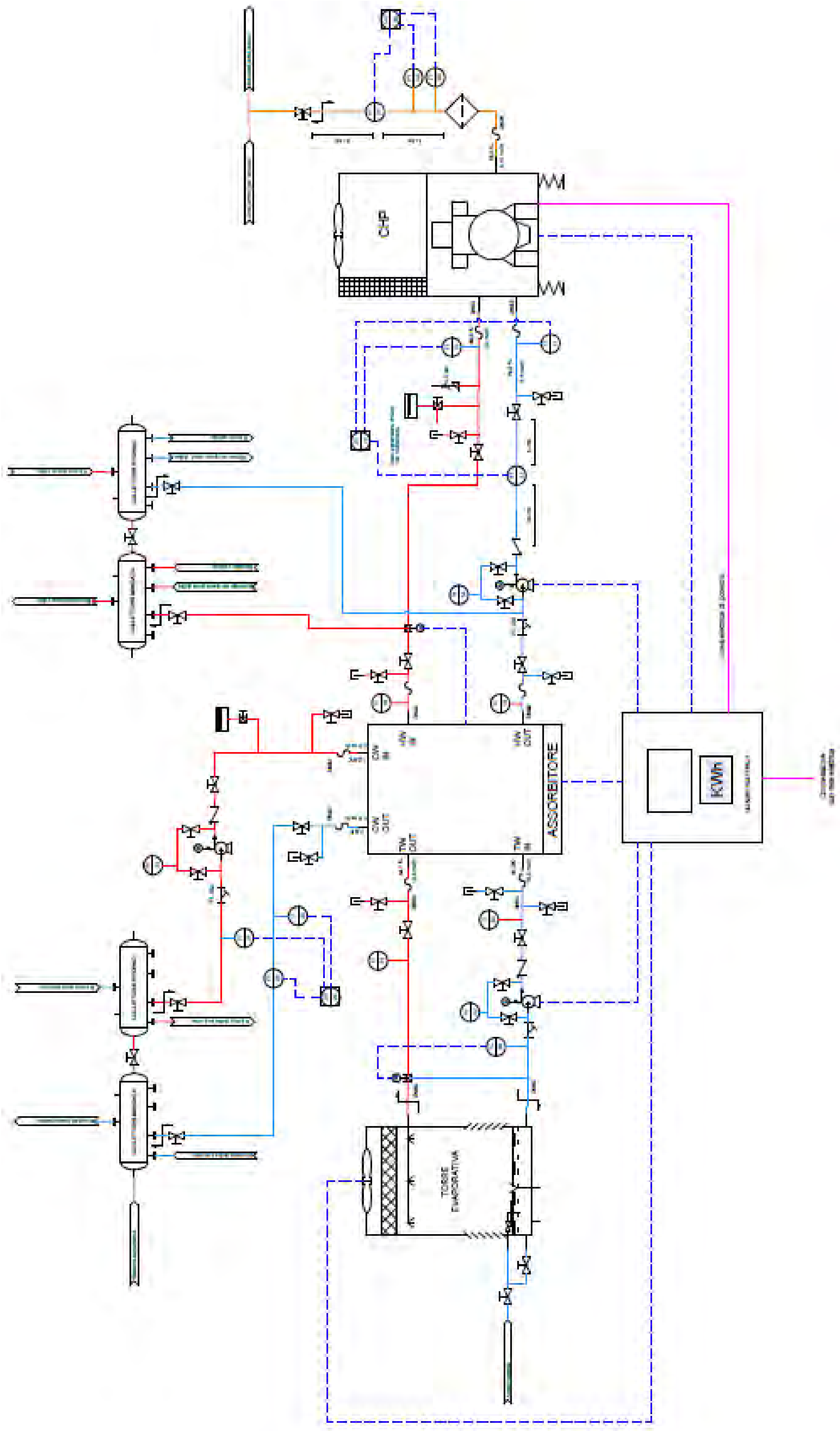


Figure 37 - "Conventional" thermal project

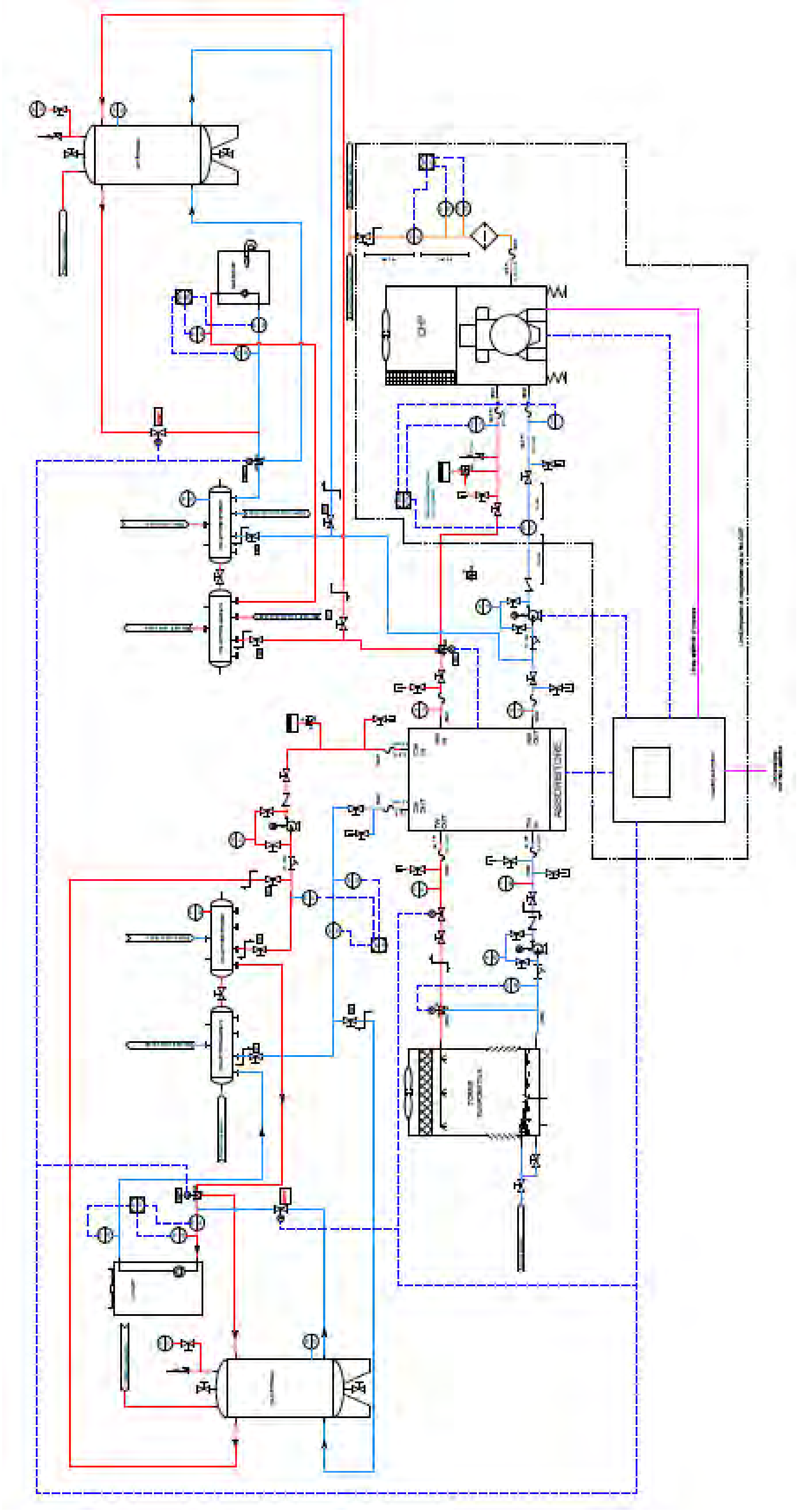


Figure 38 - Smart User thermal project

In Figure 38 can be also seen several additional piping, which allow the thermal plant to be managed in a “conventional” way (heat from the gas boiler, cooling from the electric chiller), if some matters occur with the CHP.

Some pictures of the plant can be seen in Figure 39, .

Figure 39 - Thermal storages: "cold" (blue) and "hot" (red)

3.3.2 Electric layout

The electric layout of the SU system is similar to a conventional electric layout, except to the connection points of the generation units, both renewable and fossil. Indeed, being the possibility of operating in VSO or SO of the plant, all the generators have to be connected inside the company local grid, as shown in the schematic of Figure 40.

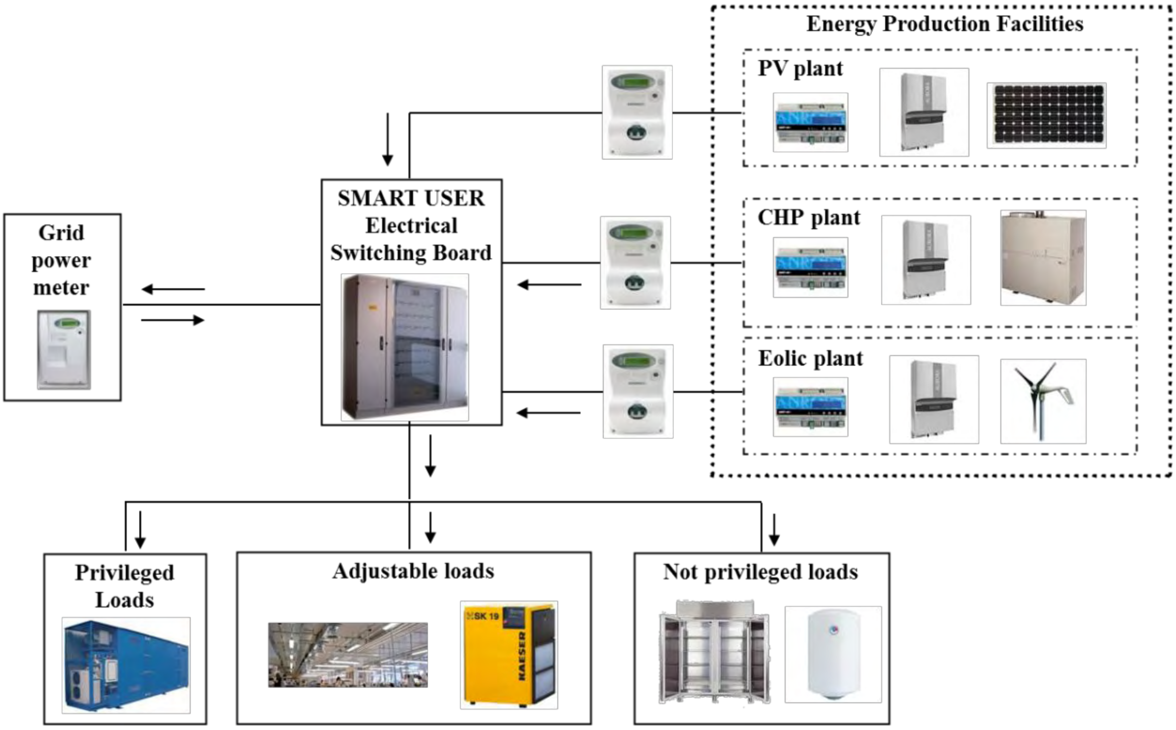


Figure 40 - Smart User electric layout

In the common installation practice, all the RES devices (except for the PV plant) are installed with the connection point directly on the distribution grid, in order to have the economic advantage of the "Tariffa Omnicomprensiva" feed-in tariffs for renewable energy production. The PV plant is connected within the factory electric network, due to the possibility to exploit the economic benefit of the "Conto Energia" incentive. About the CHP system, the connection point is generally next to the energy meter, in order to benefit of the "Scambio Sul Posto" incentive, when an excess of electricity is produced compared to the amount required by the loads.

In this case, because of the need to consider only few electric users taking part of the Smart User system, all the electric generation devices are connected inside the local power network, with just few loads contributing to the realization of the Smart User electric system, because of the too large electric request compared to the generation capability of the installed devices.

The considered loads for the SU plant are listed in Table 4.

Device	Electric rated power [kW_e]
Test bench DS3	1.5
ATLAS compressor	7
Electric chiller	25

Climatic chamber CH1200	24
Climatic chamber DCTC600P	2.5
Climatic chamber SU250	7.7
Workshop heater	1.8
Oven	2
Office lights (1st floor)	1.1
Fan coils	1.8

Table 4 - Smart User electric loads

As shown, the sum of the rated power of all the loads greatly exceeds the sum of the generators rated power, but considering the contemporarily factor of 0.45 as said in §3.3, the "effective" overall power consumption is around 35 kW_e, allowing the hypothetical user to also operate in VSA or SA conditions.

3.4 The sizing of the equipment

Being the SU system a concept involving different needs in its management and conception, the pieces of equipment installed within that context are sized in a remarkable different way than compared to a "traditional" prosumer plant.

As first, in most of the CHP (or CCHP) applications the presence of the thermal storage is avoided: indeed, the common thermal-led operation strategy (the heating power output of the prime mover follows, as far as possible, the fluctuation of the loads request) for the cogeneration system makes the presence of a water tank not useful in most cases, and sometimes detrimental, because it works like a sort of "temperature dumper", with the back-up heater switched on also when it couldn't be needed.

3.4.1 CHP system

In all the "conventional" applications, the CHP size is usually evaluated on the basis of the thermal duration curve. This graph allow to understand the frequency, in terms of hours, of all the thermal consumption of the considered plant, disposing the load request in decreasing order, as shown as an example in Figure 41.

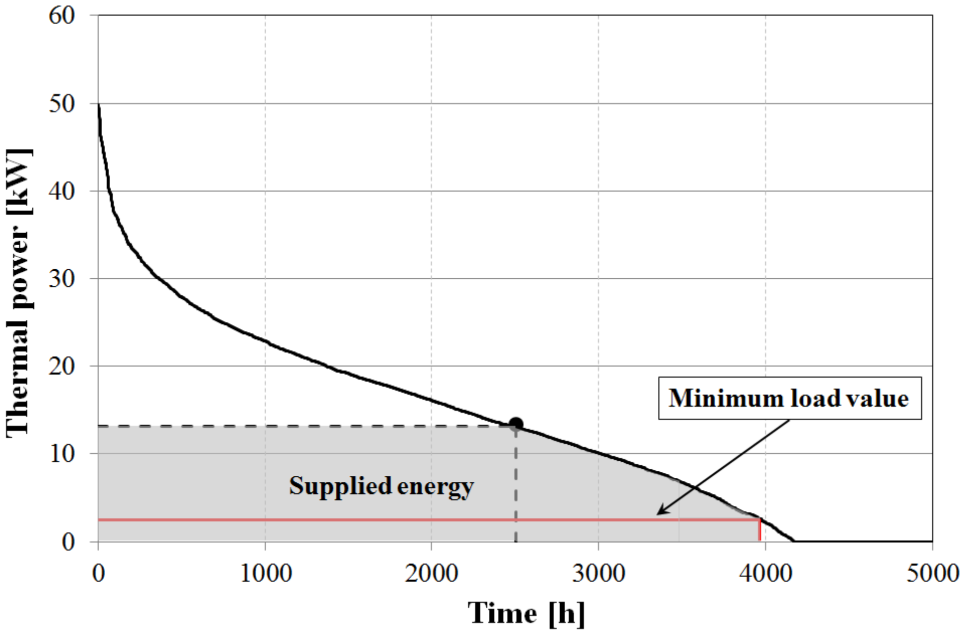


Figure 41 - Example of “conventional” sizing of a CHP [117]

The optimal rated thermal power of the CHP is chosen by finding, on the load duration curve, the rectangle of maximum area with one vertex lying at the origin and the other constrained on the curve itself. By doing so, the system ensures the maximum operation time at nominal load. Of course, the cogeneration system is also capable to produce the power loads lower than the nominal one, with the total supplied energy which is colored in grey in Figure 41. The minimum supply limit results in the more stringent between two different constraints: the lower technical power limit of the CHP (as in figure), or the maximum number of operating hours of the system, mainly dependent by maintenance intervals.

In the Smart User case, this criterion is no longer valid, due to the fact that some of the most relevant constraints result in the possibility to operate the plant in Virtual Stand-Alone or Stand-Alone conditions and to the need to balance the fluctuations of the intermittent renewable sources. For these reasons, the CHP cannot be longer considered as a “boiler with a positive side effect”, i.e. the electric production, but it must be firstly thought as an electric generator, whose efficiency is enhanced by the heat recovered from the discharge of the prime mover. As a consequence, the optimal size is determined by the sum of the privileged loads, of course considering the contemporarily factor of the users.

In the present case, the considered privileged loads are represented by the first part of Table 4, in particular:

- The durability test bench DS3;
- The Atlas compressor;

- The electric chiller;
- The climatic chamber CH1200.

The sum of the rated power of the pieces of equipment is over 57 kWe; considering a contemporarily factor of 0.45, the result is around 26 kW_e, just 1 kW_e over the rated power of the Yanmar CP25 CHP, that, as previously said, must constitute the hardware core of the research project.

3.4.2 Thermal storages

For the selection of the most suitable size of the thermal storages, a computational model was developed by using LMS AMESim software. It is a 1-D simulation tool based on the bond-graph methodology [118,119], which offers to the user the possibility to perform transient analyses, particularly desirable in case of thermal systems because of their intrinsic inertia. Anyway, the software was firstly developed for automotive companies, that’s way many useful features for an easy simulation of thermal systems are not yet present.

The computational AMESim model is composed by three main ideal blocks:

1. The electric system, which includes the CHP, the PV plant, the micro-wind turbine, the external power grid, and the users;
2. The heating system, including the heat recovery from the CHP, the heat storage, the auxiliary boiler, and the users;
3. The cooling system, representative of the absorption chiller, the cooling storage, the electric chiller, and the users.

The thermal blocks of the model are also comprehensive of two sinks, which sometimes are needed to avoid that out-of-range temperatures from the users can happen. The piping connecting the different thermal devices are not “physical”, but “signal” links. In order to avoid any problem linked to the thermal inertia of the system, which can’t be replied with signal connections, some water volumes are placed after each thermal device, thus replying the delay between the power variation of the generators or users and the corresponding temperature variation in the following part of the system due to the circulating water flow within the piping. A more detailed view of these water volume is shown (in green) in Figure 42.

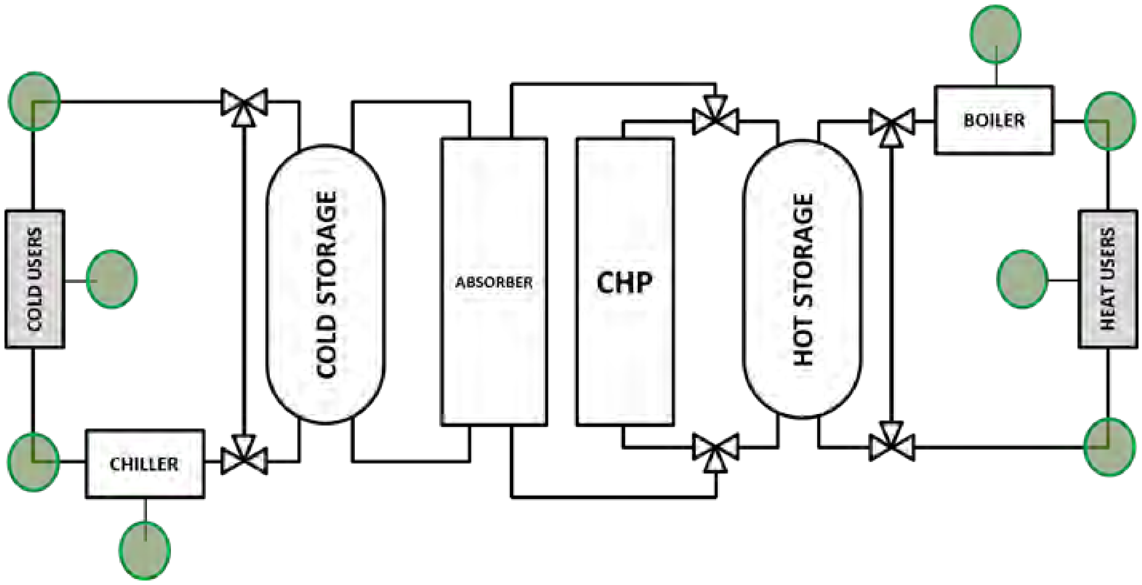


Figure 42 - Functional schematics of the thermal model

The water volumes are estimated on the basis of the effective length and diameter of the piping linking all the devices.

The AMESim schematic of the model, with the indication of the “meaning” of the various component, is shown in Figure 43.

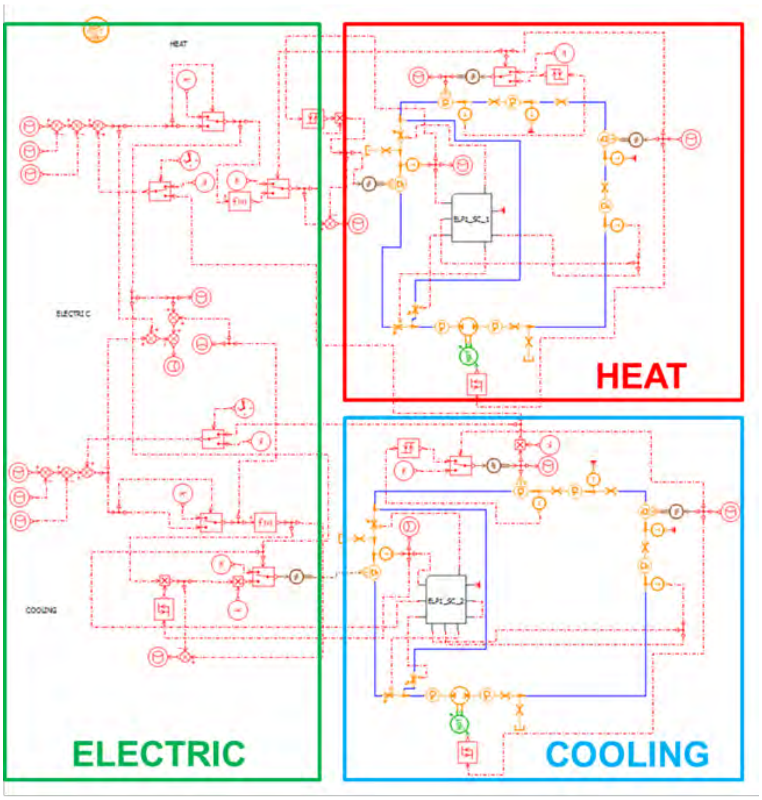


Figure 43 - AMESim developed model of the Smart User system

The model can show the user how the system works by following two different strategies for the CHP: thermal-led and power-led operations.

The input to the model is represented by the load profiles of all the users (electric, heating, and cooling) and by the production from the RES devices (PV and micro-wind turbine). As outputs, the power supplied from the CHP and the auxiliary devices, and the power from/to the grid (only in case of thermal-led operation of the CHP) are estimated. For the correct functioning of the system, many other parameters must be set-up in advance:

- The volume of the storages;
- The rated power of all the generators;
- The set-up temperatures determining the switching off and on of the auxiliary generators (boiler, electric chiller);
- The set-up temperatures determining the functioning of the three-way valves of the by-pass system.

The model thus implemented can help the user to understand the more suitable size of the CHP and of the heat and cooling storages, by performing a sort of Design Of Experiments (DOE): the final purpose is represented by the minimization of the energy consumption of the plant and, in a second step, the maximization of the revenue.

Once the size of all the generators and storages is estimated, the optimization work can focus on the most suitable set-up temperatures for the management of the auxiliary generators.

The performed simulations allow to understand the most suitable volumes of the “hot” and “cold” storages by considering the technical constraints of the SU plant.

The hypothesized load profiles are representatives of three typical working days for Pontlab Smart User plant: winter, mid-season with the absorber exploitation, summer. The electric load is the same for all the considered days, because it does not takes into account the electric chiller consumption, and it is shown in Figure 44, taken from [120].

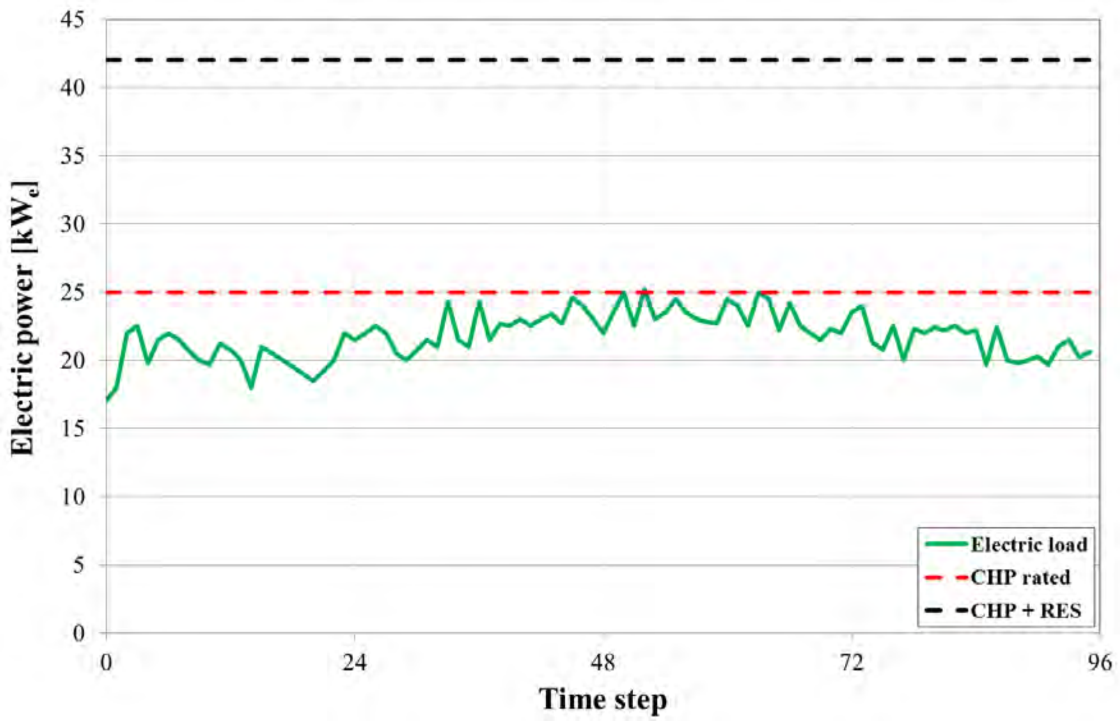


Figure 44 - Electric loads for the considered simulation day

The heat and cooling request during a typical **winter day** is shown in Figure 45: the heat demand is estimated on the basis of the room heating needs, as suggested in [120], whilst as regard as the cooling loads, the prediction is carried out on the basis of the average use of the machine in the factory, as suggested from the plant managers.

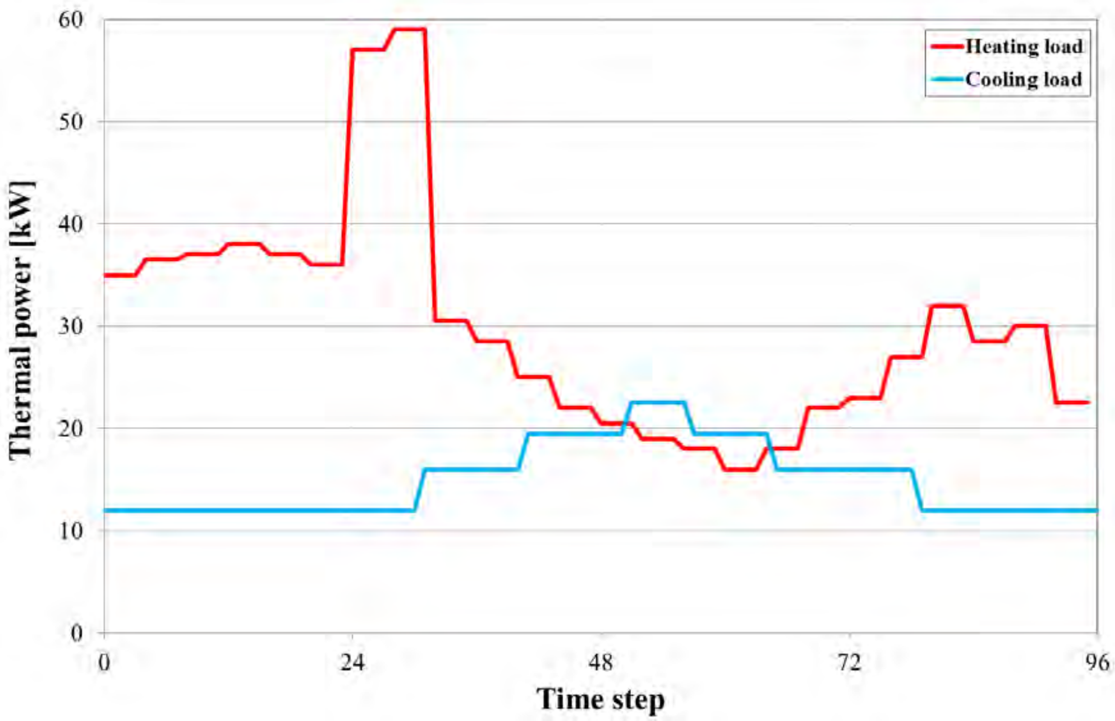


Figure 45 - Winter day heating and cooling hypothesized loads

With this loads configuration, the analysis focused on the most suitable volume for the heat storage by considering the energy supplied from the auxiliary boiler and the wasted heat from the CHP, under the hypothesis of a power-led strategy of the cogeneration system and of regime condition for the storage (its energy level at the beginning and at the end of the day is as similar as possible). The investigated sizes are 0.5 m^3, 1 m^3, 2 m^3, 3 m^3, and 5 m^3.

The analyses show that the boiler never operates, because of the low heat request for room heating compared to the CHP production, driven by the electric request. Figure 46 shows the heat wasted during the day.

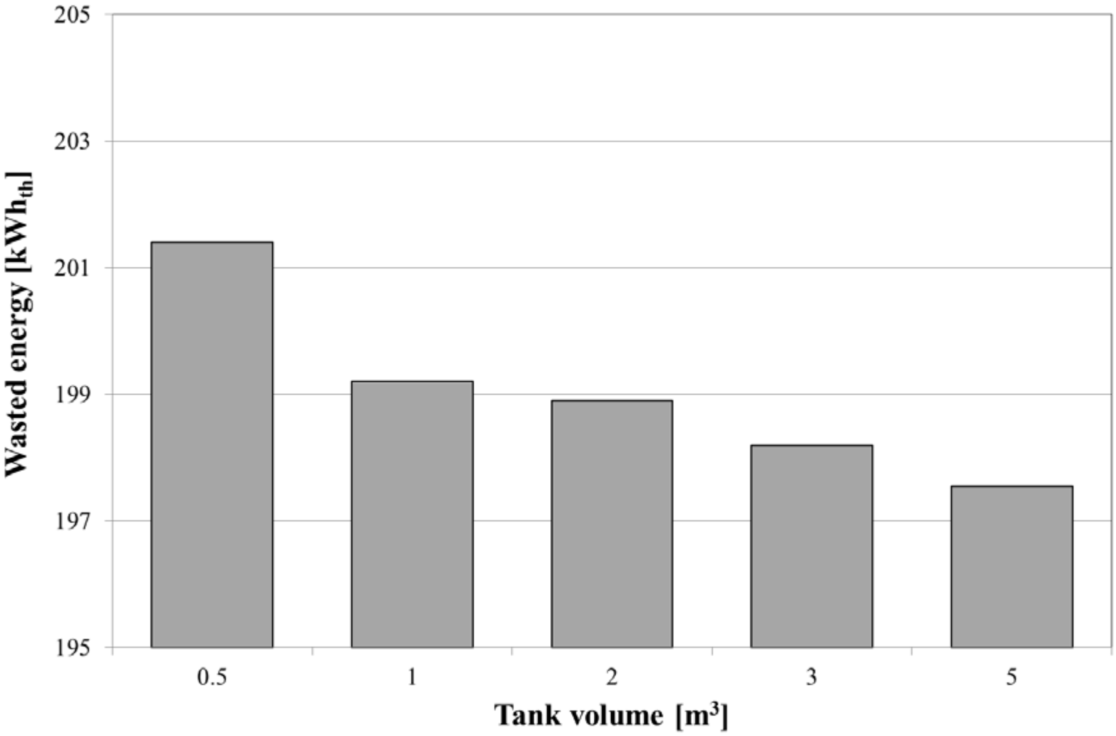


Figure 46 - Wasted thermal energy during the hypothesized winter day

As expected, the wasted energy decreases by increasing the tank volume, even if the overall amount is quite similar in all cases. For this reason a storage of 3 m^3 seems to be an appreciable compromise between wasted energy, costs and required space, also considering that the electric-led condition for the CHP would be not so frequent and that the heating loads are programmed to grow up due to the installation of new machineries in the next future.

The cooling user request profile for the **mid-season** is slightly increased compared to the winter one, due to the use of the air conditioning, with this latter contribution estimated from [120], as reported in Figure 47. The heat request is null, because the room heating is switched-off.

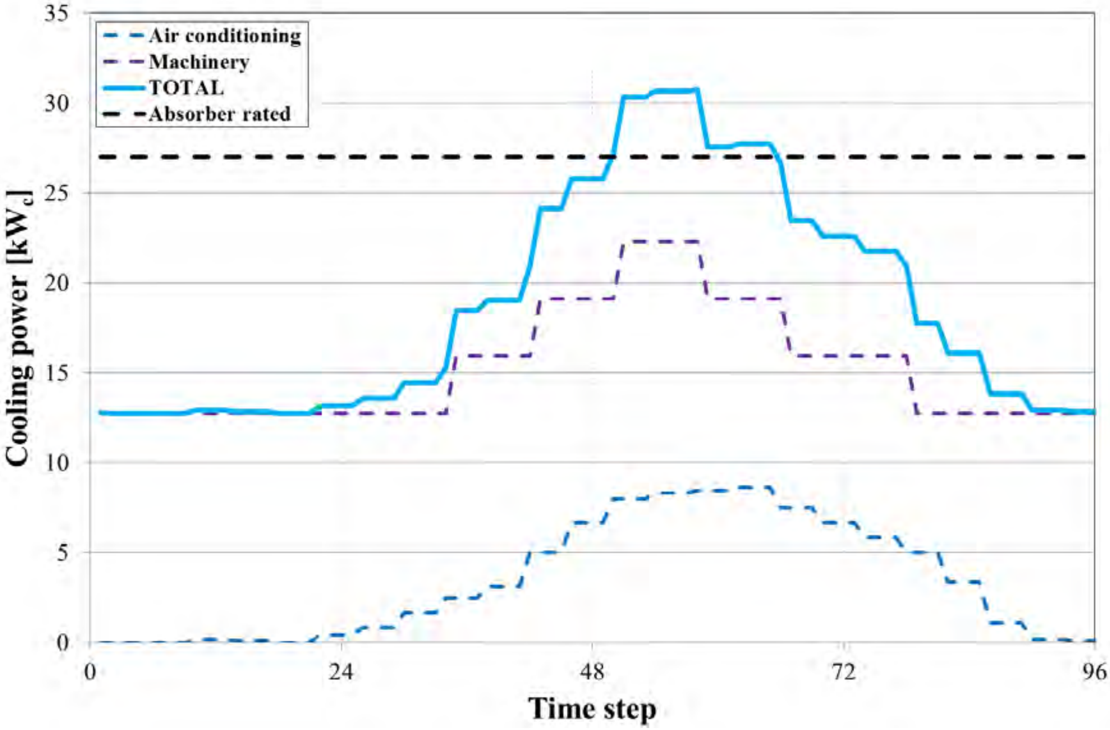


Figure 47 - Mid-season hypothesized cooling loads

In this analysis, the attention is focused on the evaluation of the most suitable volume for the cooling storage. The simulations were performed for the same sizes considered for the heat storage: 0.5 m^3, 1 m^3, 2 m^3, 3 m^3, and 5 m^3. Figure 48 shows the energy supplied from the electric chiller to match the loads requirement.

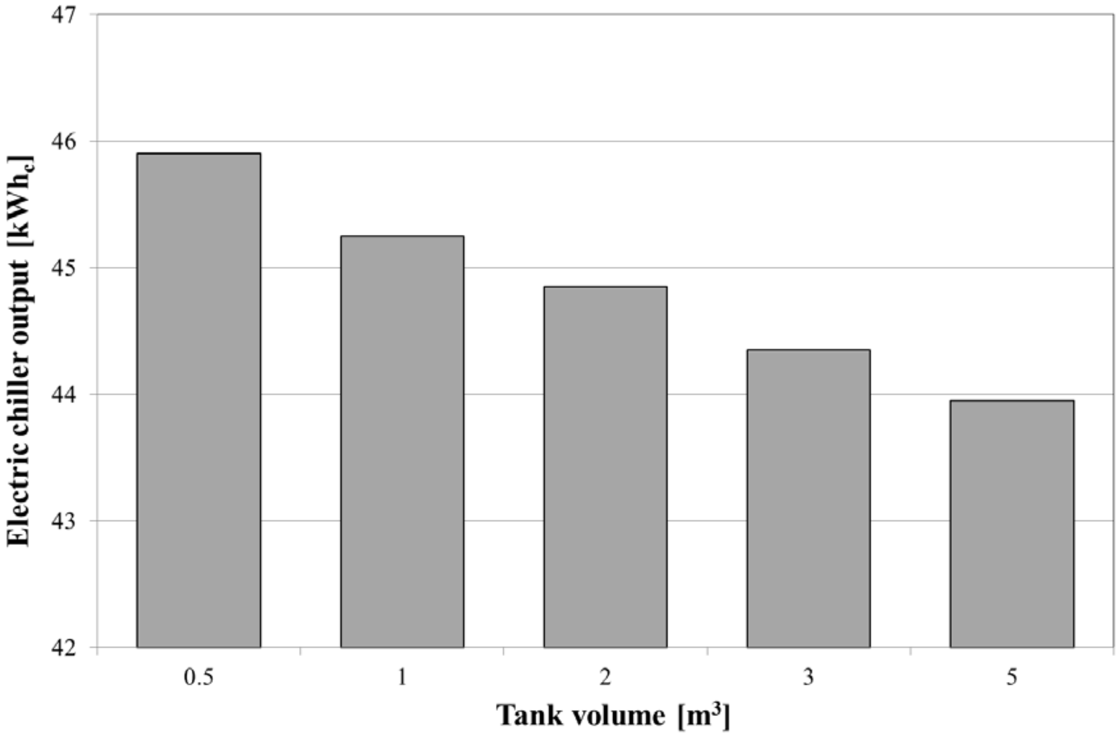


Figure 48 - Cooling energy supplied by the electric chiller in the hypothesized mid-season day

As attended, the increase of the storage volume slightly decrease the use of the electric chiller, even if the differences are quite small, due to the low cooling request during the mid-season day. A similar trend can be seen in Figure 49, showing the wasted energy.

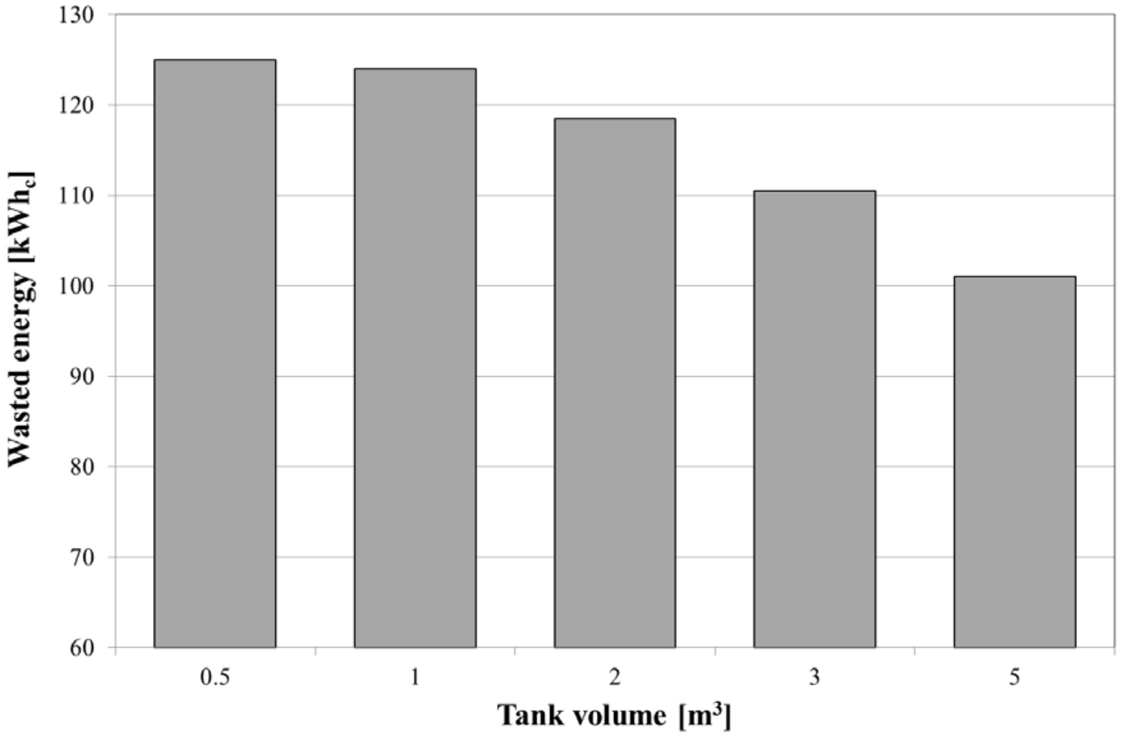


Figure 49 - Cooling energy wasted in the hypothesized mid-season day

During the considered **summer day** the heat request is null again and the cooling request is remarkably increased because of a massive use of the air conditioning, as shown in Figure 50.

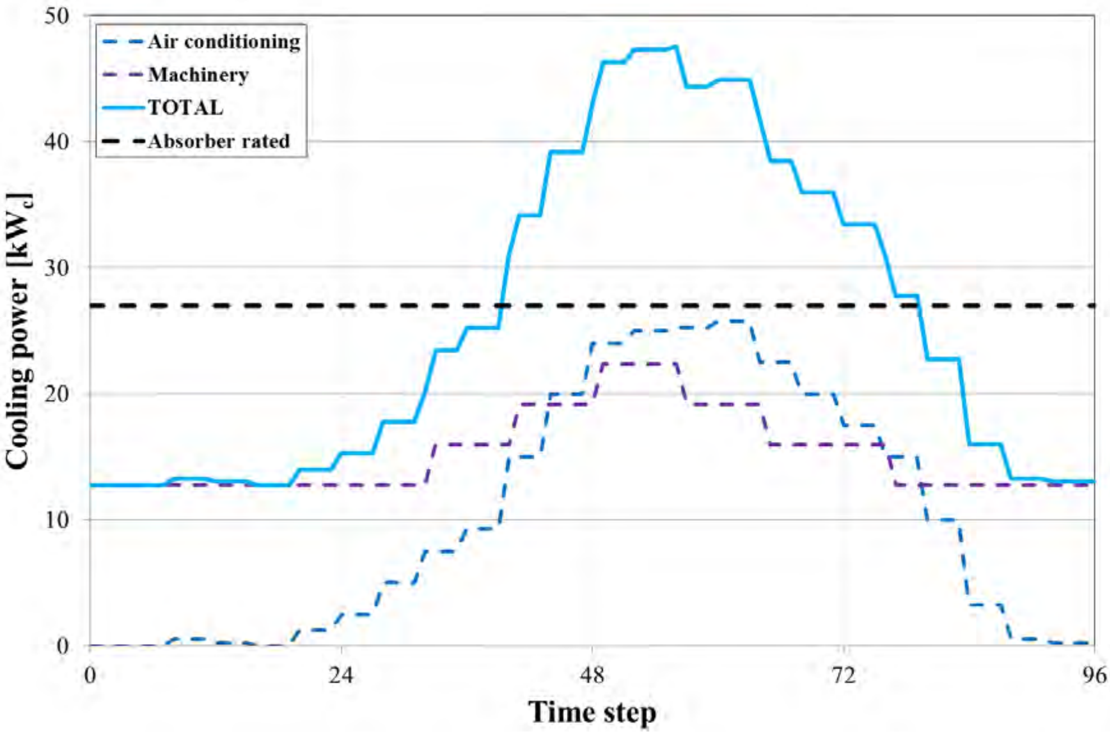


Figure 50 - Hypothesized summer day cooling loads

The aim is, once again, to estimate the suitable size for the cooling storage, combining this analysis with the mid-season one. The energy supplied by the chiller is now represented in Figure 51.

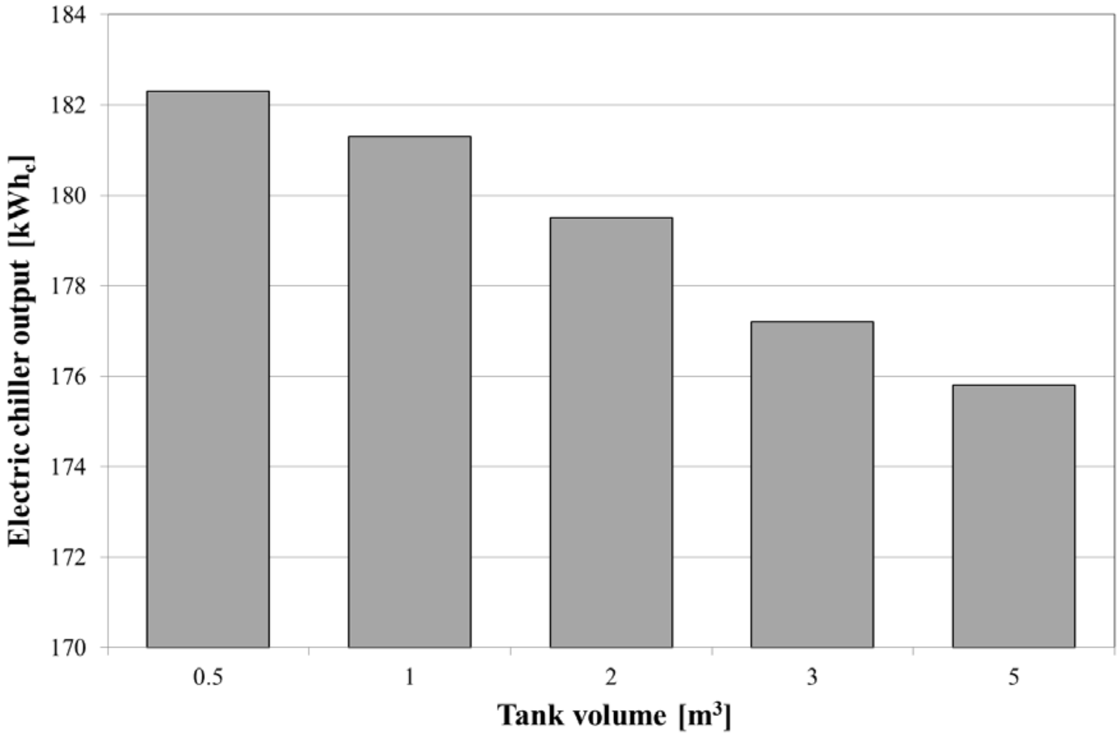


Figure 51 - Cooling energy supplied by the electric chiller in the hypothesized summer day

The overall values are, of course, higher than in mid-season, but the trend is similar, showing a decrease in the utilization of the electric chiller when the volume of the tank is increased. The wasted energy is shown in Figure 52.

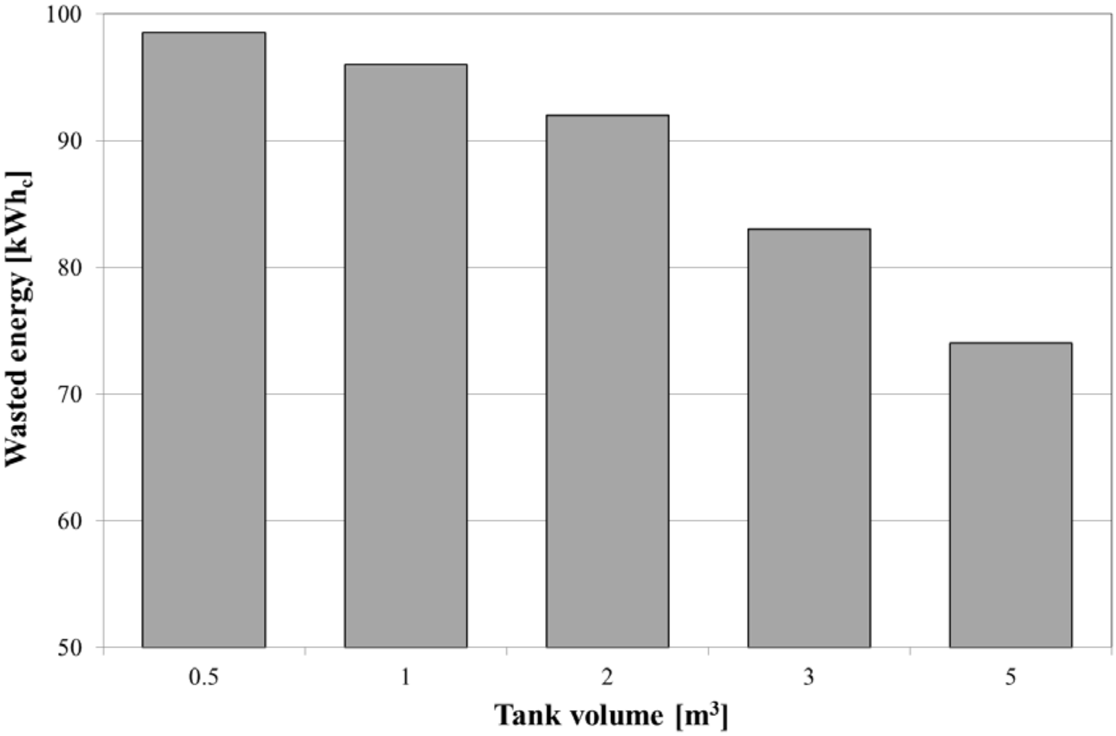


Figure 52 - Wasted cooling energy in the hypothesized summer day

Once again, the trend is similar to the others, with the increase in the energy capacity of the storage which contributes to the decrease of the energy wasted through the sink.

By considering the summer and mid-season days, it’s possible to say how the 2 m^3 size represents an acceptable compromise between energy performance and costs: the larger size solutions could not bring so many benefits capable to balance the increase of the investment.

4. The development of the energy management system

4.1 Introduction

From an hardware point of view, the Smart User system does not present remarkable differences compared to a “conventional” plant: the main difference lies in its control system, which must present improved sensors (e.g. smart energy meters), and, above all, by the management algorithm, which represent the real core of this new application.

4.2 Electronic equipment

The electronic equipment is based on standard commercial products, like energy meters, electric multi-meters, temperature sensors, and electric switches for the loads control, all these elements with improved communication characteristics based on standard communication protocols.

For the thermal plant, the smart energy meters are selected from Siemens product, in particular the UH50 model represents the choice for the system (Figure 53 and Figure 54).

Figure 53 - Energy meters of the CHP (left) and the absorption chiller (right)

Figure 54 - Energy meter of the electric chiller

It allows the communication of all the measured parameters with the PLC by the standard MODBUS-RTU RS485 protocol. In particular, the energy meters measure the thermal production of the CHP, of the absorption chiller, of the gas boiler, and of the electric chiller, as shown in Figure 55 together with all the other sensors.

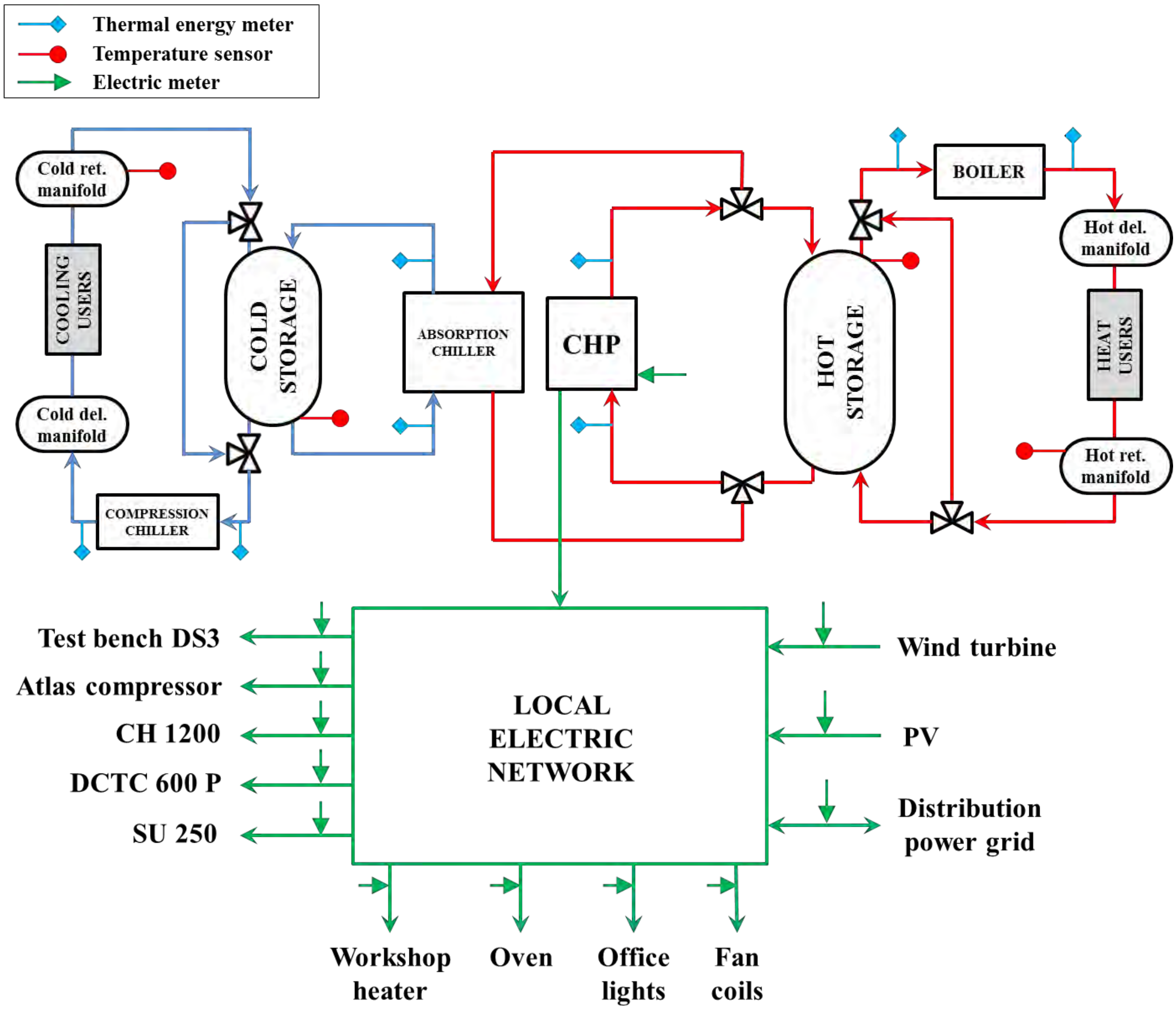


Figure 55 - Smart User sensors positioning

The temperature sensors consist in thermo-resistances PT100 (Figure 56), which are previously manually calibrated. The electric meters are multi-meters (Figure 57) placed in the electric panels, capturing the data from the Smart User system considered loads.

Figure 56 - PT100 temperature sensor

Figure 57 - Electric multi-meter

4.3 The SCADA system

The monitoring, control, and management device selected for the Smart User application is a SCADA system: Even if the complexity and the capability of such a system is excessive compared to the target of the research project, it results one of the best option if considering the requirement of flexibility, easiness in the configuration of all the parameters coming from the field, automation of the command to the devices, flexibility in the communications between the PLC of the tri-generation plant, the energy meters and all the remaining sensors, and monitoring needs.

In particular, the selected SCADA system is eXPert by s.d.i. automazione industriale, an environment created for producing automation, control and tele-control systems, and whose principle structure is shown in Figure 58.

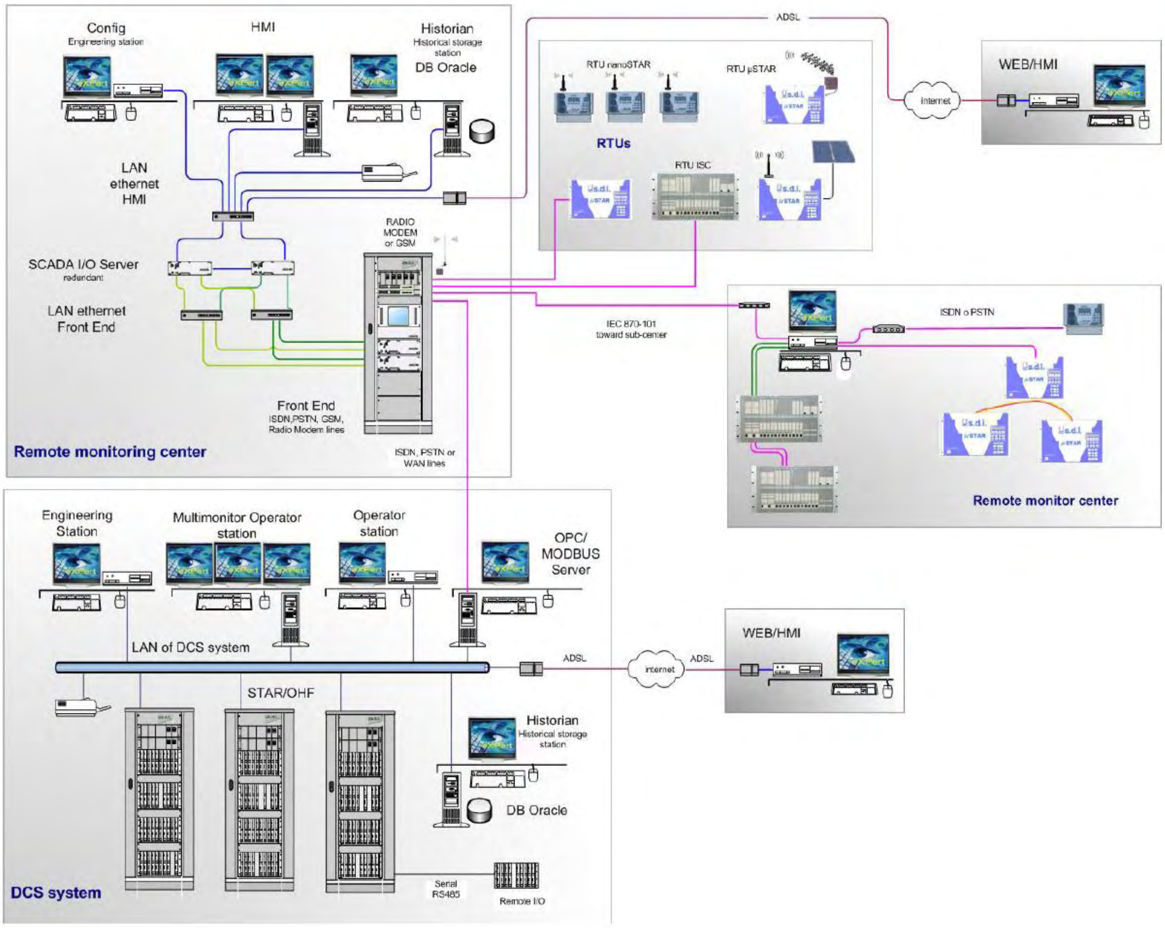


Figure 58 - eXPert functionality schematics

In its entirety, it is a set of software and hardware products designed with the aim of providing several functions. It includes the hardware apparatus directly connected to the field, used for managing acquisition, regulation and control, and also the software for processing, storing and viewing the data acquired, designed for both Microsoft Windows and Linux platforms. The hardware equipment is constituted by the eXPert field data acquisition and control group. This contains the STAR (STation for data Acquisition and Regulation) unit, composed of acquisition and regulation equipment recommended for setting up DCS systems, equipment for tele-control applications, remote terminal blocks, and micro-STAR and nano-STAR equipment created especially for tele-control applications. The eXPert Run Time Environment is the package of software components used for setting up automation and control systems. It includes SCADA and HMI systems, data storage stations (Historian), I/O Servers for establishing connections with the field and managing communication lines, and Soft PLC functions. The package includes a series of components dedicated to connectivity, used in tele-control applications or, more generally, in control applications distributed over a geographical area. The tools for connection (hierarchical or relational) include SCADA stations, a Remote Alarming package for managing alarm notification (through synoptic via web). The eXPert integrated development tools consists of system configuration tools. It includes a series of editors that allow configuration of all the components, both software and hardware, of the automation and tele-control system. The main tools are the HMI graphic page editor, SCADA data base editor, automation/regulation logics editor (Soft Logic Editor), administration utilities of the data storage server (Historian) and I/O server (I/O Server Admin). In order to interface with hardware produced by third parties, I/O servers are used, which allow interfacing with the PLC and the other equipment using standard MODBUS and TCP/IP protocols.

Complete supervision and control systems can be created by distributing eXPert Run Time Environment’s components between various PCs in network configurations that suit the application. One of the system main features is the freedom to set the architecture of the entire system depending on the characteristics of the process being controlled and the specific requirements of the end user.

The heart of the system is composed of SCADA Server and HMI components. SCADA Server manages the dynamic process data base, calculations, system logics and alarm data base. HMI acts as a client in relation to SCADA, requiring only the data necessary to display the video pages displayed at that moment by the operator.

The alarms are managed through queries by the client regarding the current alarm situation, which is controlled and kept up-to-date by SCADA. Field data acquisition and protocol management are performed by the I/O Server component. When used in tele-control applications, eXPert also provides functions for management of communication lines and protocols for peripheral acquisition and control equipment (I/O Server functions).

Historical data storage functions are provided by Historian Server, which allows various types of data base to be used for storing historical data.

Below is a brief description of the functions performed by each component.

I/O Server Functions:

- Data acquisition or transmission from/to acquisition and regulation stations in continual connection (STARs, PLCs, RTUs, programmable controllers, regulators, etc.);

- Data acquisition or transmission from/to remote RTUs (e.g. micro-STAR controllers) via the tele-control network;
- Management of modems and associated communication lines;
- Management of round cycles and/or historical data acquisition on remote stations with non-continual connections;
- Acquisition of spontaneous data transmitted from remote tele-control stations;
- Display of data acquired from local/remote SCADA stations, with interfacing that is independent of the type of protocols and lines being managed;
- Standardization and conversion of data originating from different types of equipment.

SCADA functions:

- Data acquisition or transmission from acquisition stations (STAR stations, PLCs, programmable controllers, regulators, etc.) via the field network;
- Creation of a dynamic system data base containing an image, updated in real time, of the data acquired from the plant or calculated by SCADA itself;
- Management of ordered and controlled access to the system's dynamic data bases;
- Server functions in relation to additional HMIs and any other stations (PCs, Workstations, etc.);
- Standard calculations;
- Alarm detection;
- Alarm data storage;
- Alarm printing;
- Telephone calls or SMS/email to external operators in the event of an alarm;
- Management of plant devices;
- Command management;
- Daily Report printing;
- Production of printouts;
- Functions supporting application programs;
- Query interface for the access to dynamic system data base from external systems via the network.

Historian Functions:

- Management of data storage in binary and/or relational files;
- Server functions regarding requests for display and retrieval of historical data.

HMI Functions:

- Management of the HMI synoptic interface, on single or multiple monitors, with extensive use of colored graphics, Microsoft Windows-style windows, and numerous methods of accessing and presenting data;
- Management of the graphic/interactive display of historical data stored by the station;
- Management of color hard copies, with the option of centralizing the printer.

SoftPLC Functions:

- Direct connection with the field Bus;
- Execution of automation logics.

For the present application, some HMI functionality are purposefully developed, to allow the user of the experimental plant an easier control of all the production parameters and SU functionalities. In particular, the diagnostic graphical schematics and the synoptic of both the electric and thermal plant are created, as shown respectively in Figure 59, Figure 60 and Figure 61.

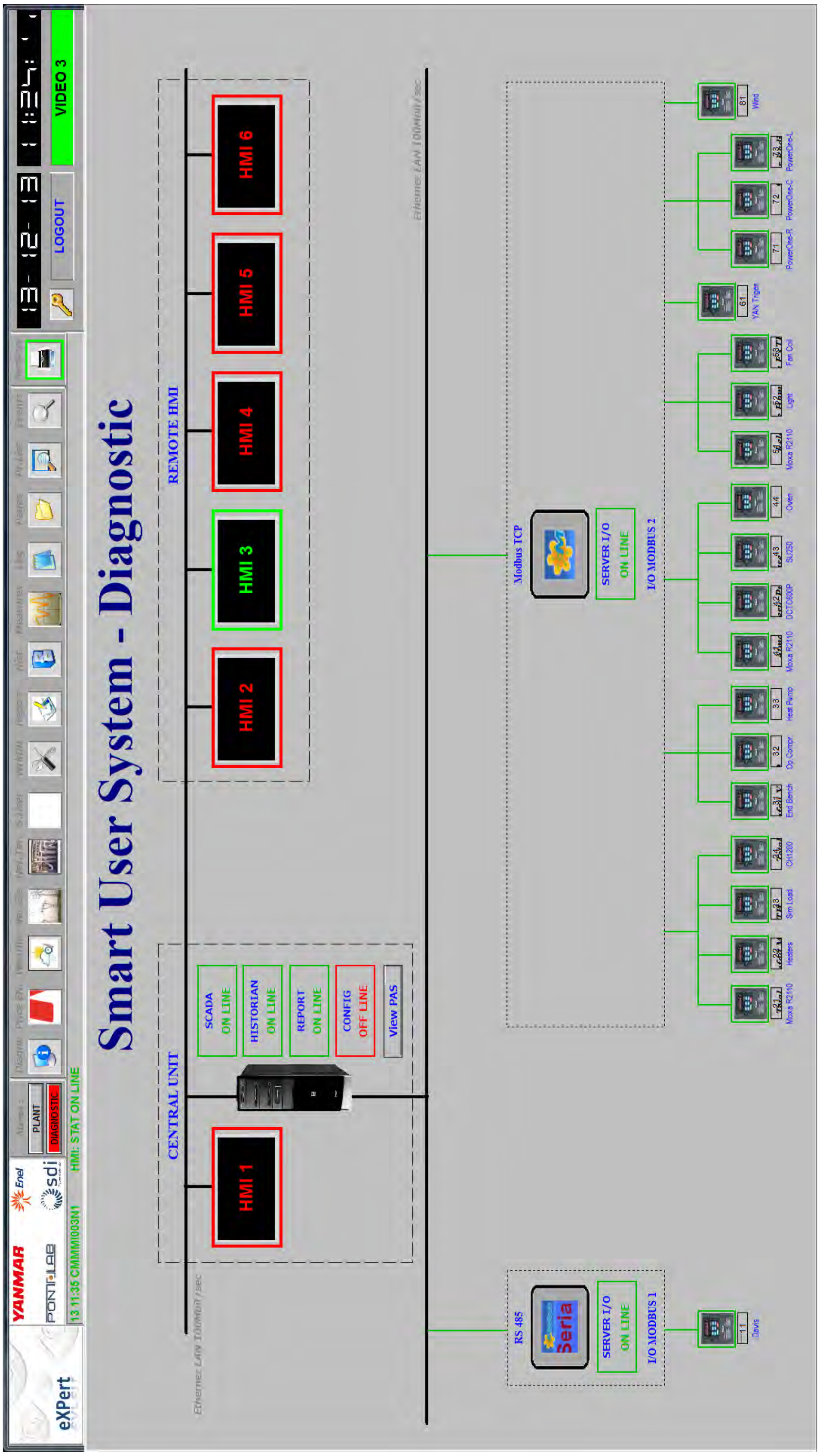


Figure 59 - Diagnostic HMI page

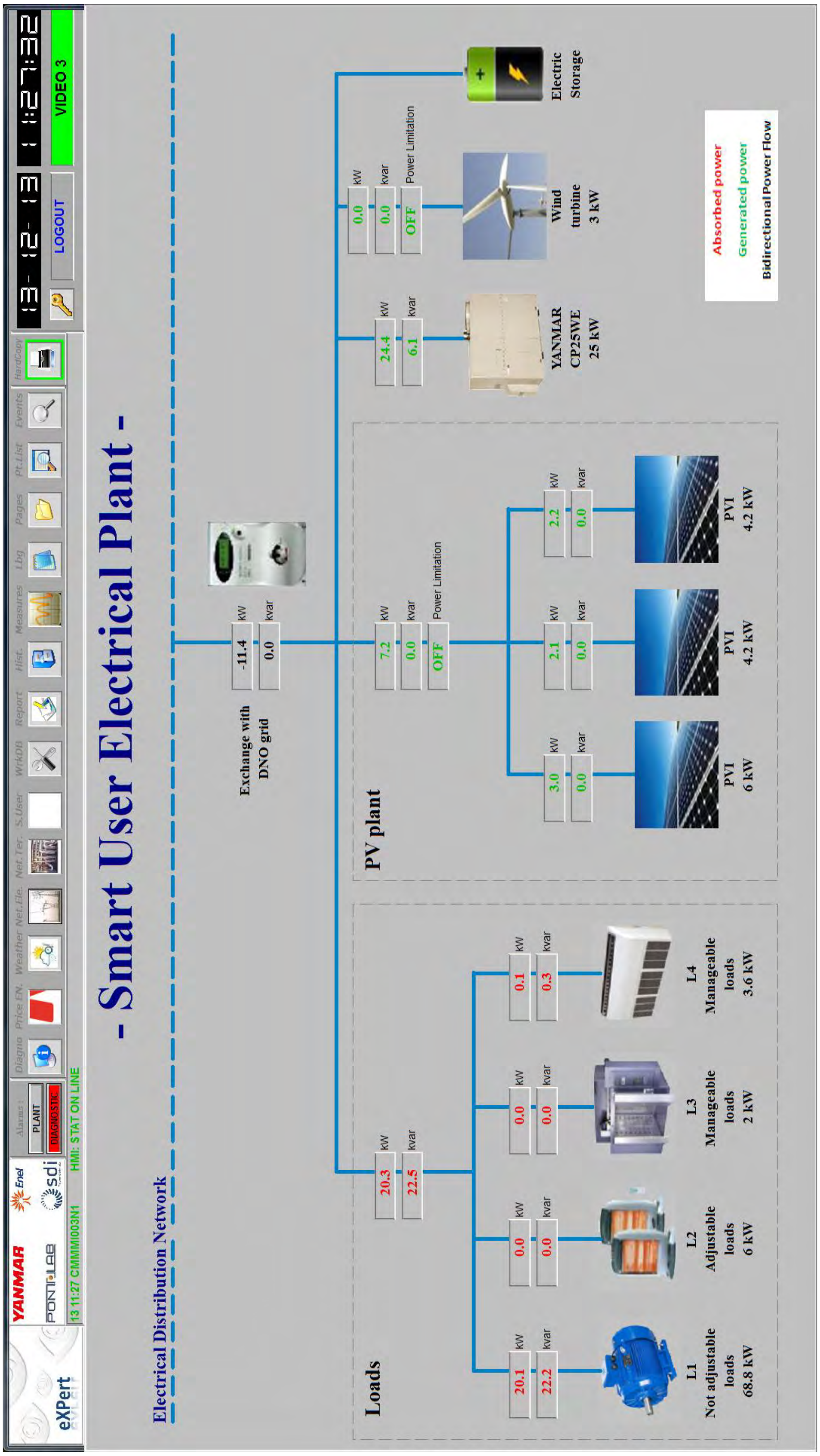


Figure 60 - Electric plant HMI synoptic

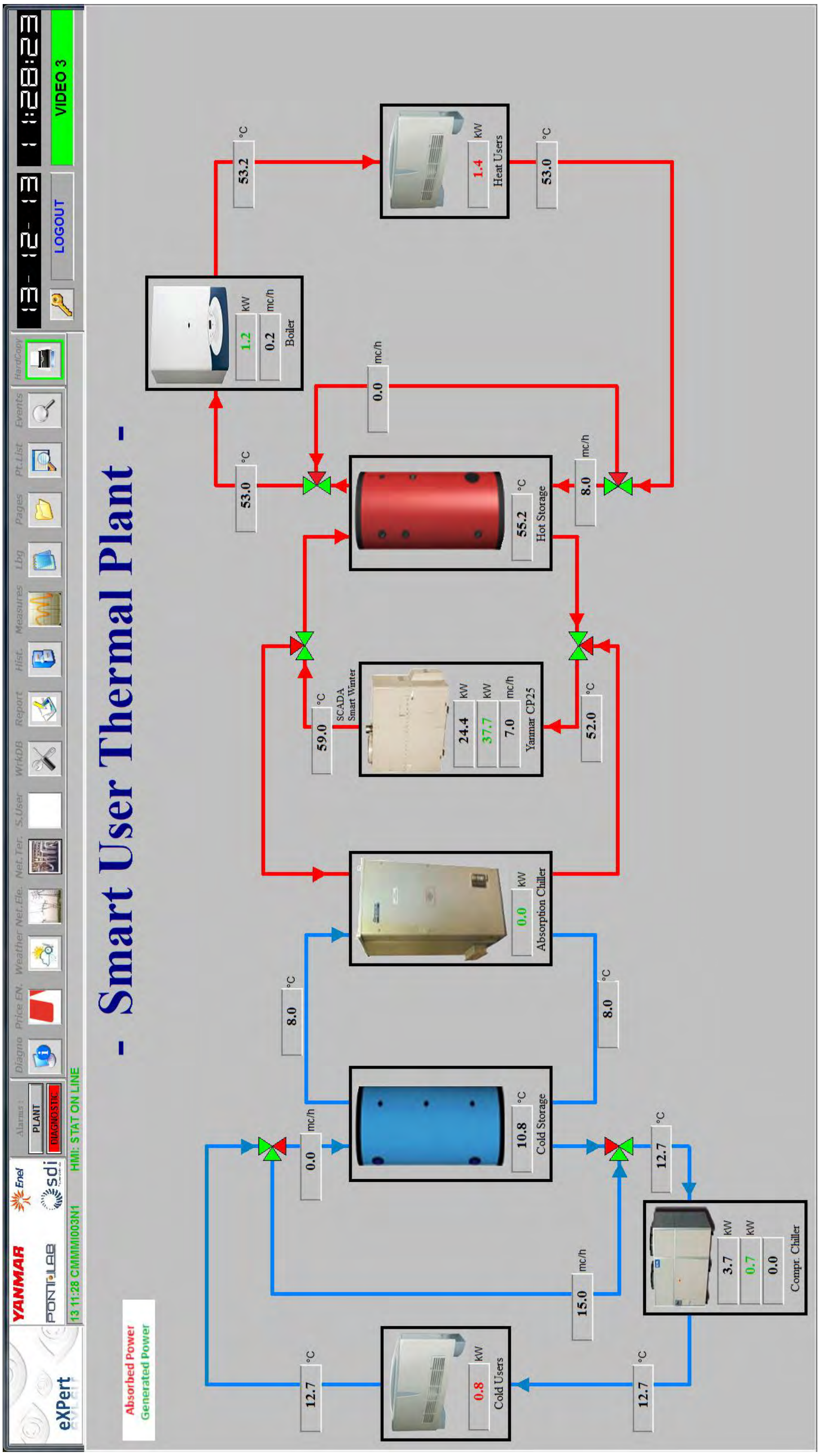
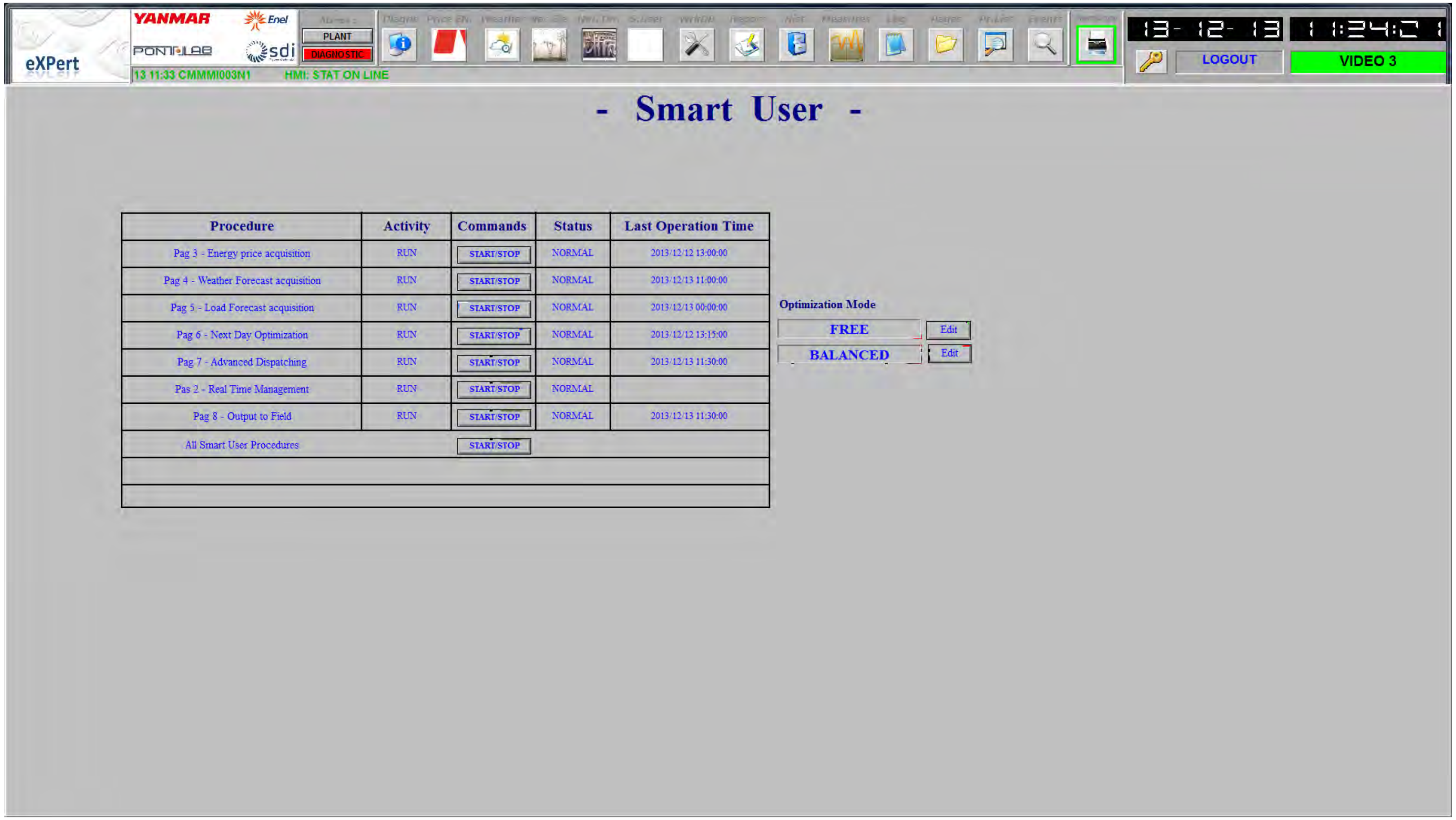


Figure 61 - Thermal plant HMI synoptic

A page containing the commands for all the Smart User operation is also created (Figure 62).



- Smart User -

Procedure	Activity	Commands	Status	Last Operation Time
Pag 3 - Energy price acquisition	RUN	START/STOP	NORMAL	2013/12/12 13:00:00
Pag 4 - Weather Forecast acquisition	RUN	START/STOP	NORMAL	2013/12/13 11:00:00
Pag 5 - Load Forecast acquisition	RUN	START/STOP	NORMAL	2013/12/13 00:00:00
Pag 6 - Next Day Optimization	RUN	START/STOP	NORMAL	2013/12/12 13:15:00
Pag 7 - Advanced Dispatching	RUN	START/STOP	NORMAL	2013/12/13 11:30:00
Pas 2 - Real Time Management	RUN	START/STOP	NORMAL	
Pag 8 - Output to Field	RUN	START/STOP	NORMAL	2013/12/13 11:30:00
All Smart User Procedures		START/STOP		

Optimization Mode

FREE Edit

BALANCED Edit

Figure 62 - SU management options HMI page

Also the parameters coming from the weather station are graphically summarized, as reported in Figure 63.

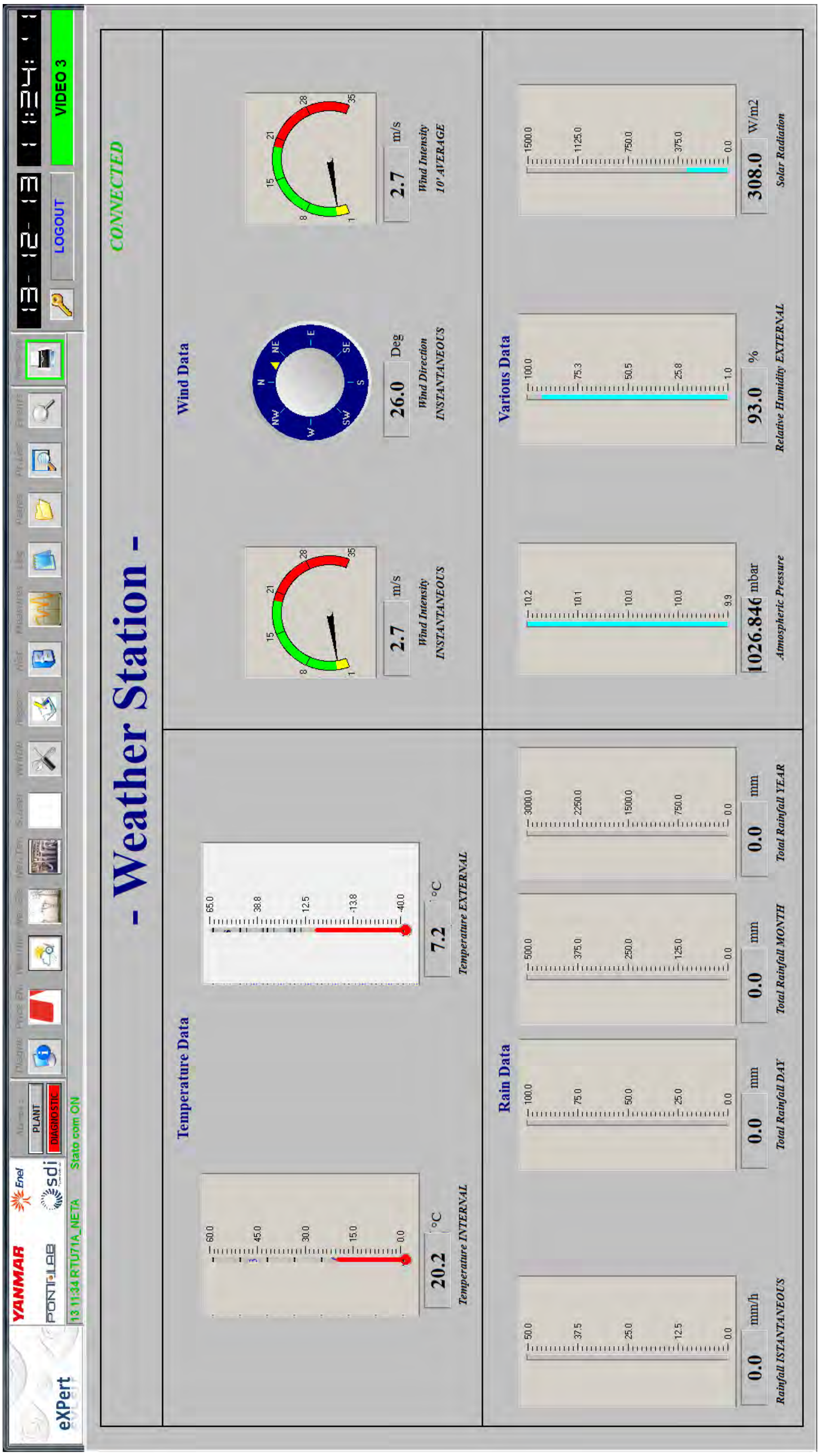


Figure 63 - Weather station parameters HMI page

Some useful graphics are also created, in order to visualize the behavior of the plant and other statistical data: the weather forecast from the web provider and the MGP electricity prices (Figure 64 and Figure 65), the acquired power request of the electric loads and the correspondent supply from the generators and the global electric profile, as shown respectively in Figure 66, Figure 67 and Figure 68, the heating and cooling plant operations (Figure 69 and Figure 70), and the programmed set-point values for the next day in terms of generators production and grid power exchange, reported respectively in Figure 71 and Figure 72.

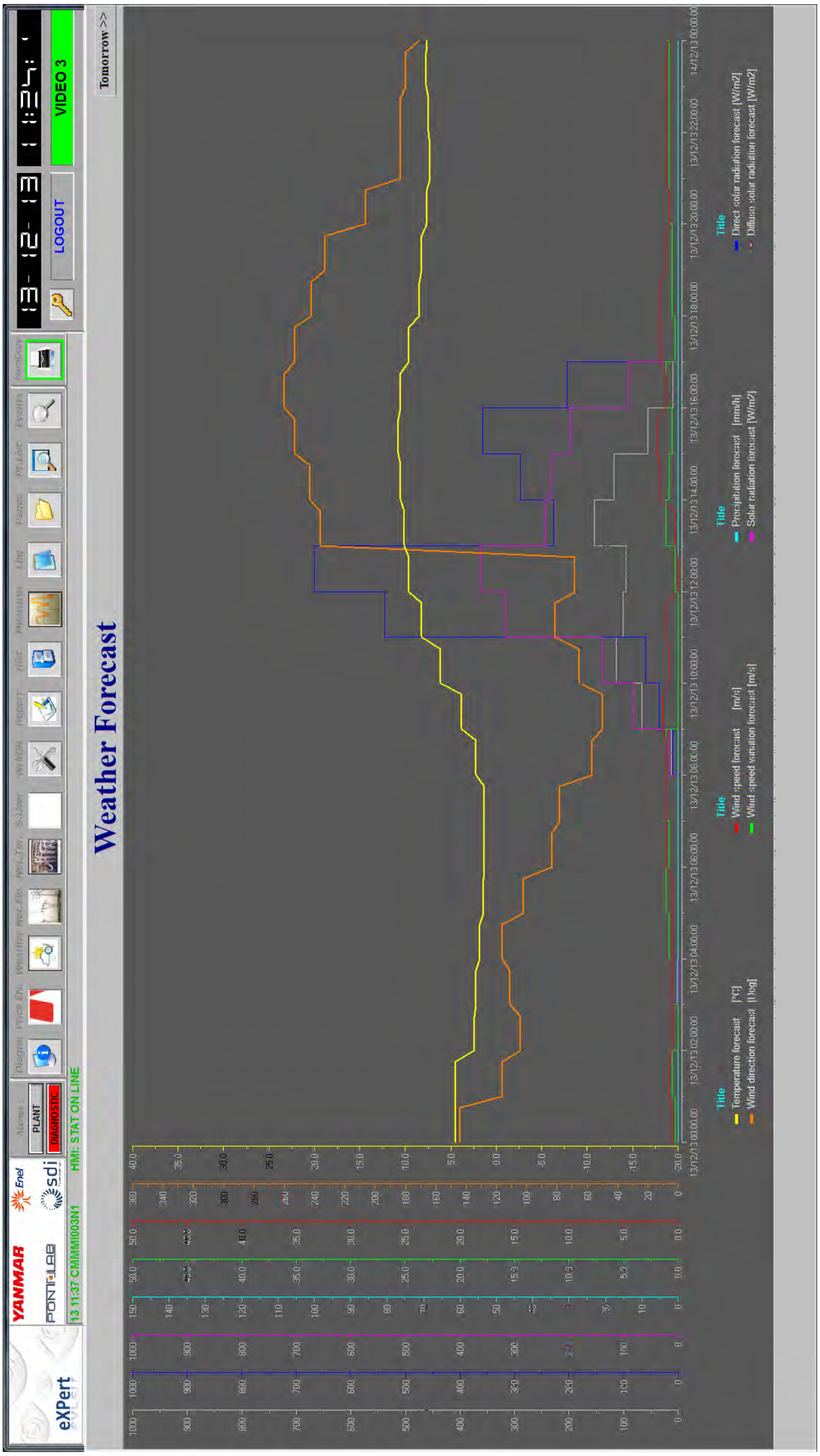


Figure 64 - Weather forecast HMI page

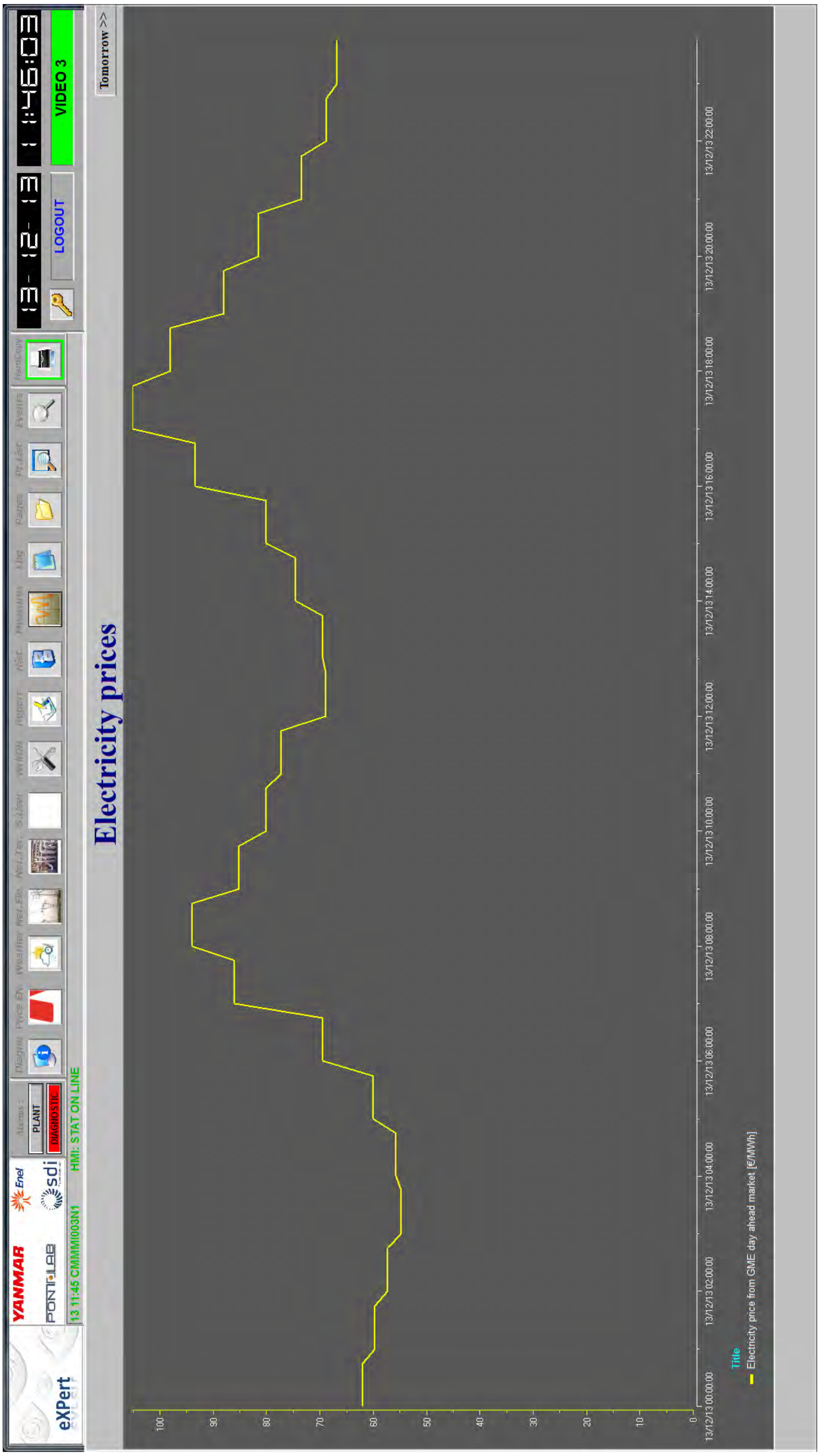


Figure 65 - Electricity prices HMI page

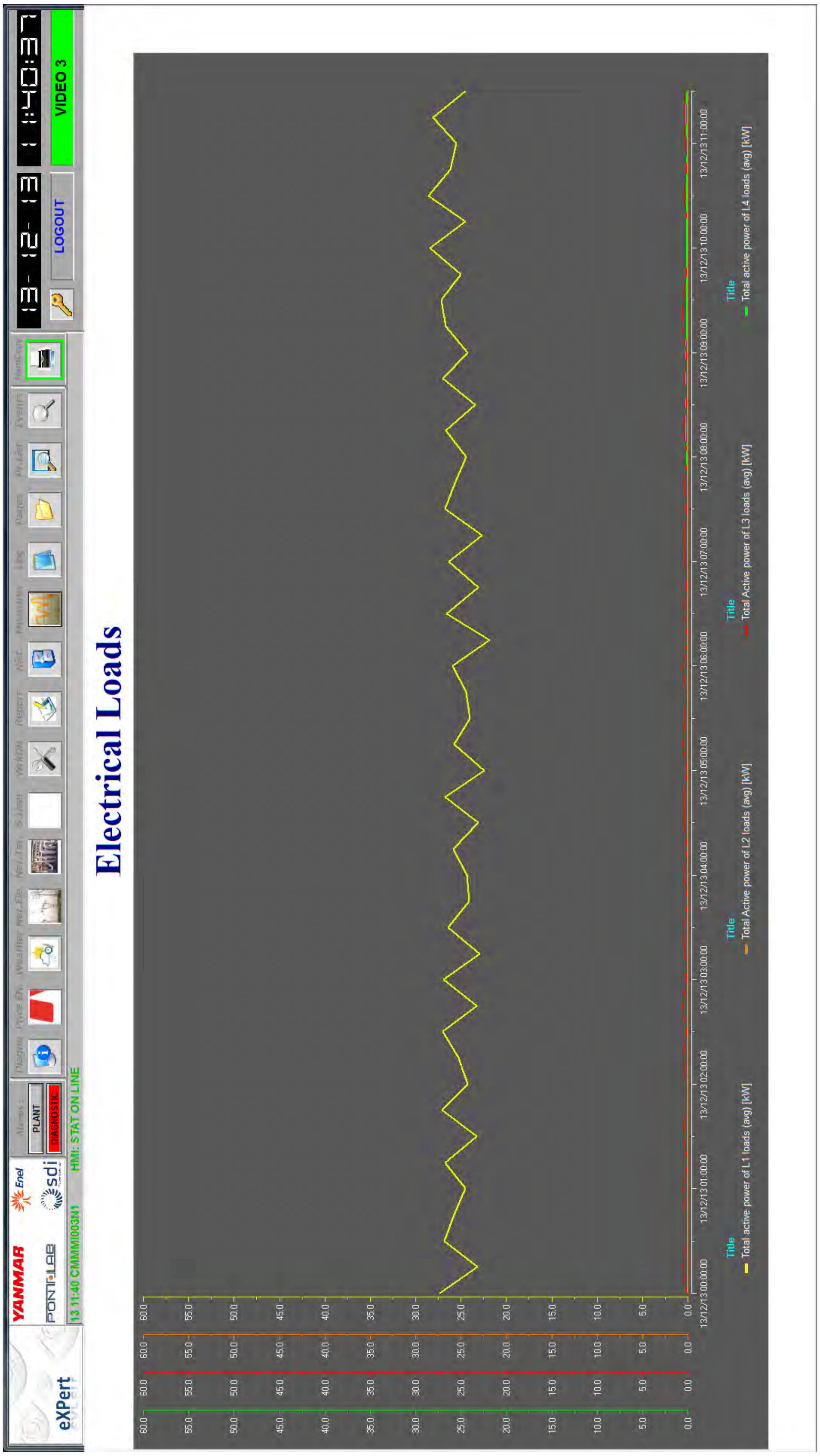


Figure 66 - Electric loads request acquisition HMI page

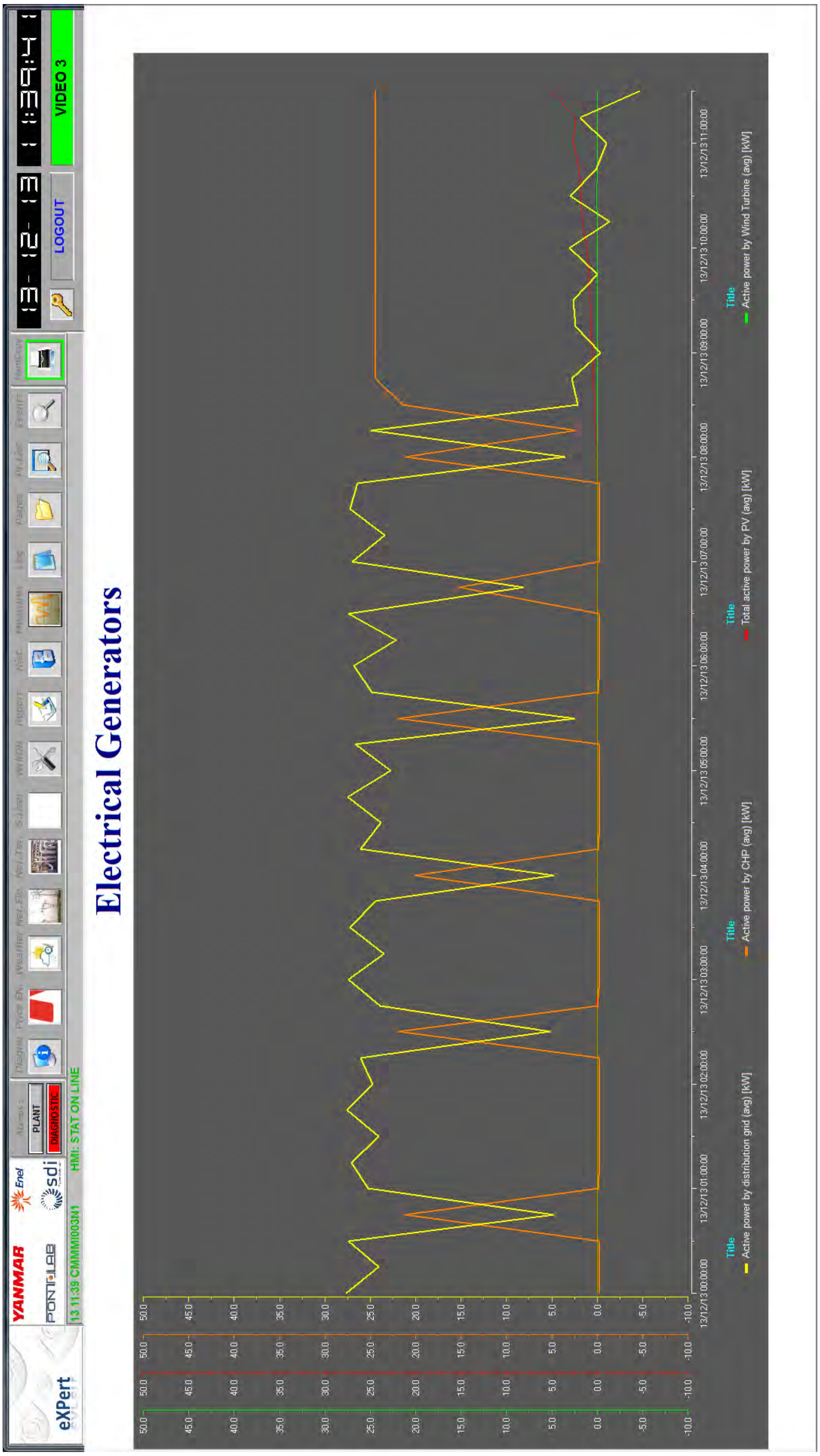


Figure 67 - Electric production HMI page

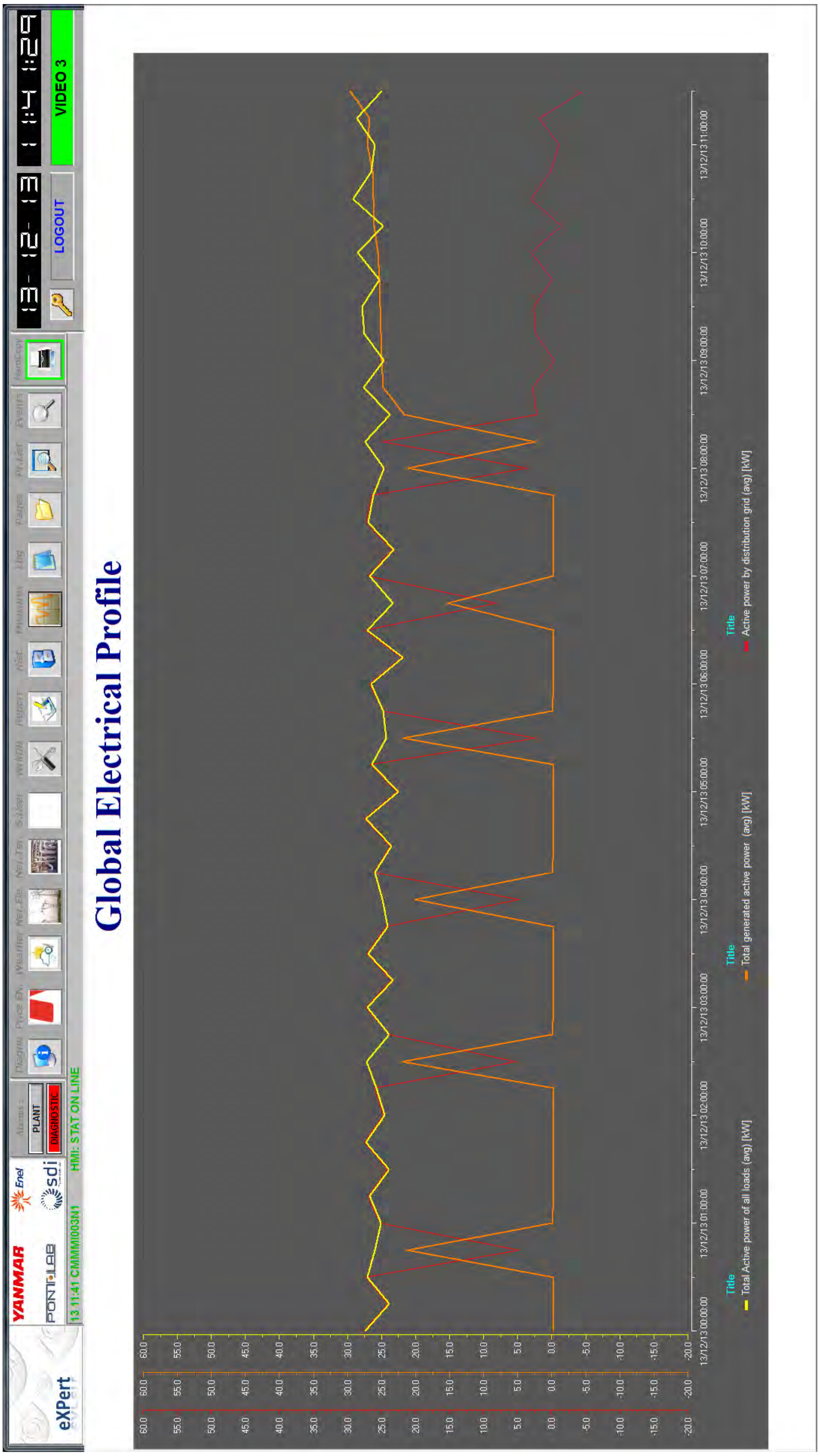


Figure 68 - Global electric profile HMI page

Figure 69 - Heating plant HMI page

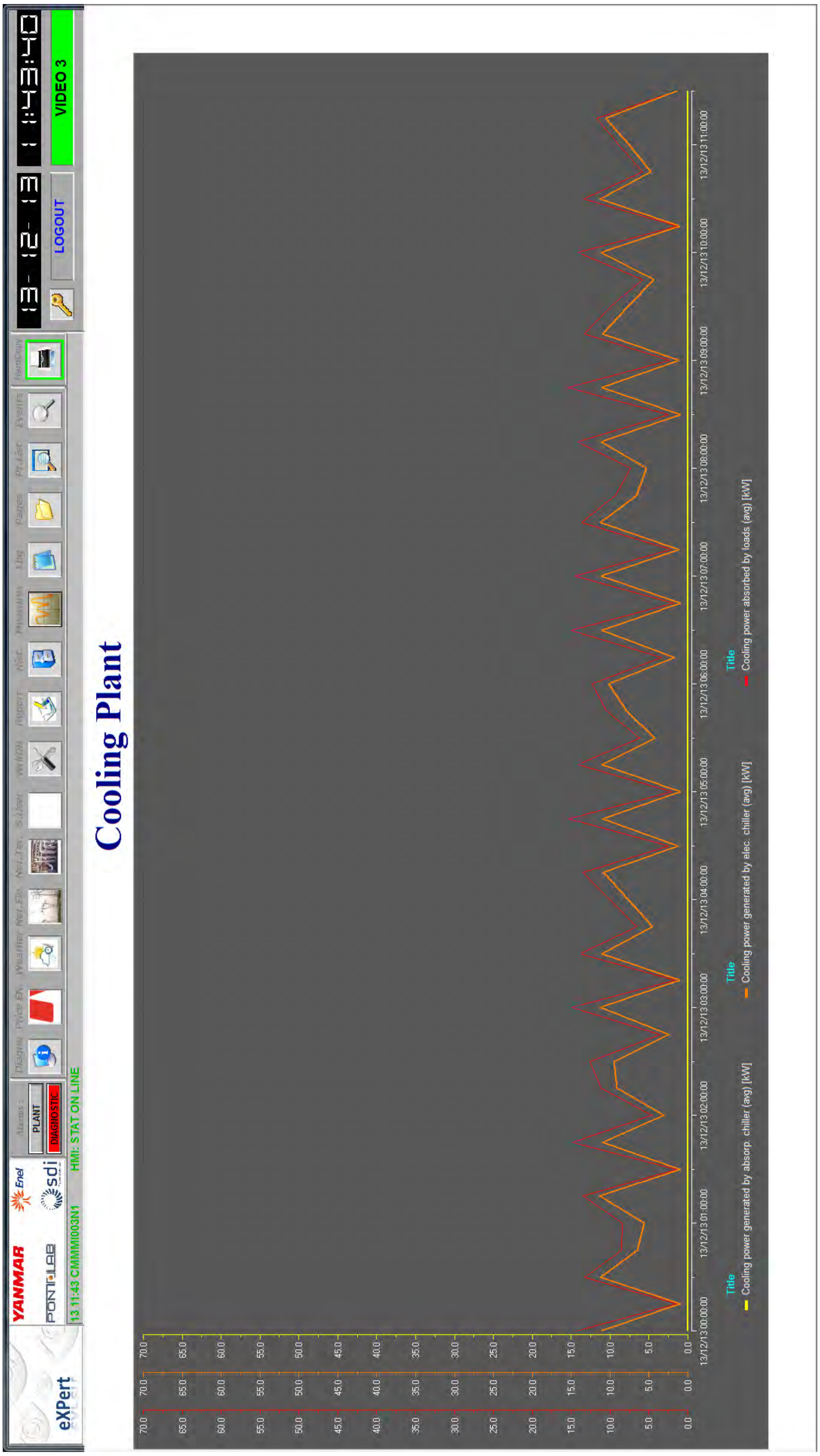


Figure 70 - Cooling plant HMI page

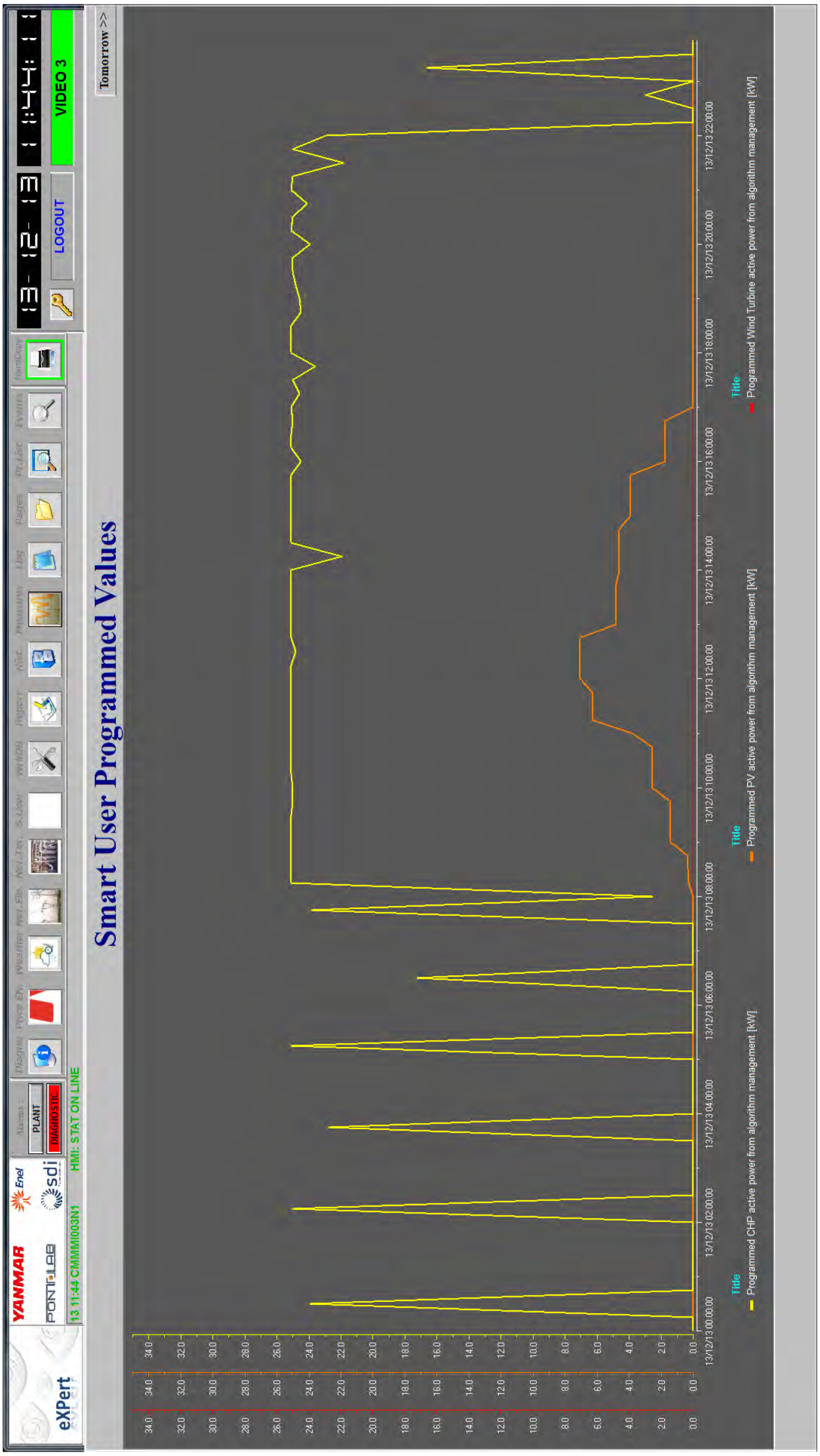


Figure 71 - Programmed set-point values HMI page

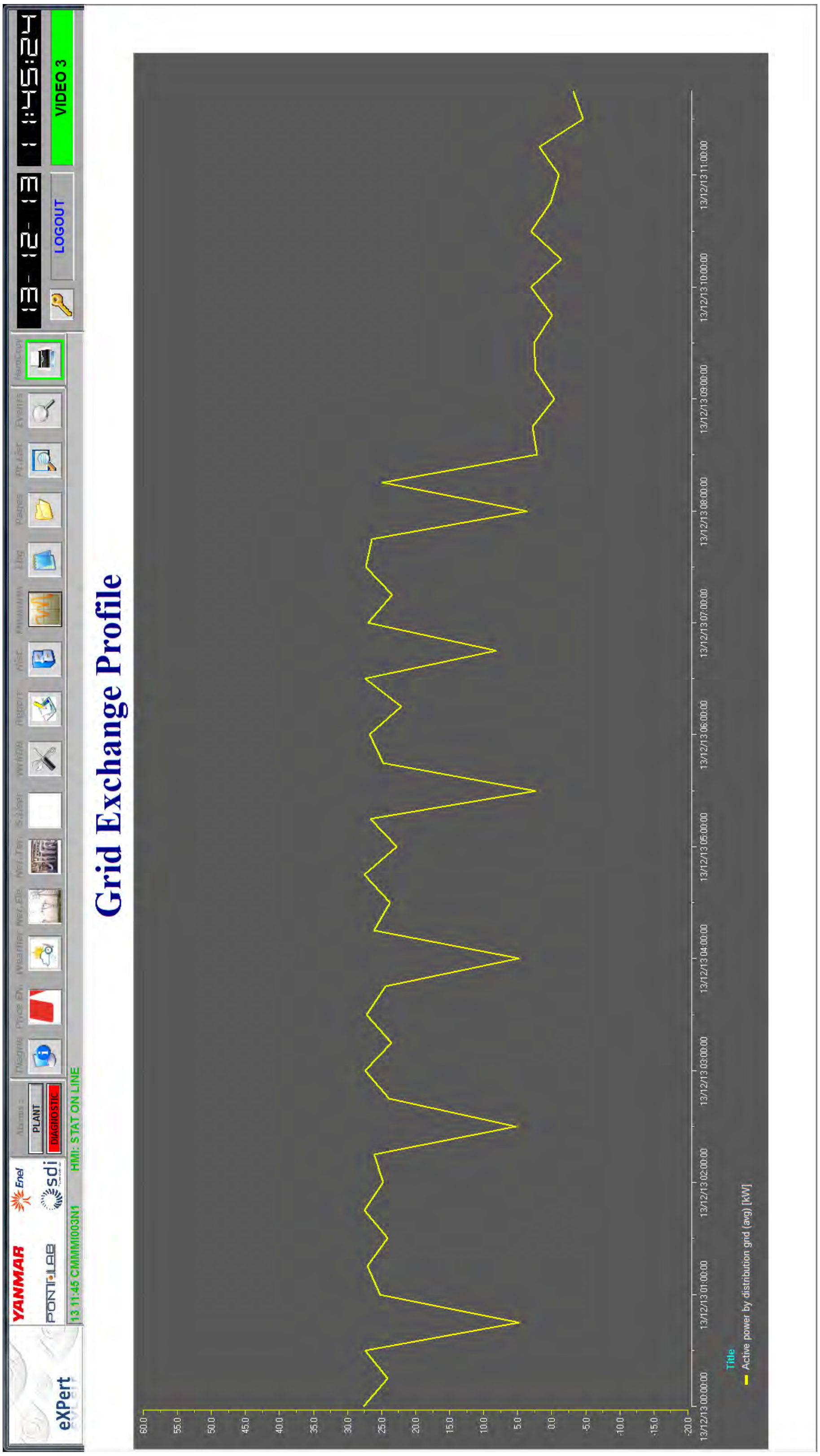


Figure 72 - Programmed gird power exchange HMI page

4.4 The optimization algorithm

From the software point of view, the optimization algorithm is the element which better characterizes the SU plant from a “conventional” plant: the exploited devices, both electric and thermal, all comes from the market, thus the different must lie in their improved management, ensuring more efficient performance and reduced running costs.

The development of the algorithm is carried out starting from the considerations that it has to be applicable, very null or very simple modifications, to different context than the experimentally tested one: for this reason, all the technical parameters characterizing the layout of the Smart User plant (the rated power of the generators and their de-rating curves, the characteristics of the loads, etc.) are considered as parametric, and they can be easily modified each time.

4.4.1 Types of optimization algorithms

Several optimization techniques are available in technical literature, each of them with benefits and drawbacks.

In the field of **heuristic algorithms**, some of the most recent techniques are the ant colony optimization and the particle swarm optimization.

The ant colony optimization [121-123] was developed by Dorigo at the beginning of the Nineties, starting from the observation of the behavior of the ants making part of real colonies. It is mostly used in combinatory optimization problems, and it is based on the concept of the stigmergy [124]. Briefly, when ants move on a territory, they release the pheromone, and the amount of its release is increased when they transport the food: in time, the most efficient itinerary is the one with the major amount of pheromone, and it is covered by most of the ant population, as shown in Figure 73.

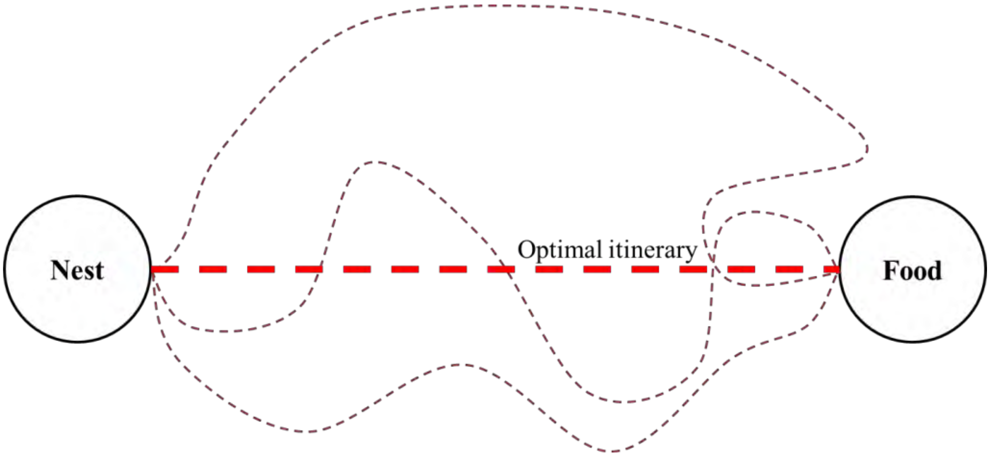


Figure 73 - Ant colony optimization principle

The optimization is carried out on the trip that the ant must cover, not on the final result of the process: for that reason, this technique cannot be applied to the SU system.

The particle swarm optimization was firstly introduced by Kennedy and Eberhart in 1995, starting from the analysis of the behavior of the birds when moving in flocks, and it is particularly suitable for numeric optimization problems [125-127]. The behavior of birds in travel is very complex, considering also that there is no “leader” coordinating the movements: it follows that some factors related to the communication and imitation happen. A simple reproduction model exploits the concepts of the separation (to avoid collisions, similar to a repulsion at short distance), of the alignment (to point the average flock direction), and of the cohesion (to point at the average direction of the closer birds, similar to an attraction at long distance). At a determined instant, one particle assumes a certain position and speed, with a fitness function estimating the good behavior. Each particle has a memory of the past best positions, and also has a knowledge of the best position of the closest particles. By the communication between all the particles, happening for the contemporary research of a local and optimal best, the optimal solution is identified. One example of this technique used for the optimized scheduling of a small-scale energy system on the basis of a demand-response strategy can be found in [128].

In energy optimization matters, also **analytical methods** are often exploited, in particular Mixed-Integer Linear Programming (MILP) and Mixed-Integer Non-Linear Programming (MINLP) techniques, allowing to solve the problem in a closed form, even with very heavy implementation matters, computational costs, and scarce flexibility to the variations of the problem configuration.

Some examples of the MILP method can be found in [129-135]. In more detail, [129] propose the MILP method for the optimization of the energy supply of a factory needing electricity, heat, and steam for the industrial process, selecting the production from different generators: an heat pump, a condensing turbine, and a gas boiler. Also in [130] the MILP technique is exploited for increasing the Fuel Energy Savings Ratio (FESR) of a small on-grid power plant, constituted by a CHP, a gas boiler, and both electric and heating load. In [131], the mentioned method is adopted to estimate the best energy supply option when a mix of generators of different kind is considered, including CHPs, micro-turbines, FCs, and some renewable sources like PV and wind turbines, considering that the schedule have to be carried out under uncertainties involving both the load request and the RESs future production. In [132] MILP mathematical model is exploited for the optimal chose of the generators sizing and their yearly scheduling for a small MG context, considering as the objective function the yearly cost revenue.

An example of the exploitation of the MINLP method can be retrieved in [133], with the aim of deciding the optimal schedule of six VPPs for increasing the efficiency and the energy saving in the management of a small distribution grid. The cited optimization method is used in [134] for the thermo-economic optimization of a CHP system in Beijing, with the target of increasing the energy efficiency and decreasing the CO_2 emissions. Another example of the MINLP technique application can be found in [135], in the optic of increasing the efficiency of the energy supply within a SG, in which considers several VPP and the presence of EV with a V2G approach.

4.4.2 Genetic Algorithms

Evolutionary algorithm, in particular those based on Genetic Algorithms (GAs), represent a good solution to find the optimum whenever the search space (i.e. the space of all the possible solution to the problem) is very large. In this case the exploitation of GAs allows to reduce the computational costs in terms of both memory and time respect to an analytical algorithm, even if it does not ensure to reach the most suitable solution possible, because it starts from random conditions, which can be quite far from the optimum for the problem. In other words, an evolutionary algorithm ensures to find a relative minimum (or maximum) of the objective function, but it could not be the absolute one. Yet, the application of this method to many engineering problems shows how their behavior is generally good [136-139].

GAs are based on the human evolutionary principle, starting from the consideration that in a population of individuals the reproduction tends, in the long term, to give individuals with characteristics improved for the environment they live in compared to their parents, thanks to the crossing of the chromosomes characterizing each person. In particular, each individual represents a possible solution to the problem, randomly chosen within the search space of all the possible solutions. The chromosomes of the single person represent the variables of the problem. The algorithm starts its operations from a population of individuals. The global characteristics of each of them are evaluated on the basis of a fitness function, which in the human evolution represents the adaptability of the individual to its environment: in the computational case the fitness function is representative of the objective function. Once that all the individuals are assigned with a fitness value, the worsts of them are rejected, and their place is taken by the best ones, in a fixed percentage. At the end of the individuals replacement, the "reproduction" process is started, with the crossover of the chromosomes between adjacent individuals: a part of a single chromosome is substituted with the same one of the same chromosome of a randomly selected person, in order to change its value, which will be, however, close to the original one.

At the end of the crossover process, the population has changed, and it is evaluated again by means of the fitness function. To summarize, the cycle of the GA is represented by:

- The evaluation of each individual (i.e. the possible solution to the problem) by means of the fitness function (i.e. the value that the objective function assumes);
- The substitution of a fixed percentage of the population (the worst individuals) with the best ones, in order to carry out an evolution of the population itself;
- The reproduction, consisting in the crossing between the chromosomes of randomly selected individuals, in order to have a different population;
- The mutation, which takes place in a very low percentage, of one gene (i.e. one bit constituting the binary value of the variable) of a randomly selected chromosome of an individual.

The cycle is repeated many times, ending when the stopping criterion condition is achieved.

In summary, the flow chart of a genetic algorithm can be built as in Figure 74.

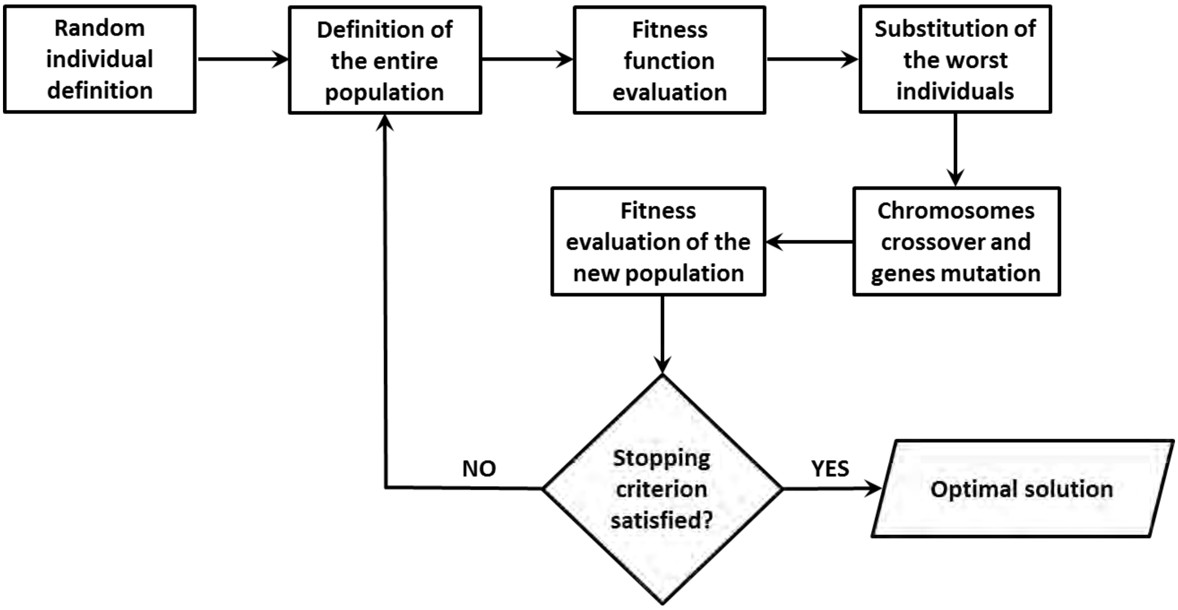


Figure 74 - Genetic algorithm flow chart

If the general structure of a GA is very simple, the techniques which can be applied for the various processes taking place during its operation can remarkably vary.

The initial population of individuals can be generated completely random, or some individuals can be compiled following prescribed rules, generally considering some solution to the problem which could be close to the optimal one, in a fixed percentage. Yet, there is a wide availability of crossover techniques: the most common is the one-point strategy, consisting in the selection of a random point for the crossing of the chromosomes, and replacing the first part of one parent with the homologous part of the other one, as graphically shown in Figure 75.

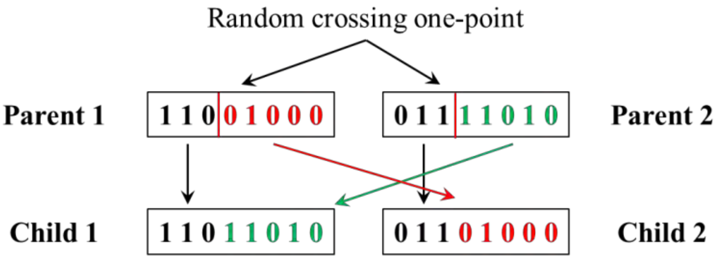


Figure 75 - One-point crossover technique

Another example of crossover technique is the two-point one: the randomly selected points for the crossing are two, and the replacement is carried out among the different parts (Figure 76).

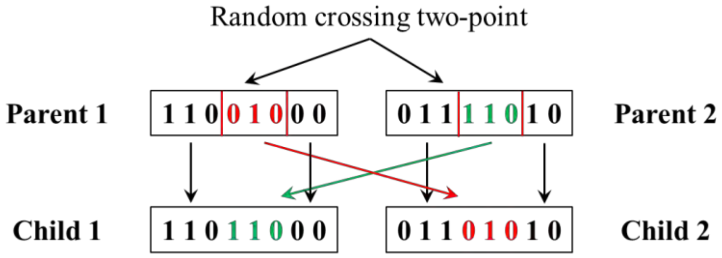


Figure 76 - Two-point crossover technique

Another technique frequently exploited is the casual one, in which a mix between the genes of the two parents takes place in a random way, as shown in Figure 77.

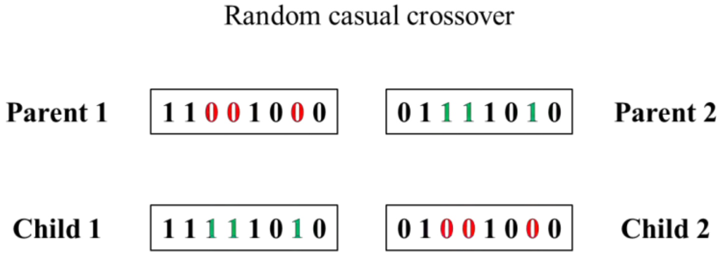


Figure 77 - Casual crossover technique

In case of particular applications, the number of individuals of the population can change with the iterations progress, as well as the percentage of the crossover and of the mutation, in order to limit the search space zone, thus increasing the possibility to find an optimal solution in a previously detected solution area.

Also about the stopping criterion, several options are available: when the difference between the value of the best individual of the population at the n^{th} step and the corresponding for the $(n+1)^{th}$ step is under an established tolerance, or when the variance of the fitness value of all the individuals is below a predetermined target, or when a prescribed number of cycles is reached.

4.5 The Smart User algorithm

The algorithm purposefully developed for the Smart User plant optimization is based on GAs. The individual of the population represents one of the possible solutions to the energy supply of the plant, with each variable corresponding to a chromosome of the individual.

The time scale that is decided to adopt for the optimization is an entire day, divided into time steps of 15-minutes length. In general, the weather forecasts (necessary for the estimation of RESs production) and the energy prices are given by the providers with a time scale of 1 hour: the selection of a shorter time step is determined by the future constraint that DSOs shall require to all the "prosumers", which is forecasted to be a prescribed energy exchange with the distribution grid in that time length. The day is thus divided into 96 time steps.

4.5.1 Objective function

The objective function needed for the estimation of the fitness function is represented by the cost of the energy supply to the Smart User plant. In more detail, the considered cost parameters are summarized in Table 5.

Equipment	Voice
CHP	Natural gas supply
	O&M
	"Titoli di Efficienza Energetica"
	Natural gas tax reduction for high efficiency
Gas boiler	Natural gas supply
	O&M
PV panels	O&M
	"Conto Energia"
Micro-wind turbine	O&M
Electric chiller	O&M
Absorption chiller	O&M
Grid	Energy supply
	Energy selling
	Prescribed exchange profile penalty
Non-privileged loads	Electric
	Heating
	Cooling

Table 5 - Parameters of the objective function

The natural gas cost is divided into two contributions, one for the CHP and the other for the boiler supply: indeed, the Italian market prescribes different costs on the basis of the use of the fuel. In case of energy generation use, there is a fixed percentage of the final bill cost (the same in the whole Italian territory) for the selling service and for the network service, to be added to the so-called “energy” percentage, for which the selling share is a fixed value (in €/Sm^3), while network service cost changes on the basis of the estimated (or calculated, at the end of each fiscal year) amount of consumption, like the example in Table 6, updated to July 1st, 2013.

Amount [Sm^3/y]	**Selling service [€/Sm^3]**	**Network service [€/Sm^3]**
0 - 120	0.386434	0.064205
121 - 480		0.193169
481 - 1,560		0.169528
1,561 - 5,000		0.165128
5,000 - 80,000		0.138717
80,001 - 200,000		0.100072
200,001 - 1,000,000		0.080625
> 1,000,000		0.068779
Fixed share [€/y]	55.40	35.44

Table 6 - Energy use natural gas tariffs for Tuscany region [140]

About the use of the natural gas for cooking or room heating, the difference with the energy use consists in a lower fixed percentage of the selling service, while the network service is paid as the same of energy use. The variable selling service is the same, while the network service is slightly decreased (Table 7).

Amount [Sm^3/y]	**Selling service [€/Sm^3]**	**Network service [€/Sm^3]**
0 - 120	0.386434	0.063070
121 - 480		0.192034
481 - 1,560		0.168393
1,561 - 5,000		0.163993
5,000 - 80,000		0.137582
80,001 - 200,000		0.098937
200,001 - 1,000,000		0.079490
> 1,000,000		0.067644

Fixed share [€/y]	40.34	35.44

Table 7 - Domestic use natural gas tariffs for Tuscany region [141]

VAT percentage, in addition to national and local taxes, must be added to the indicated costs, to perceive to the final natural gas cost. In our analyses, the cost of the natural gas resulted very close to 0.60 €/Sm3 for both applications, and this is the value which is considered within the algorithm. Of course, this value can remarkably change with time, that's why this is an external input to the procedure, which can be easily changed anytime. In addition, the gas price can be differently quoted on the basis of the hour of the day, with the possibility to consider a next future dynamic natural gas market.

The electricity supplied by the grid is considered with a hourly variable cost, estimated on the basis of the "Mercato del Giorno Prima" (MGP, the day-ahead electric market), and with a comparison with the available company electric bill: the analysis allowed to identify 2 coefficients, one fixed and the other dependent by the energy exchange, measured in kWh_e, which are respectively 0.09 and 1.2144. An example of the electricity prices of the day-ahead market is shown in , referred to the market in December 10th, 2013 for the energy prices of the next day.

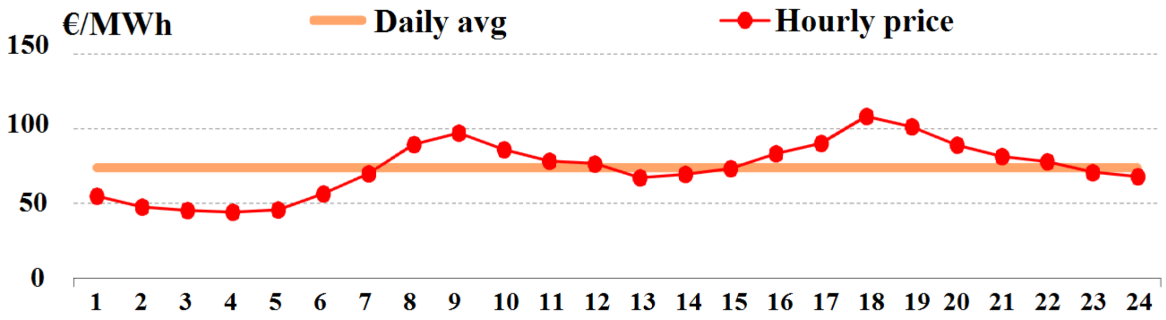


Figure 78 - MGP electricity price [142]

About the selling of the electricity produced by the generators within the Smart User site to the grid, a fixed price is considered, independently to the hour of the day and to the production equipment: this latter consideration comes from the impossibility to understand the origin of the energy which is sold to the grid, so any kind of incentive for RES production could bring to misleading results. The reference for the electricity selling price is the amount earned by any user for the exceeding production from a CHP, estimated in 0.10 €/kWh_e.

Regarding RESs incentives for electricity production, only "Conto Energia" is considered for PV production and self-consumption: the plant installed in Pontlab site benefited of the second “edition” of this kind of incentive. Consequently, the additional earning is estimated in 0.403 €/kWh$_e$ [143].

The incentive provided by the Italian regulations for the CHP energy production are guaranteed only if some threshold performance are achieved by the cogeneration unit. In particular, the Decree of the Ministry for the Economic Development approved in September 6th, 2011 [144] allow a decrease in the taxes on the natural gas of about 0.20 €/Sm^3 if two conditions are satisfied (CAR operation of the plant): for mini- and micro-CHP plants (rated electric power under 1 MW$_e$) with the PM being an Internal Combustion Engine, the Primary Energy Saving (PES) parameter must be higher than zero, and contemporarily the total efficiency of the cogeneration unit must be over 75 %. The total efficiency of the CHP is considered by the algorithm in terms of exploited useful energy: if some thermal power is wasted, it is not accounted in the calculation of the cogeneration unit performance. The regulation prescribes that the overall efficiency must be estimated like:

$$\eta_{globale} = \frac{E + H_{chp}}{F} > 0$$

where E is the electricity produced from the CHP in kWh$_e$, H$_{chp}$ is the useful heat produced by the engine and exploited by the plant in kWh$_{th}$, and F is the energy from the fuel in kWh$_{th}$.

The PES is defined as:

$$PES = \left[1 - \frac{1}{\frac{\eta_{H,chp}}{\eta_{H,ref}} + \frac{\eta_{E,chp}}{\eta_{E,ref}}} \right]$$

where $\eta_{H,chp}$ is the thermal efficiency of the CHP, $\eta_{H,ref}$ is the thermal efficiency of reference for Italy, defined in the Attachment V of the Decree of September 5th, 2011 [145], $\eta_{E,chp}$ is the electric efficiency of the cogeneration unit and $\eta_{E,ref}$ is the Italian reference electric efficiency of the power grid, defined in the Attachment IV of the previously cited Decree.

If both constraints are satisfied, then the natural gas used for the CHP can benefit of the tax decrease. In addition, the electric energy sold to the grid can also benefit of the “Titoli di Efficienza Energetica” (TEE, energy efficiency certifications), also known as “White Certificates” (“Certificati Bianchi”) , whose average value, in year

2012, was 99.50 € [146]. A single TEE is given in case the high efficiency intervention allow the loss of consumption of 1 TEP.

Some other parameters which are considered within the objective function are the O&M costs for the generators: the data useful for their determination are difficult to achieve, so a rough estimation is considered.

In particular, for the estimation of PV costs it is considered that during their life span, established by the producer in 20 years, the 3 inverters are substituted once, for a total amount of about 6,000 €: by dividing this amount for the total life hours of the panels, we perceive to the result of 0.023 €/h, which are also due when the energy production is off.

A similar principle is applied to the estimation of the O&M costs for the micro-wind turbine. In this case, we consider the substitution of a single inverter, with an approximated cost of 2,000 €, during the life of the device, again estimated in 20 years, bringing to the result of 0.023 €/h. Again, the cost is due also when the turbine is off.

A more appropriated estimation of the O&M costs of the RESs would consider the O&M costs only in case the devices are producing energy, condition which is particularly verified for the wind turbine. Nevertheless, the O&M costs would be very hard to estimate, because they are dependent by the operating equivalent hours, which are not exactly predictable. For this reason, in order to avoid misleading evaluations and for having reliable estimations during the years, the described choice is considered the best one.

About the O&M of the CHP and the absorption chiller, the proposed data are directly taken by the service company, which propose fixed rates with established maintenance intervals. The hourly O&M cost for the CHP thus results in 0.45 €/h, while for the absorber the amount is 0.071 €/h, in both cases only when the device is switched on.

For the gas boiler and the electric chiller, the producers suggest to carry out the maintenance operations once a year, independently by their operating equivalent hours. By the knowledge of the cost of the yearly intervention, the O&M costs can thus be estimated in 0.057 €/h for both of them, which are due also when the pieces of equipment are switched off.

The last parameters which the economic objective function has to consider are relative to the fees for curtailing the electric, heating, and cooling loads, and for not achieving the prescribed electricity exchange with the grid. At present, all these parameters are difficult to be estimated, and no general rule can be retrieved in technical literature. For this reason, no imposed value is established, but a sensitivity analysis was performed to try to understand what could be a suitable value for each of them.

4.5.2 Algorithm variables

The definition of the variables is a strict function of the constraints to the Smart User matter.

As external constraints to the algorithm, constituting part of the input to the problem, the following parameters are considered:

- The electric, heating, and cooling privileged loads;
- The weather forecast, which allow to estimate the production of the RESs;
- The energy prices, both of electricity and natural gas;
- The technical constraints of each piece of equipment (generators rated power, CHP minimum technical power, etc.).

Considering the management characteristics that the system must ensure, the selected variables are established in the number of 6:

1. The CHP electric power output;
2. The PV plant power output, of course respect to the available power allowed by the weather conditions;
3. The wind turbine power output;
4. The non-privileged electric load ($L2_e$);
5. The non-privileged heat load ($L2_{th}$);
6. The non-privileged cooling load ($L2_c$).

Once that the value of all these variables are known, all the other parameters can be easily calculated on the basis of the energy balance.

Considering the electric "branch" of the Smart User plant, the energy balance can be written as:

$$P_{L1,e} = P_{CHP,e} + P_{PV,e} + P_{wind,e} + P_{grid,e} + P_{L2,e}$$

in which $P_{L1,e}$,e is the privileged electric load, $P_{CHP,e}$ is the electric power output of the cogeneration unit, $P_{PV,e}$ is the power output from the photovoltaic panels, $P_{wind,e}$ is the production of the micro-wind turbine $P_{grid,e}$ is the power exchange with the distribution grid (positive if the energy is supplied by the grid, thus acting like a generator for the plant), and $P_{L2,e}$ is the curtailed electric load. Starting from the previous considerations, the balance is not closed, because the power exchange with the distribution grid is not defined: the degree of freedom constituted by this parameter allow to close the electric balance by its calculation.

As regard as the heat balance, it can be written in the following fashion:

$$P_{L1,th} = P_{CHP,th} + P_{boiler,th} + P_{storage,th} + P_{L2,th}$$

with $P_{L1,th}$ indicating the privileged heating loads, $P_{CHP,th}$ is the heating power output of the CHP (determined by the correspondent electric output by means of the performance curve of the CHP), $P_{boiler,th}$ is the power output of the gas boiler, $P_{storage,th}$ being the contribution of the "hot" storage, and $P_{L2,th}$ representing the curtailed heating load. Differently to the electric balance, all the values are determined by the external constraints or by the guess value imposed by the optimization algorithm, except for 2 parameters: the gas boiler output and the storage contribution. In this case, a logic procedure determines the power of the two pieces of equipment: the algorithm privileges the operation of the storage when the heating balance is negative (i.e. the power request is higher than the production), with a limit given by the most stringent between the maximum deliverable power by the tank (considering the design values of both the temperature drop and the water flow), and the reaching of the lower energy level of the storage. In case the contribution of the accumulator is not sufficient to cover the loads requirement, the gas boiler is switched on. This behavior perfectly reflect the layout and the operation strategy of the plant: for the reliability reasons exposed in §3.3.1, the auxiliary boiler cannot be managed by the optimization system, but only operates like a back-up device.

Similar considerations can be carried out for the cooling balance:

$$P_{L1,c} = P_{absorber,c} + P_{chiller,c} + P_{storage,c} + P_{L2,c}$$

in which $P_{L1,c}$ is the privileged cooling load, $P_{absorber,c}$ is the power output from the absorption chiller (determined by the CHP load, on the basis of its thermal functioning curve coupled to the one of the cooling device), $P_{chiller,c}$ is the cooling produced by the electric chiller, $P_{storage,c}$ is the contribution of the "cold" storage, and $P_{L2,c}$ represents the curtailed cooling loads. The contribution of the storage and of the electric chiller are estimated in the same way of the heating balance: the priority device is constituted by the water tank, with the chiller being the back-up equipment.

4.5.3 Inputs and outputs

The algorithm procedure is developed in C++ computational language, and considers some input and an output files written under the “Comma Separated Values” (CSV) format.

Three input files are considered for the procedure, on the basis of the type of the parameters (arrays or scalar values), and of the functionality they have to perform. The array input file, called “INPUT_VETTORI.csv”, includes all the parameters needed by the algorithm which can change on a time step basis, in more detail:

- All the energy constraints for the Smart User plant:
    - The predicted privileged electric, heating, and cooling loads;
    - The predicted non-privileged electric, heating, and cooling loads;
    - The predicted production of the RES generators (the PV panels and the micro-wind turbine);
    - The eventual predicted electricity exchange profile with the external grid;
    - The eventual request from the external grid of ancillary services;
- All the variable costs of the plant:
    - The cost for the natural gas supply, divided on the basis of the final use (domestic, electric generation);
    - The cost for the electricity supply by the external grid, based on the MGP market;
    - The fee for the mismatch between the predicted power profile with the grid and the effective one;
    - The penalty for the curtailment of the non-privileged electric, heating, and cooling loads;
    - The income for selling electricity to the external grid;
    - The income for supplying ancillary services to the grid.

The input file with all the scalar values needed by the plant for the correct operations of the fitness evaluation, which includes the technical constraints of the generators, is the “TECH.csv” file, and in detail it includes:

- All the technical constraints of the Smart User plant:
    - The rated and the minimum technical electric power of the CHP;
    - The rated and the minimum technical thermal power of the gas boiler, of the electric chiller, of the absorption chiller, and of the “hot” and “cold” storages

  - The maximum and minimum operating temperatures of the thermal plant, both heating and cooling;
  - The volume of the thermal storages;
  - The coefficients for the estimation of the operating characteristic curves of the generation devices;
  - The predicted temperatures of the thermal storages at the beginning of the day, for the knowledge of their energy levels;
- The parameters for the smart management of the plant:
  - The percentage limits for the maximum and minimum operative conditions of the generators and the storages;
- The fixed cost parameters:
  - The O&M costs for the CHP, the PV plant, the micro-wind turbine, the absorption and electric chillers, the gas boiler;
  - The values of the incentives for the CHP (CAR) and the PV plant;
- Other auxiliary parameters:
  - The period of the year, allowing the algorithm to understand if the heat from the CHP can be exploited by the heating loads, or must be delivered to the absorption chiller;
  - The PES and efficiency limit values for achieving the CAR for the cogeneration unit;
  - The LHV of the natural gas.

The last considered input file (“AG.csv”) is inherent to the parameters driving the operation of the genetic algorithm, in more detail:

- The number of chromosomes of a single individual (i.e. the variables of the problem);
- The number of individuals of the population;
- The number of genes (i.e. the bits number) of each chromosome;
- The percentage for the crossover process;
- The percentage for the mutation process;
- The number of individuals for the selection process;
- The selection of the probability option for the choice of the individuals which must participate to the crossover process;
- The selection of the “seeding” option for the starting population, related to the possibility of create some individuals representing the thermal-led, power-led, or conventional energy supply of the plant, in addition to their percentage;

- The maximum tolerance value allowed for the algorithm convergence;
- The maximum number of iterations allowed for the algorithm convergence.

The unique output file is comprehensive of the array of the set point values allowing the command to the devices within the SU plant, in addition to other parameters useful for a better understanding of the instantaneous operations of the plant:

- The CHP electric power output, and the correspondent heat output or cooling output from the absorption chiller;
- The PV panels and micro-wind turbine electric power output;
- The curtailment of the non-privileged electric, heating, and cooling loads;
- The power output from both the thermal storages;
- The estimated temperature of the storages at the end of each time step, also including the estimated energy residual content;
- The heating and cooling power output from respectively the gas boiler and the electric chiller, with the estimation of the electric request of this latter device;
- The expected power exchange with the grid, if no predetermined profile is constrained;
- The total supply cost per each time step, with the detail of the contribution of each piece of equipment.
- The number of iteration of the GA to reach the convergence.

The input and output values can be easily added in the files, with poor modifications within the source C++ code.

4.5.4 “Whole-day” optimization

For an optimized schedule of the SU plant, and in particular for an active management of the thermal storages, the most suitable option is to consider as an individual the set of solutions for the entire day, rather than for a single time step. If the operations of the plant are optimized for a single time step, the algorithm cannot consider the management of the generators during the period before the considered time step, and, similarly, is not able to foresee which will be the future consumptions and the energy prices. Indeed, due to the presence of the storage, the sum of the minimum cost for each time step could be remarkably different from the minimum of the sum of all the time steps.

In the simple case of a conventional plant, without accumulators, the optimal scheduling for a whole day can be easily performed with a step-by-step procedure: what is done in the present time step does not affects other time intervals. On the contrary, when any kind of storage (both thermal and electric) is considered, an excess or lack of production respect to the requirements reverberates in the future performance of the plant.

With this concept clear in mind, the individuals thought for the GA are composed by 6 chromosomes per each 15-minutes time step, for a total amount of 576 variables for the daily scheduling. Considering for each variable a definition of n bits, the problem presents a very large number of possible solutions: the searching characteristics of the algorithm must be very challenging to reach a local minimum within such a search space. Indeed, the possible solutions, in case of adopting 8 bits for defining each variable, are in the number of 255^{576}, representing a very wide search space for searching the optimized solution. Even lowering the number of bits, thus the “resolution” for the management of the variables, the search space is slightly decreased, because the most influent parameter in the number of possible combinations is the exponential, not its basis.

4.5.5 “Single time-step” optimization

As underlined in §4.5.4, a possible strategy for pursuing the efficient schedule of the Smart User is to proceed with a step-by-step optimization of the plant performance. This way of proceeding results very similar to the “whole-day” method when the size of the storage is small: in that case, the influence of the past time steps on the present one and the effect of the present management on the future time period is reduced.

Such a strategy does not allow an active management of the storage: starting from any guess value of the individual of the GA, the economic result drives the plant to the emptying of the storage. A more forward-looking strategy would be decisive for the exploitation of the reserve constituted by the accumulator in a more appropriate time step: e.g. in case of low electricity prices and poor thermal load, the convenience would lay having the storage at a sufficiently high energy level, for switching off the CHP and exploiting that residual from the other time step.

By the other hand, the “single time-step” would allow a decreased number of variables: any optimized step would be composed of only 6 parameters, with a number of possible combination of the solution which, if considering 8 bits for each of them, would result 255^{6}. In this case the required computational resources would be heavily reduced, with shortened calculation time for the optimized scheduling of the plant compared to the "whole-day" optimization. In addition to that, such an algorithm would allow the plant to operate, within the same day, in "winter" or "summer" layout indifferently, on the basis of the instantaneous most convenient configuration.

4.6 Smart User system operations

As a general principle, the Smart User plant must pursue three different steps for the correct operations.

First of all, there must be the collection of all the info and data needed for defining the boundary conditions (Figure 79), both from the field (storage temperatures, loads and generators charging, weather conditions) and the net (energy prices, weather forecast).

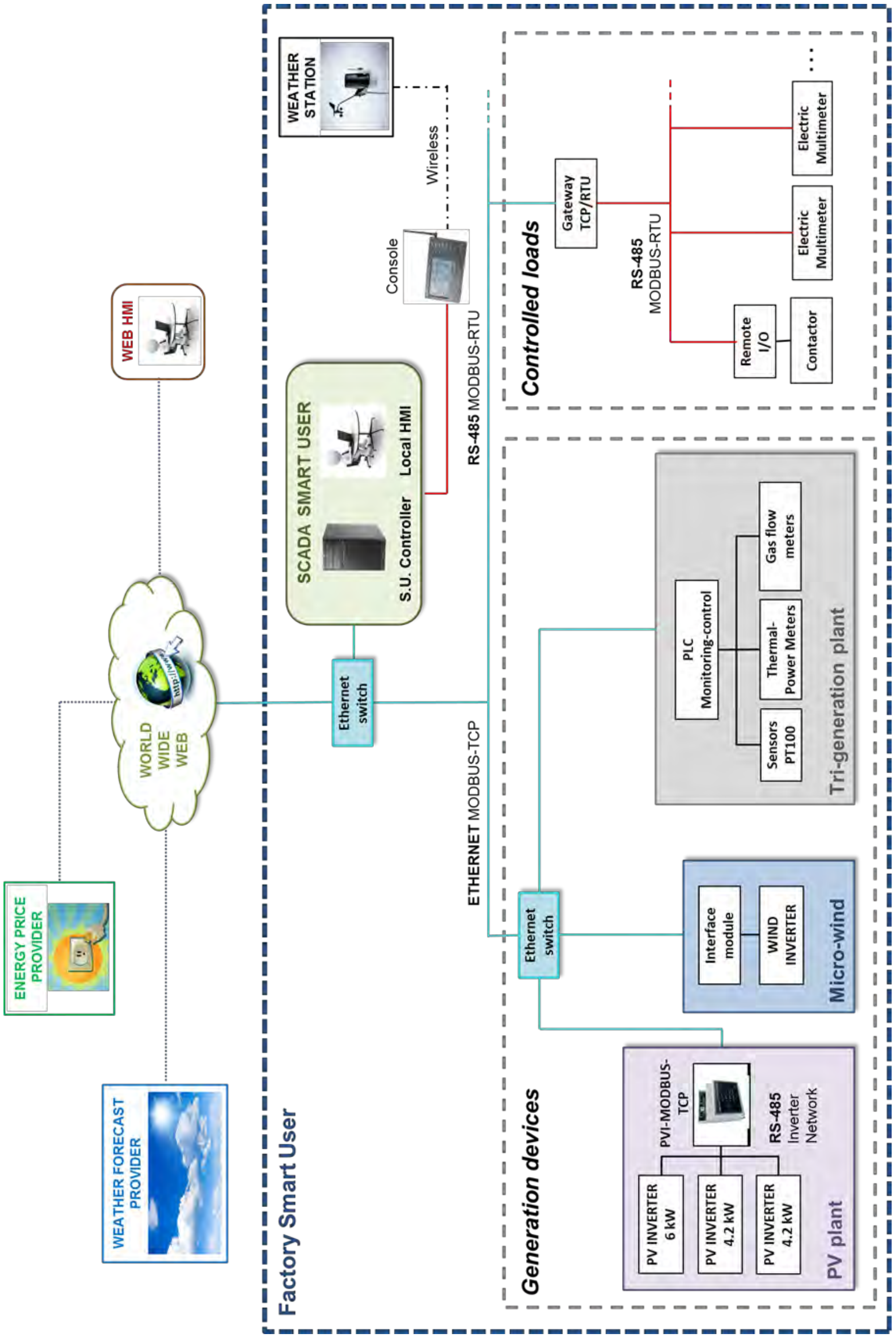


Figure 79 - SU data acquisition/monitoring

Then the algorithm is run by the SCADA system, giving as output the set-point values of the generators, the curtailments of the non-privileged loads, and the request to the storages (Figure 80).

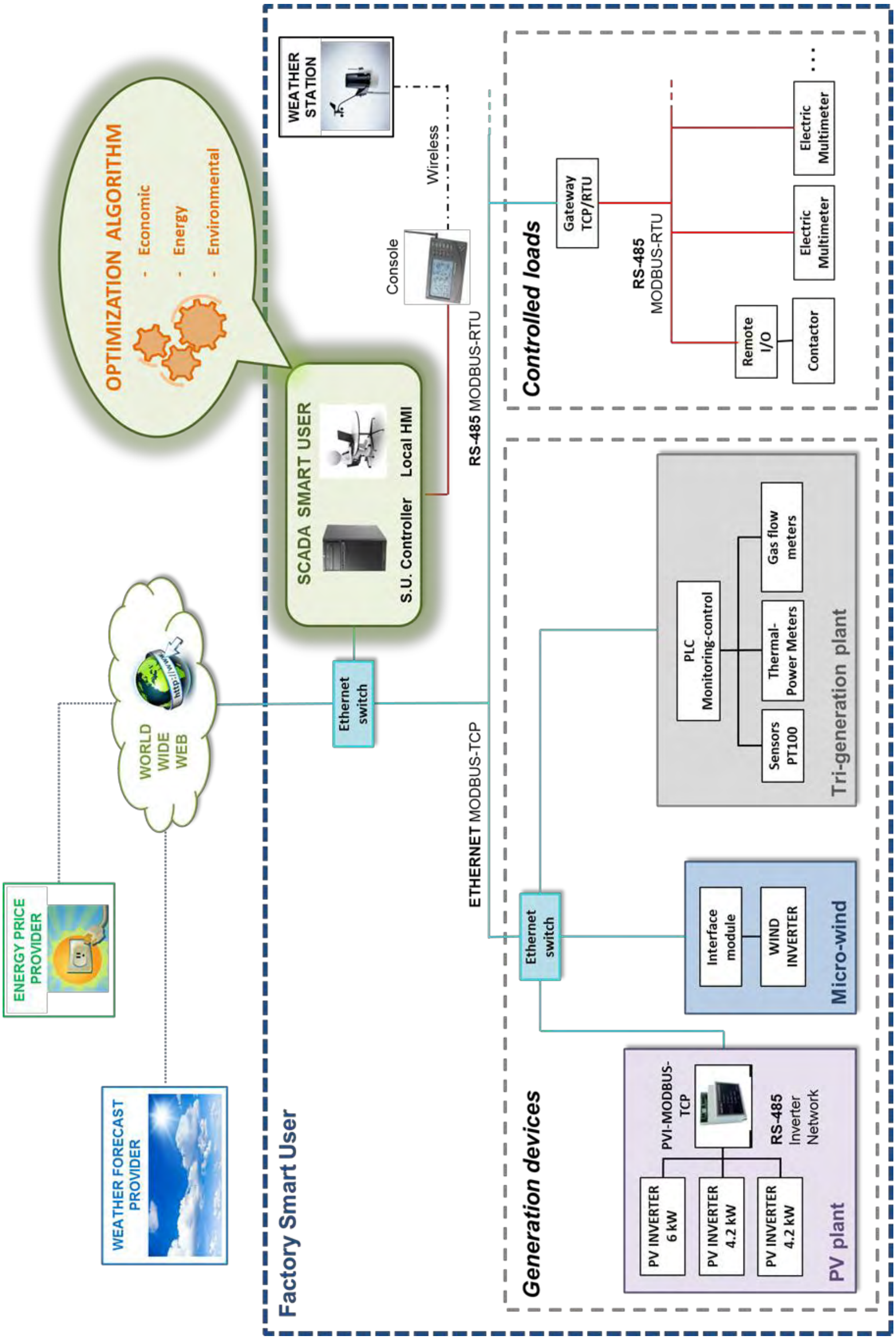


Figure 80 - SU optimization algorithm run

At last, the set-point values are transferred as command to the field from the SCADA system (Figure 81).

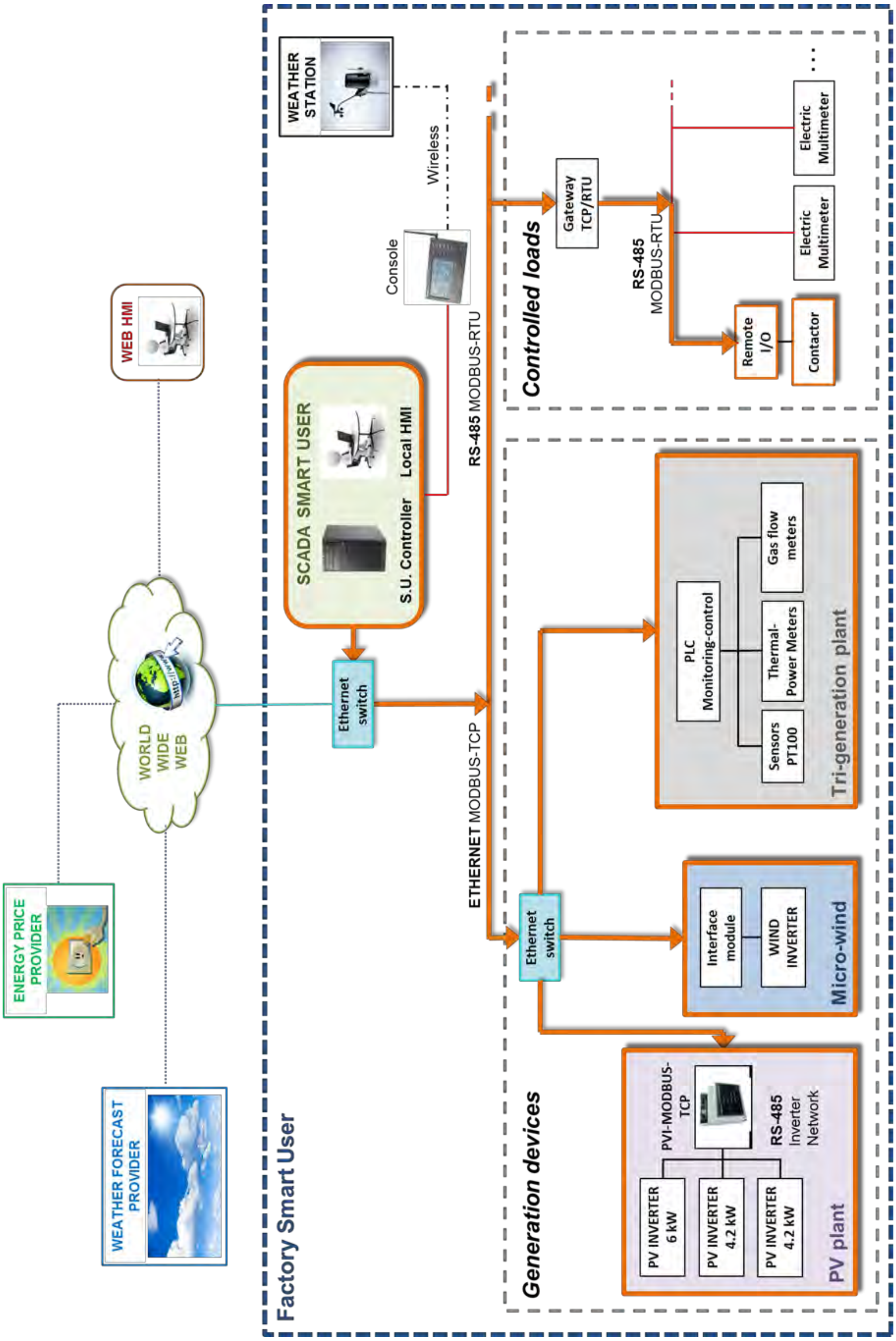


Figure 81 - SU production and consumption control

The system is planned to operate the plant in 3 different ways, for the achievement of three different goals.

At first, the algorithm is run for optimizing the performance of the plant for the next day: on the basis of the loads predictions and of the weather forecasts, the scheduling of the plant for the entire next day is optimized.

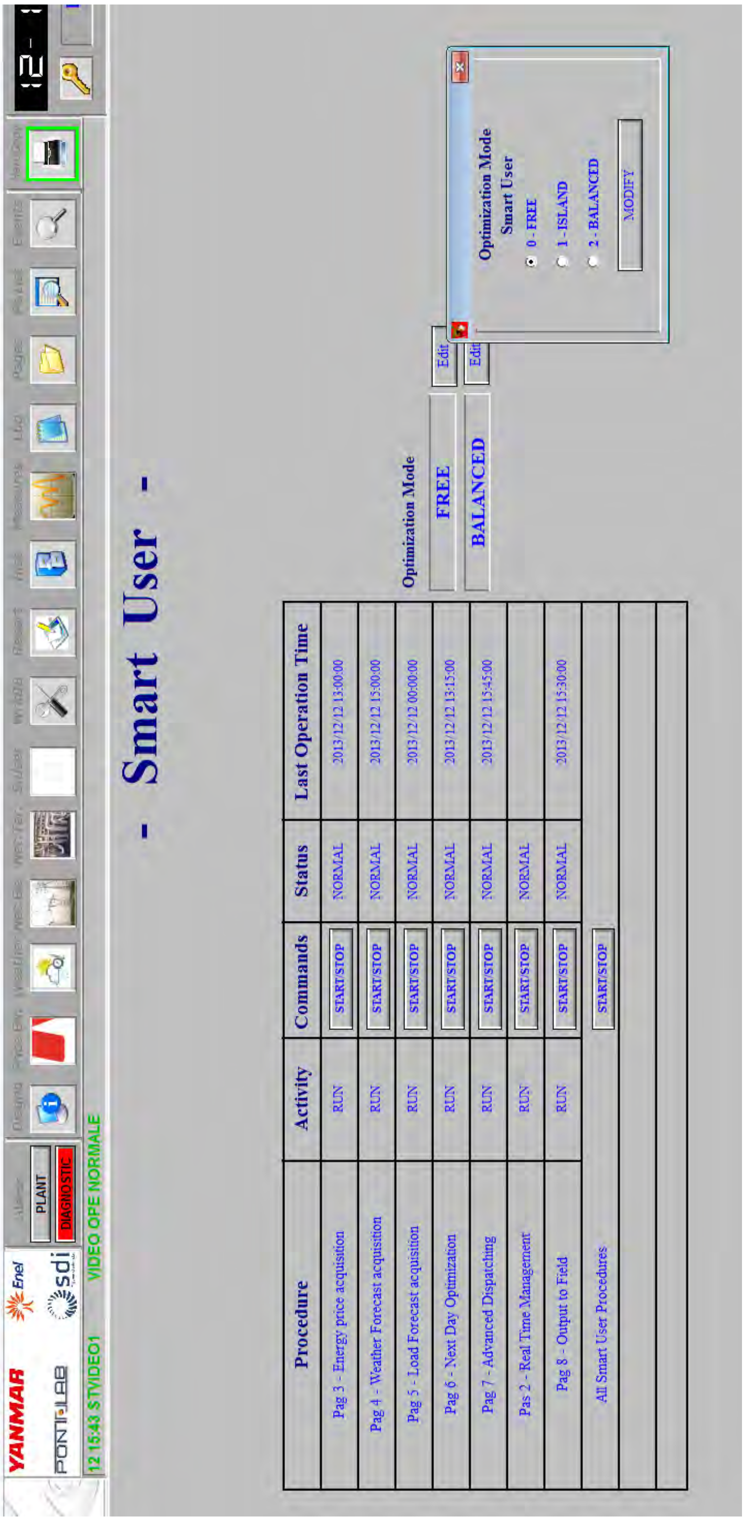
Nevertheless, the climatic conditions could be updated, and there could be unexpected increasing or decreasing loads respect to what was previously planned. For these reasons, before the end of each scheduled time step, an advanced dispatching procedure is considered: the algorithm is run by the time interval successive at the present one, until the end of the day, for trying to improve the performance of the SU plant considering the modified conditions.

In case that a prescribed exchange with the external gird must be ensured, a simple definition of the set-point of the various devices in a time period of 15 minutes is not sufficient to achieve this goal: a procedure with a shorter time horizon is indispensable.

4.6.1 Next-Day optimization

The so-called “Next-Day” optimization allows to generate the scheduling of the generators and storages through running the genetic algorithm. In this case, the energy input are given by the loads and weather forecast, in addition to the storages energy level predicted for the end of the day prior to the one which is being evaluated.

This procedure can run on the basis of three different boundary conditions regarding the electric power exchange with the external grid: an unplanned profile, a prescribed profile, or the VSA operation of the plant, respectively indicated as “free”, “balanced”, and “islanded” in Figure 82.



- Smart User -

Procedure	Activity	Commands	Status	Last Operation Time
Pag 3 - Energy price acquisition	RUN	START/STOP	NORMAL	2013/12/12 13:00:00
Pag 4 - Weather Forecast acquisition	RUN	START/STOP	NORMAL	2013/12/12 15:00:00
Pag 5 - Load Forecast acquisition	RUN	START/STOP	NORMAL	2013/12/12 00:00:00
Pag 6 - Next Day Optimization	RUN	START/STOP	NORMAL	2013/12/12 13:15:00
Pag 7 - Advanced Dispatching	RUN	START/STOP	NORMAL	2013/12/12 15:45:00
Pas 2 - Real Time Management	RUN	START/STOP	NORMAL	
Pag 8 - Output to Field	RUN	START/STOP	NORMAL	2013/12/12 15:30:00
All Smart User Procedures		START/STOP		

Optimization Mode
FREE
BALANCED

Optimization Mode
Smart User
● 0 - FREE
○ 1 - ISLAND
○ 2 - BALANCED

Figure 82 - SCADA procedures management page

In case the imposed profile with the grid is in “free” mode, there is no constraints about the power exchange. the algorithm is run just considering the most profitable scheduling for the Smart User.

If the “islanded” option is selected, the algorithm automatically sets to zero the exchange objective with the external power grid, and at the same the routine does not consider as acceptable all the scheduling results which consider the electricity supply from/to the distribution grid. In addition, the limits in the exploitation of the generators are reduced compared to their technical constraints (e.g. the operating range of the CHP can be reduced from 2.5-25.1 kW_e to the interval 5-20 kW_e, on the basis of the percentage imposed in the input file “TECH.csv”): by doing so, if some mismatching between predictions and actual consumptions are experienced, they can be balanced by the complete exploitation of the full power capacity of the pieces of equipment.

The selection of the “balanced” option allow to operate the algorithm similarly to the “islanded” mode, but in this case a predetermined exchange objective with the grid must be specified as an input. The mismatching between the prescribed and the guess value of the electric exchange with the grid provides now an economic penalty, which is considered in the fitness function. Again, a reduced operating range for the generation devices and for the storages can be considered.

4.6.2 Advanced Dispatching

The “Advanced Dispatching” procedure allows the plant to be optimized when the loads conditions or the weather forecasts are updated, respectively by the user or by the weather forecast provider. It exploits the same optimization algorithm developed for the “next-day”, with the difference of a decreased number of time intervals: in particular, the procedure is performed after 10 minutes from the beginning of the time step, with the objective of optimizing the performance of the plant starting from the next time period to the end of the day.

Similarly to the “Next-Day” procedure, the optimization can be carried out on the basis of three different options: with a free exchange profile with the external grid, or with a prescribed profile, or in VSO.

In this case, the “balanced” option can be selected even in case the “next-day” optimization was performed as “free”: indeed, the exchange profile to be achieved is the result of the scheduling predicted the day before.

In addition, the operating range of all the devices is restored to its full capacity, for exploiting the best performance of each equipment.

4.6.3 Real Time

The “Real Time” procedure allows the plant to follow a prescribed power exchange with the external grid. This duty seems to be the next future for all the DG devices which the users must achieve to have the authorization from the DSOs for the connection to the distribution grid.

The procedure is completely different from the optimization performed with the “Next-Day” and the “Advanced Dispatching”, mainly due to the changed target it must accomplish. Indeed, the optimization of the performance of the SU plant through the algorithm is carried out by keeping the devices at a constant set-point for a relatively large time interval. From the electric point of view, within the 15-minutes time step large power fluctuations can happen, because the intrinsic dynamic of the electric and electronic devices (i.e. computers, lightings, etc.) has a very short transitory (less than 1 second). For this reason, a logic procedure is developed to perform the “Real Time” adjustment of the power exchanged with the grid at the connection point, with a time horizon of 1 second.

Within the SU plant, the power exchange adjustment could be performed by the electric generators and by the non-privileged loads: the first ones would be able to increase or reduce their power output, the latter ones could be only curtailed for increasing the power supplied to the grid or decreasing the absorption from the connection point. Nevertheless, a very frequent modulation of both the loads and the generators could bring to heavy reliability problem, in addition to a decrease of the efficiency of the plant due to the persistent transient conditions. For these reasons, the most suitable choice appears to be the adoption of an electric storage, with the unique purpose of balancing the oscillation of the power exchange at the grid connection point: such kind of solution allows good performance with low technical efforts, thanks to their reliability and fast response to the power requests.

In order to understand the most suitable size of the electric storage, and avoiding a wrong investment, the electric storage is only virtual, and its dynamic behavior is simulated within the SCADA, by means of a graphic procedure which is internationally unified: the APS method.

As anticipated, the “Real Time” procedure aims to level the power exchange at the connection point with the prescribed value by means of an electric storage, considering a time step of 1 second. During this operation, the batteries obviously vary their State-Of-Charge from the initial value to another one: in case there is no cyclic behavior of the plant, in a relatively long time the storage tends to be completely filled up or down, not allowing its further utilization. Hence, another procedure must be conceived with a larger time horizon, with the objective of restoring the starting energy level of the batteries and balancing eventual mismatching between the actual and the prescribed power exchange with the grid that the storage could not accomplish because of its technical limits. Of course, this latter procedure must be carried out within the 15-minutes time interval, to allow the maximum reliability of the procedure. Indeed, when a prescribed energy exchange is considered, some lack of balance during some instants of the considered time interval can be later compensated.

Thus, 2 procedures are developed within the SCADA:

1. The 1-second balancing;
2. The 5-minutes recovering.

The logical schematics of the first one is shown in Figure 83.

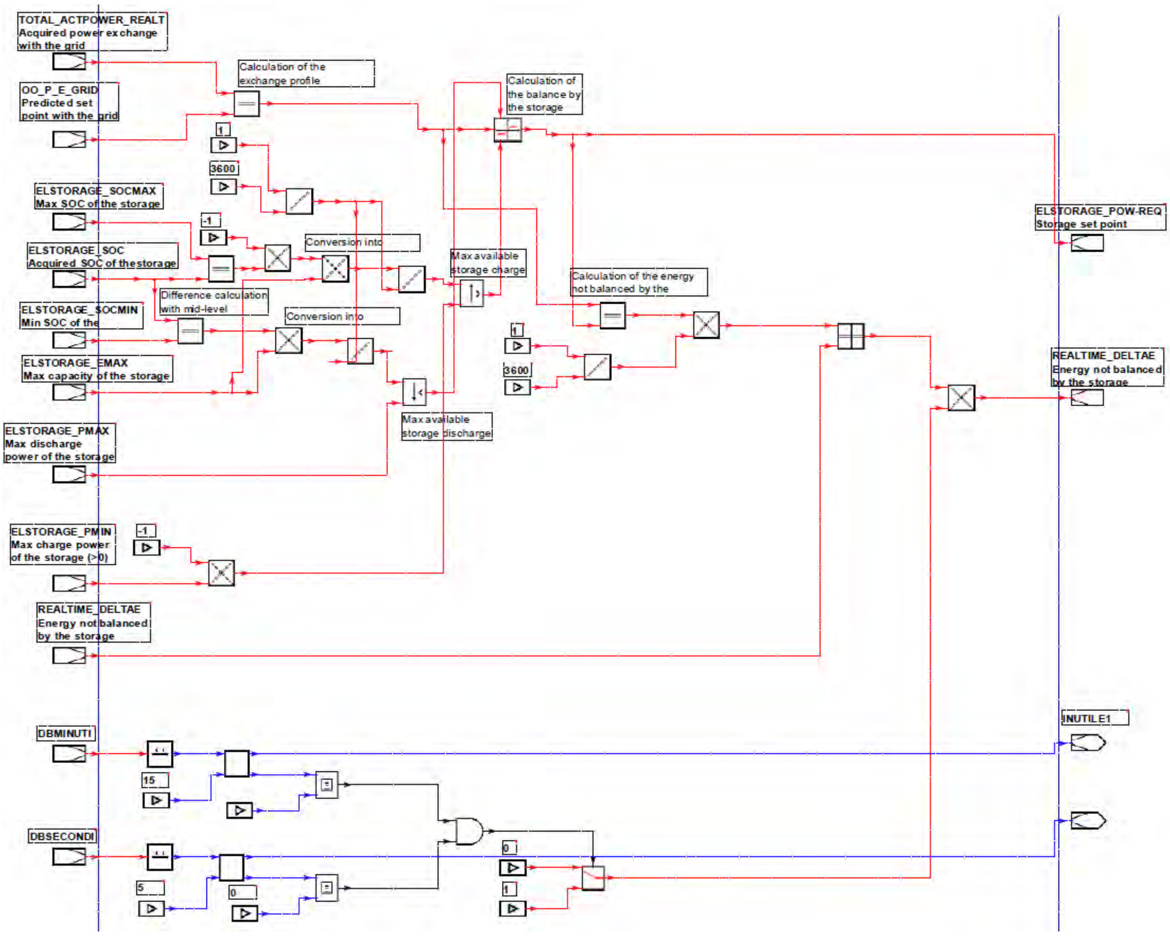


Figure 83 - 1-second "Real Time" procedure GAPS schematic

The input to the model are the technical parameters of the storage (the acquired SOC, minimum and maximum admitted SOC, energy capacity, maximum charge and discharge power), the acquired power exchange with the grid, the acquisition of the predetermined grid exchange objective from the SCADA internal archive, and the time at which the procedure is carried out.

Whenever a mismatching between the prescribed power exchange value and the actual acquisition is determined, the difference between the two values is compared with the maximum charge or discharge value available for the storage. This latter value is the more stringent between the technical power limit of the batteries and the value allowed by the SOC. If the power request to the electric storage is compliant with the technical limits, the batteries balance the instantaneous fluctuations, otherwise they operate until reaching their limit, and the remaining power request is stored in a purposefully defined variable, called “DELTAE_REALTIME”. The instantaneous mismatching between the prescribed and the actual exchange with the grid does not represent a critical drawback, lying the objective of the management in the exchange of a predetermined energy amount within a 15-minutes period. The variable so defined must be zero at the end of that time step for achieving the prescribed profile with the grid.

The 5-minutes recovering procedure is developed for changing the set point of the CHP and of the non-privileged electric loads for the achievement of two purposes: the restore of the initial SOC of the electric storage, and the balancing of the DELTAE_REALTIME variable. The GAPS schematic of this procedure is shown in Figure 84.

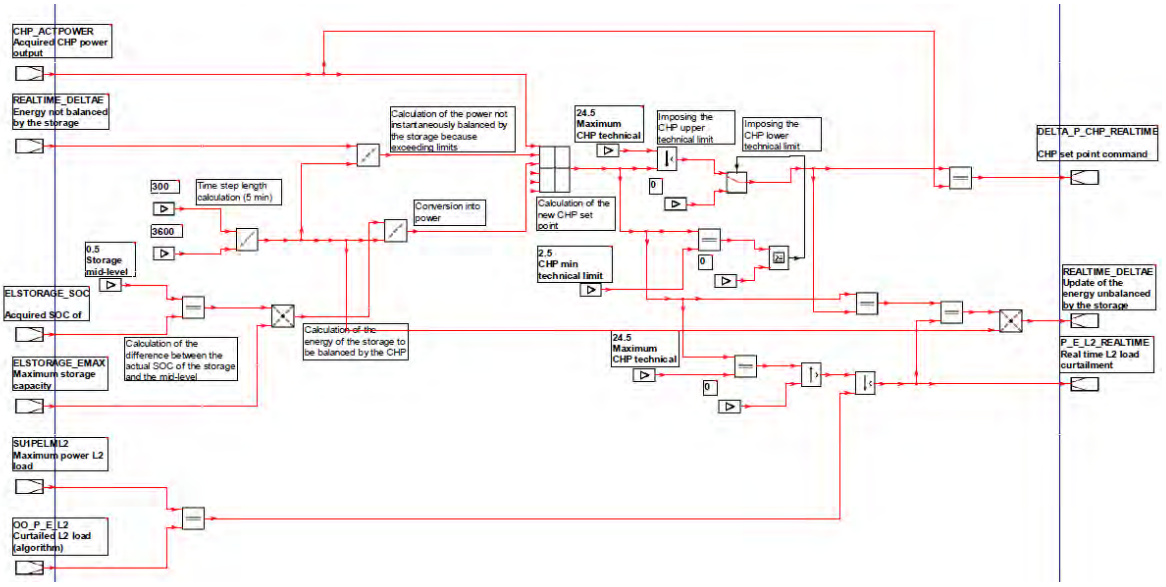


Figure 84 - 5-minutes “Real time” procedure GAPS schematic

At the end of the 15-minutes time step, the value of the DELTAE_REALTIME parameter, if different from null, is automatically reset to zero: indeed in that case the objective grid exchange is not accomplished and cannot be recovered.

Of course, the described procedure needs as a basis the definition of the simulated electric storage, whose GAPS schematic can be seen in Figure 85.

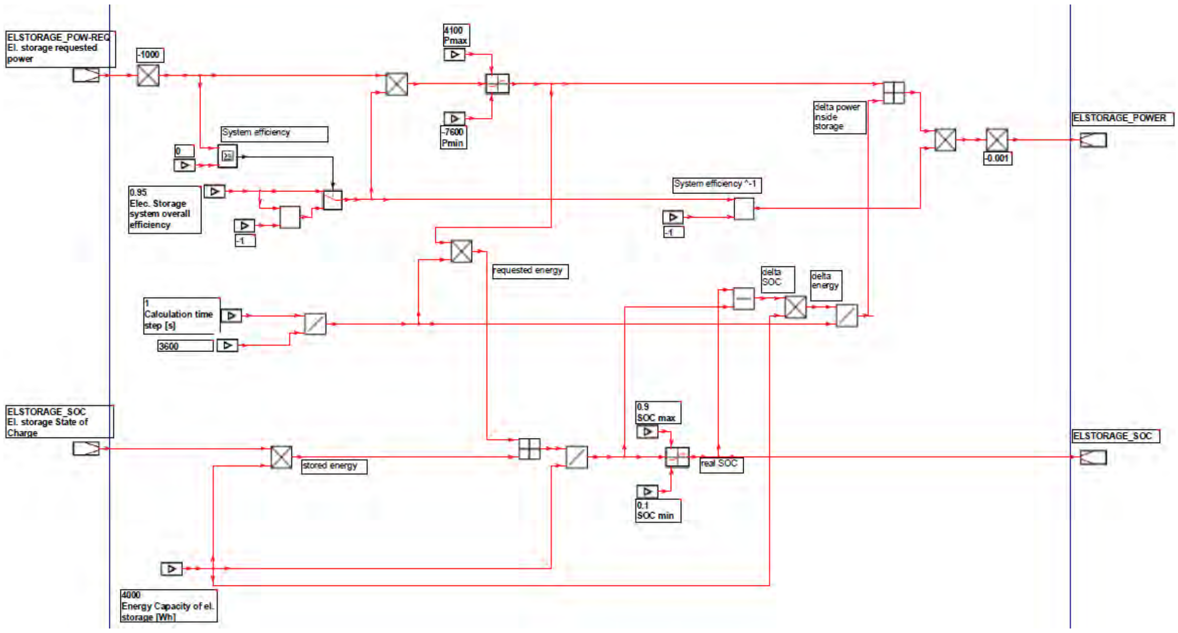


Figure 85 - Electric storage GAPS schematic

The technical parameters of the storage are set in the SCADA archive, to allow an easier procedure in case the size of the storage has to be changed. The batteries are characterized by maximum and minimum SOC values, by a maximum charge and discharge power, by an energy capacity, and by a device efficiency: all these data are taken by commercial products.

5. Results

5.1 Introduction

Some results of the carried out investigations are going to be presented, both for verifying the correct behavior of the optimization algorithm and for the confirmation of the expectations on the experimental plant.

In addition to that, a DOE analysis is performed, in order to understand, in the actual energy scenario and for the considered case study, the influence of all the cost parameters on the economic performance of the SU plant, together with an analysis of the influence of the errors of both the loads and the weather forecasts on the final economic results, in order to individuate the guidelines for the next future development of the Smart User functionalities and improvements.

5.2 Algorithm off-line running: “whole-day”

After the implementation of the algorithm, the obliged step is to verify its performance with several off-line simulations, involving different boundary conditions in terms of energy prices, electric and thermal loads, RESs production. But, as a first investigation, the differences in the behavior of the “whole-day” and “single time step” optimization have to be compared.

As first, the “whole-day” version of the algorithm was implemented, and its performance analyzed, only in terms of CHP, PV plant, and wind-turbine management. Theoretically, this optimizer configuration should allow better results, thanks to the active management of the heat storage of the plant. Anyway, its large number of variables (even reduced in this version) and the consequent massive search space could not allow to find effective or repetitive optimized solution for this kind of algorithm.

In Figure 86 the results of the “whole-day” optimization for the case study are shown, without imposing any prescribed energy exchange with the power grid, and considering the GA parameters setting as reported in Table 8.

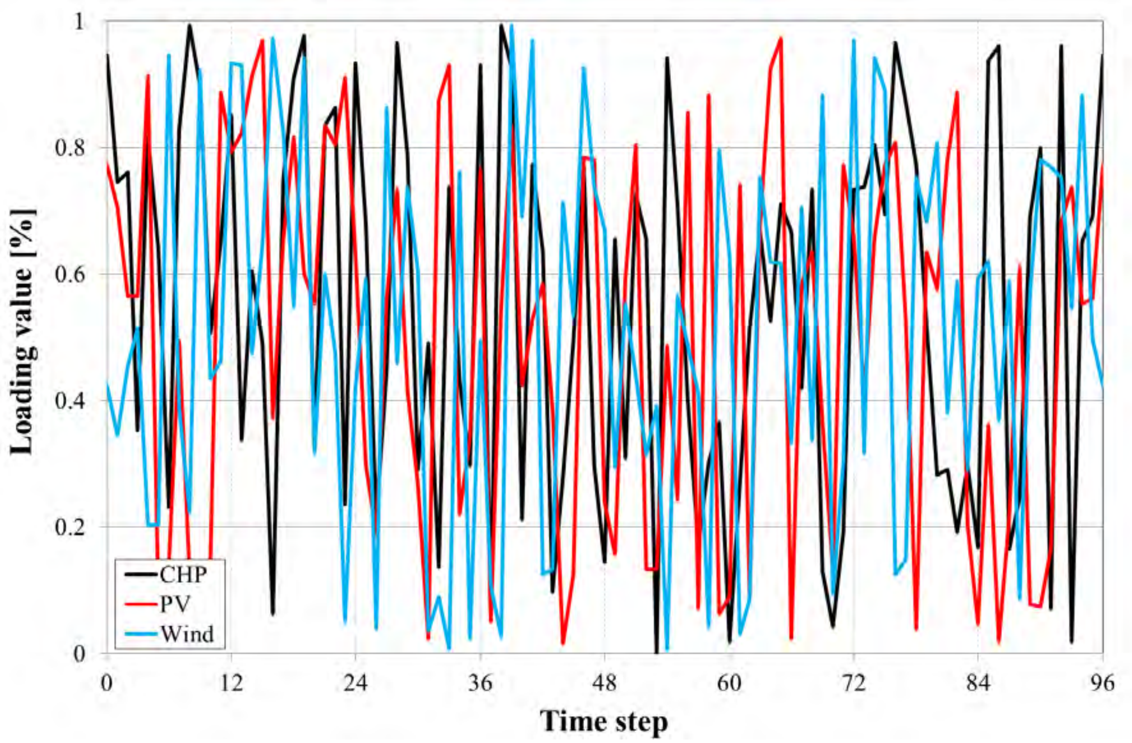


Figure 86 - Results of the "whole-day" optimization (1^{st} run)

Parameter	Value
Population size	250
Bits number per variable	8
Crossover percentage	20 %
Mutation percentage	0.2 %
Selection number	5
Variance tolerance	0.1
Max number of iterations	1000

Table 8 - GA parameters for the first “whole-day” algorithm trial

The set point scheduling performed by the algorithm shows an incoherent behavior, with evident ripples of the output values between the different time-steps. Also for the PV plant output, which should be always exploited to its upper limit in reason of the very favorable incentive, it is clearly evident how the algorithm is not capable to individuate the local minimum for the fitness function. In addition to that, as largely expected after the first trial, the results of the optimization does not show the repeatability which is needed from a reliable and robust algorithm, as visible comparing Figure 86 with Figure 87.

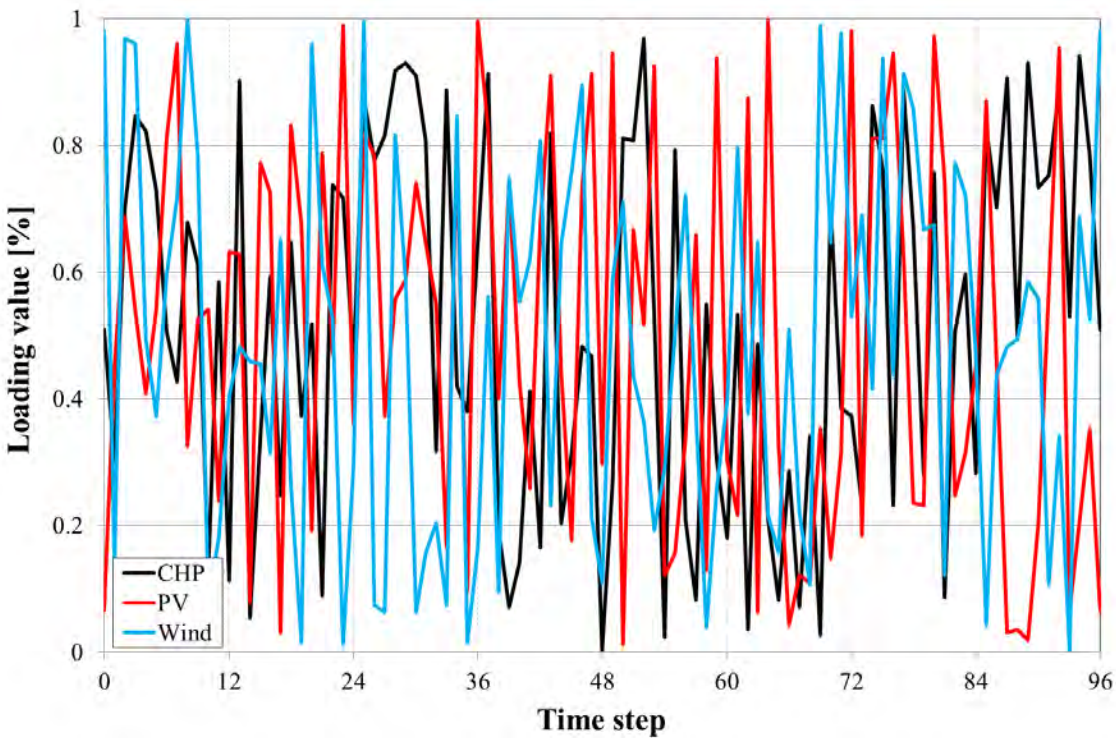


Figure 87 - Results of the "whole-day" optimization (2nd run)

Some other attempts are carried out by varying the genetic parameters, in order to allow the algorithm to analyze a wider area of the search space. In particular, the parameters which have been changed are summarized in Table 9, together with their trial range of variation.

Parameter	Experimented values
Population size	250 - 500 - 1,000 - 2,000 - 5,000
Bits number per variable	4 - 6 - 8
Crossover percentage	5 - 10 - 15 - 20 - 30 %

Mutation percentage	0 - 0.05 - 0.1 - 0.2 - 0.5 %
Selection number	2 - 5 - 10 - 15
Variance tolerance	0.1 - 0.5 - 1
Max number of iterations	1,000 - 5,000 - 10,000 - 20,000

Table 9 - GA parameters trial for the “whole-day” algorithm

Generally speaking, when in a GA the population size is increased its searching ability is increased, and a similar effect is obtained when the percentage of crossover and mutation grow. Nevertheless, such interventions also increase the dispersion of the solution obtained after the crossover and the mutation, acting as an obstacle to reach the stopping criterion based on the tolerance on the variance of the fitness function for the convergence of the algorithm, also in case the maximum number of iterations allowed is remarkably increased and contemporarily the tolerance is less strict. One of the theoretically most useful interventions result the decrease in the number of bits per variable, which has a direct effect in defining the dimensions of the search space, even if lowering the “resolution” of the variables output: nevertheless, the variation only affects the basis of the number defining all the possible combinations of the solution, not the exponential, so decreasing the effectiveness of the variation.

Even reducing the number of considered time steps for the day (i.e. increasing their length) down to 48 values, the number of possible combination is still large enough not to allow an effective optimization of the problem. In Figure 88 the result is shown when considering the GA parameters as reported in Table 10.

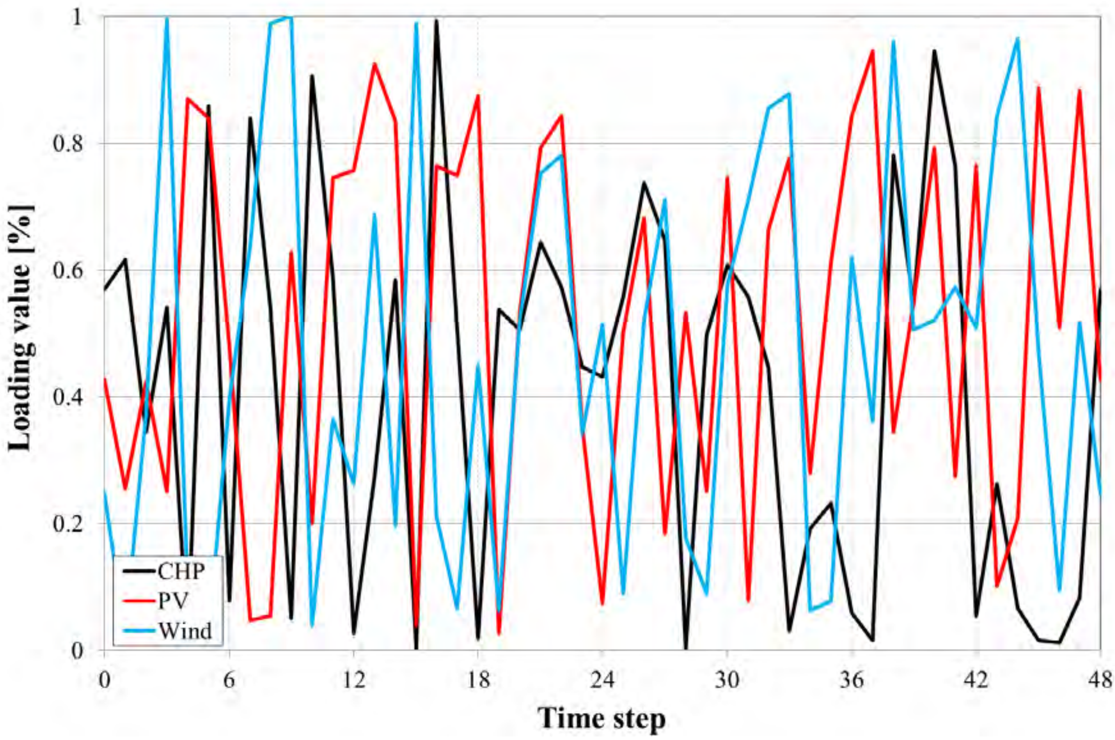


Figure 88 - Results of the “whole-day” optimization with 48 time intervals

Parameter	Value
Population size	250
Bits number per variable	8
Crossover percentage	20 %
Mutation percentage	0.01 %
Selection number	2
Variance tolerance	0.5
Max number of iterations	5,000

Table 10 - GA parameters for 24 time intervals trial

5.3 Algorithm off-line running: “single time-step”

Considering the matters in §5.2, the algorithm selected for the implementation within the SCADA system is the so-called “single time-step” one.

Thanks to the heavily reduced search space, the convergence and repeatability of the GA outputs is always verified: the demonstration of that by comparing the results with the same conditions is here neglected.

This version of the algorithm, even with the drawback of the "passive" management of the thermal storages, has the advantage of being relatively simple, requiring low computational efforts, giving the user the possibility to be performed in both the "next-day" and the "advanced dispatching" optimization, with very poor differences among them. In addition to that, especially in mid-season conditions when both heating and cooling power is required by the loads, the algorithm can easily switch step by step from the "winter" to the "summer" configuration, without any kind of problem.

5.3.1 Algorithm scheduling

Some simulations are initially carried out to verify the reliable and robust behavior of the "single time-step" optimization algorithm, without considering any prescribed electric energy exchange with the external grid, in order to better understand if, under particular conditions, the obtained results are similar or close to the expected ones. In more detail, some preliminary trials are carried out in order to achieve with the algorithm the thermal and electric-led scheduling of the CHP and a "conventional" energy supply of the factory, consisting in the purchase of the electricity from the external grid and of the heat from the gas boiler.

As first, the input parameters of the optimization algorithm are set in order to obtain the thermal-led CHP operations during the winter period, without considering the possibility to curtail any load. To achieve the expected result, the external constraints modified respect to the actual values are reported in Table 11.

Parameter	Value
Natural gas purchase cost (generation use)	1 €/Sm^3
Natural gas purchase cost (civil use)	2 €/Sm^3
Electricity selling cost to the grid	0 €/kWh$_e$

Table 11 - Input variation for the algorithm CHP thermal-led experiment (winter)

The load curves considered for the investigation are chosen randomly, with the constraint that the maximum heating request must lie below the rated thermal power of the CHP, and the minimum above its lower technical limit; the curves, including the PV production forecast taken from the weather forecasts, are shown in Figure 89.

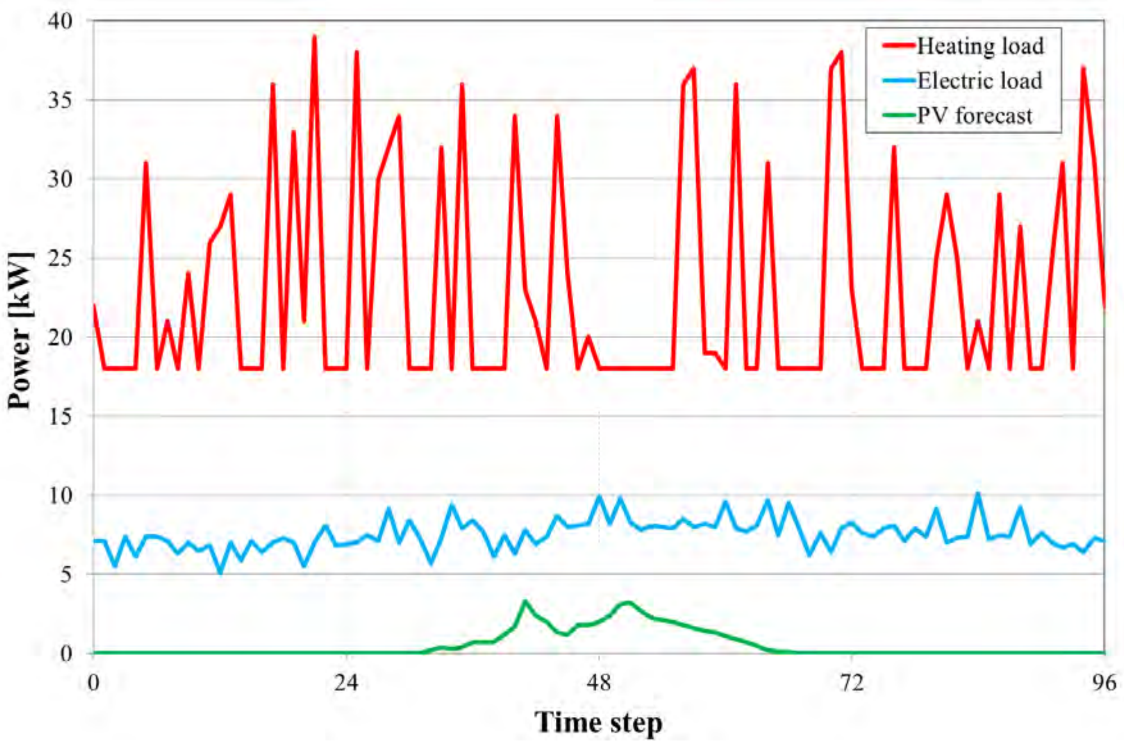


Figure 89 - Load curves for the algorithm CHP thermal-led experiment (winter)

By imposing such a kind of thermal request curve, and considering that the cost of the natural gas feeding the boiler is twice the supply for the ICE, the cogeneration unit is continuously running, with its thermal output corresponding to the load request; in addition, the PV output is always exploited from the factory (Figure 90), while the boiler output is always null (except some small production outputs, which can be considered as a “noise” of the GA functioning).

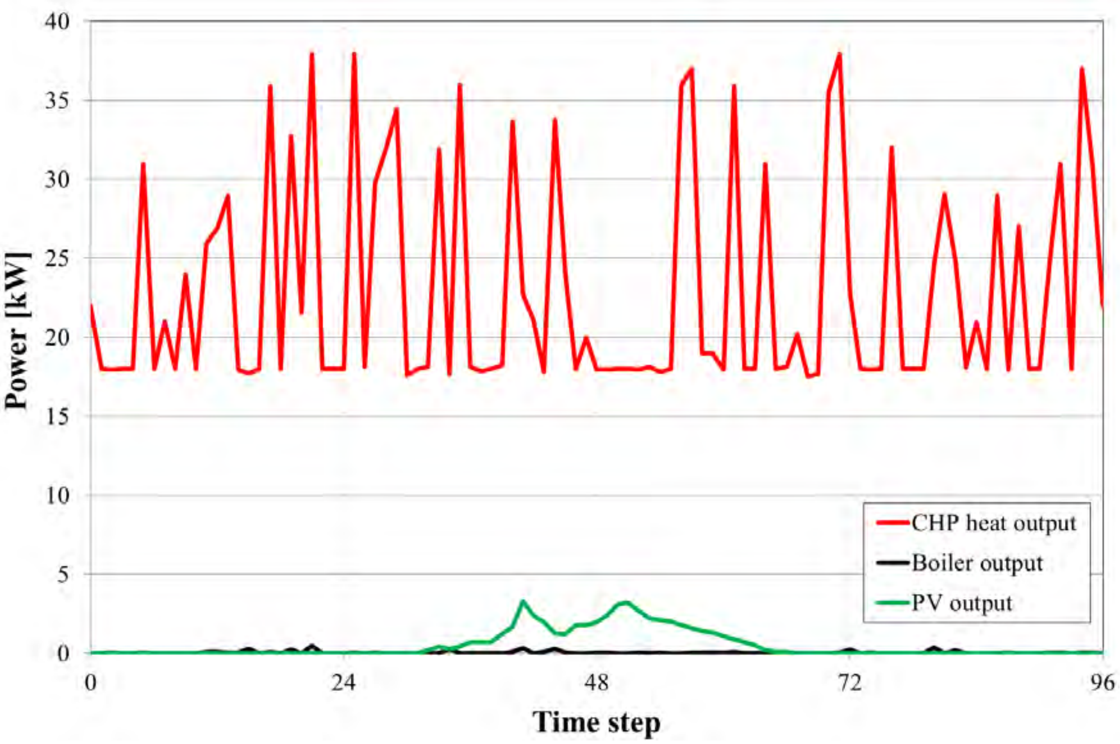


Figure 90 - Output for the algorithm CHP thermal-led experiment (winter, 1st run)

In order to understand if the algorithm allows an easy reply of the results, a second run is carried out keeping the input as the same of the previous trial. Figure 91 shows that during 3 time steps the CHP is switched off and the load request is satisfied by means of the gas boiler. Nevertheless, the economic result is very similar in both cases, as shown in Figure 92.

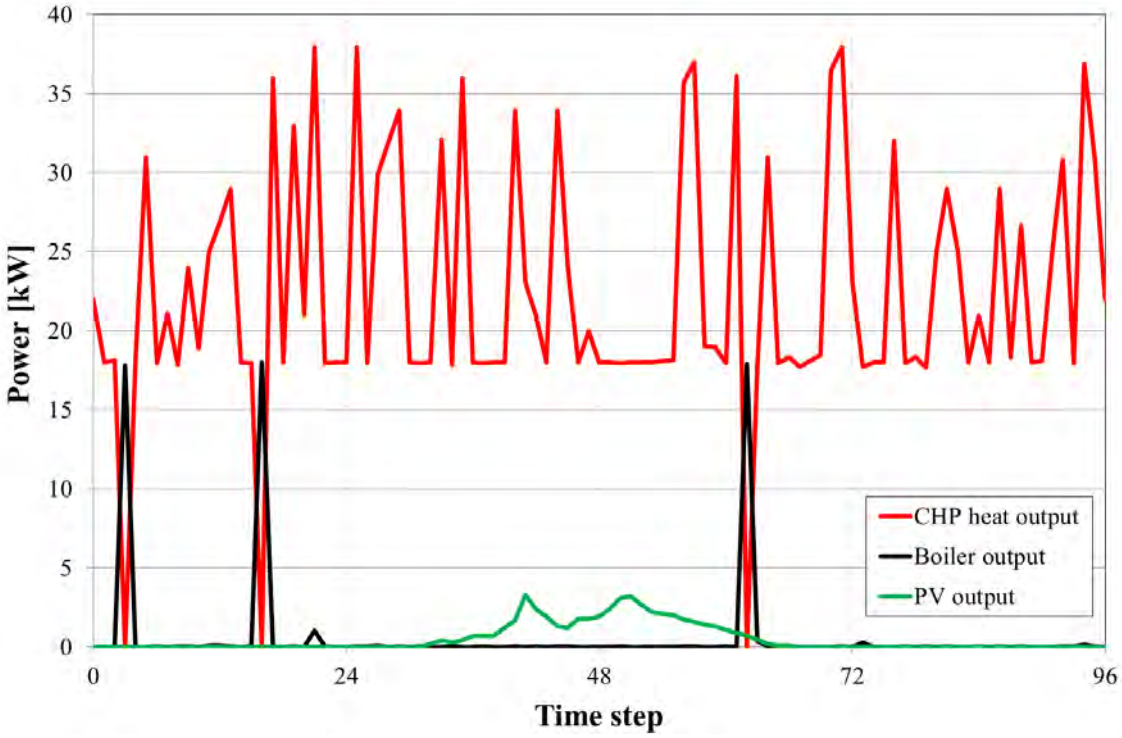


Figure 91 - Output for the algorithm CHP thermal-led experiment (winter, 2nd run)

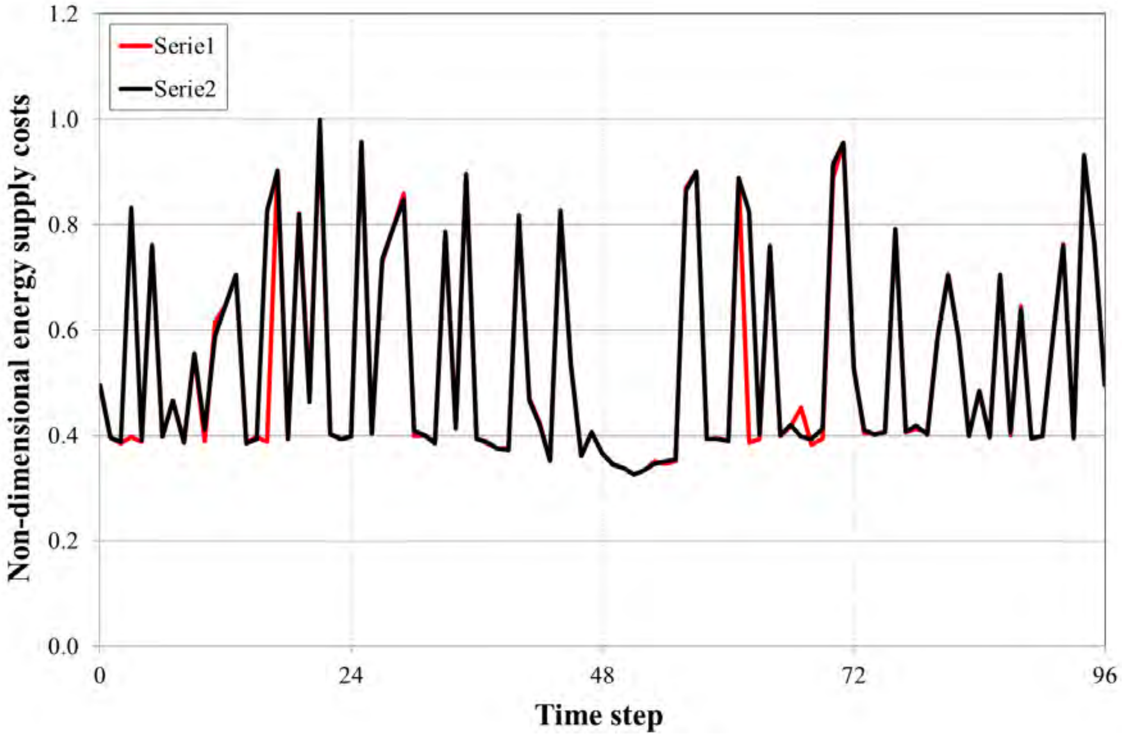


Figure 92 - Cost comparison between the 1st and 2nd run results for the algorithm CHP thermal-led experiment (winter)

For verifying the correct behavior of the algorithm when also dealing with the loads curtailment, a similar experiment is performed, considering a different heating load curve (Figure 93) and introducing the possibility for their curtailment, with a penalty established in 0.2 €/kWh$_{th}$.

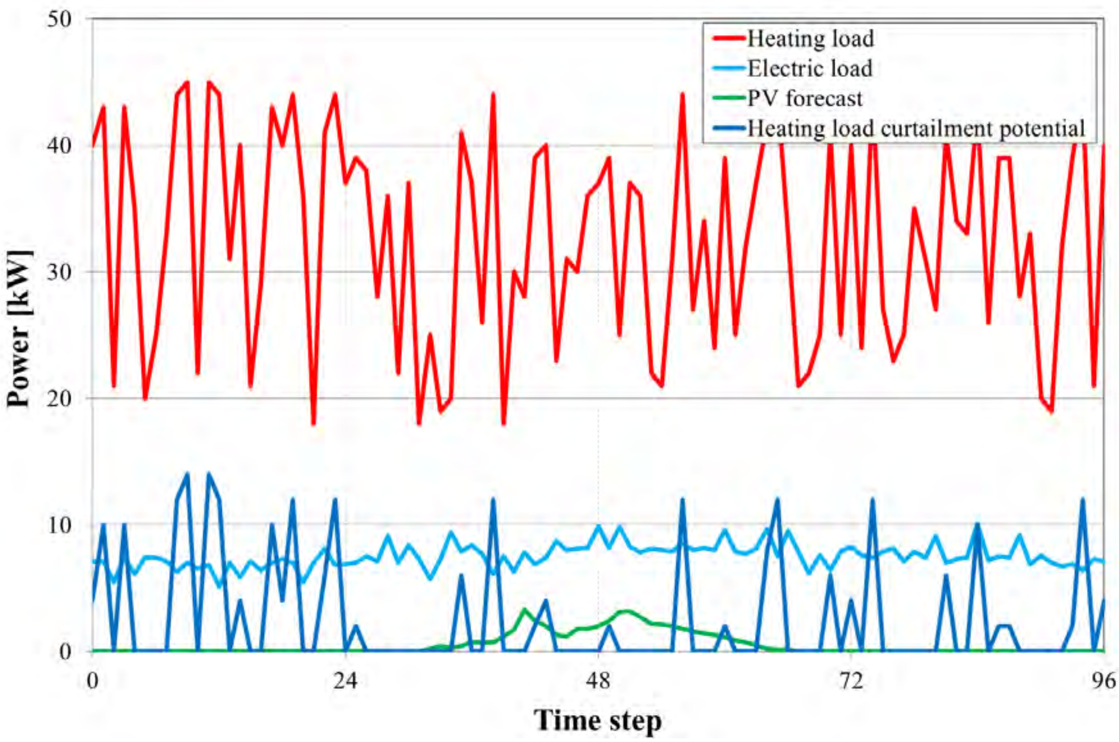


Figure 93 - Load curves for the algorithm CHP thermal-led with load curtailment experiment (winter)

In order to verify the correct behavior of the optimizer, the load curtailment potential is considered twice the value which allows the CHP to operate at the rated thermal power. The results of the 1st algorithm run is shown in Figure 94.

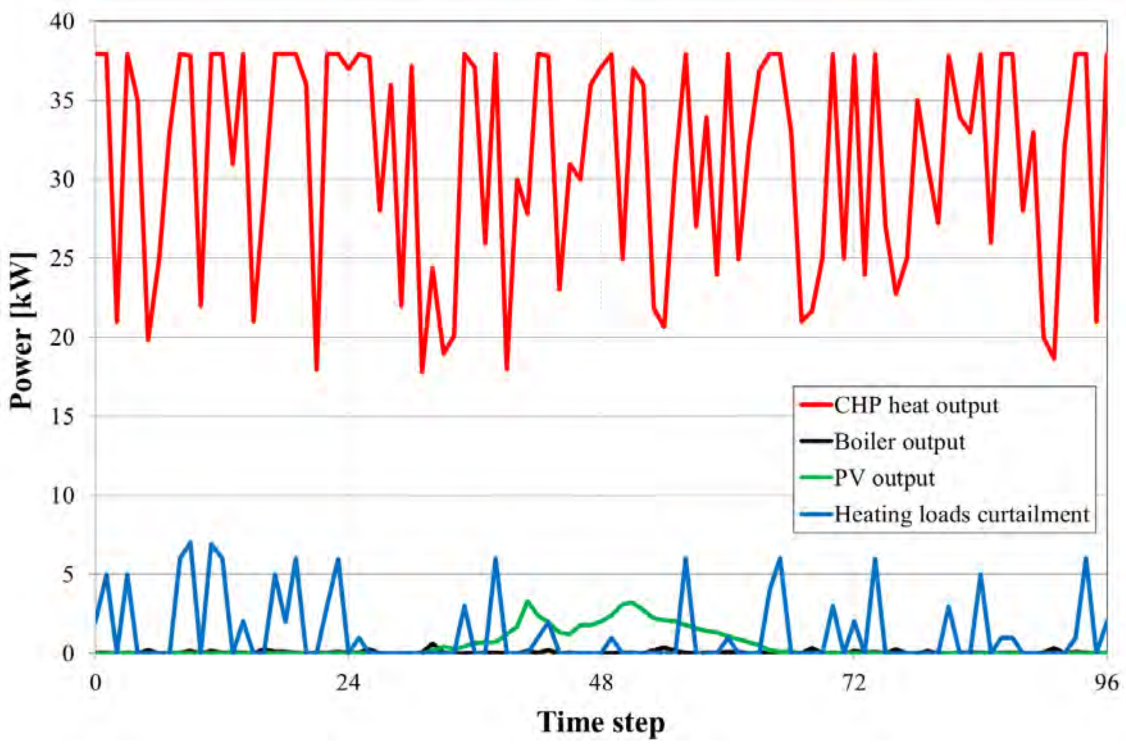


Figure 94 - Output for the algorithm CHP thermal-led with load curtailment experiment (winter, 1st run)

Also in this case, the CHP is continuously running following the heating load request whenever it is possible, and curtailing the user demand when the request is higher than the maximum technical limit of the ICE, with this latter one operating at its rated power output. Again, the PV potential is considered fully exploited by the factory and the gas boiler is always switched off.

The output of the 2nd run of the algorithm, to verify the repeatability of the results, is shown in Figure 95.

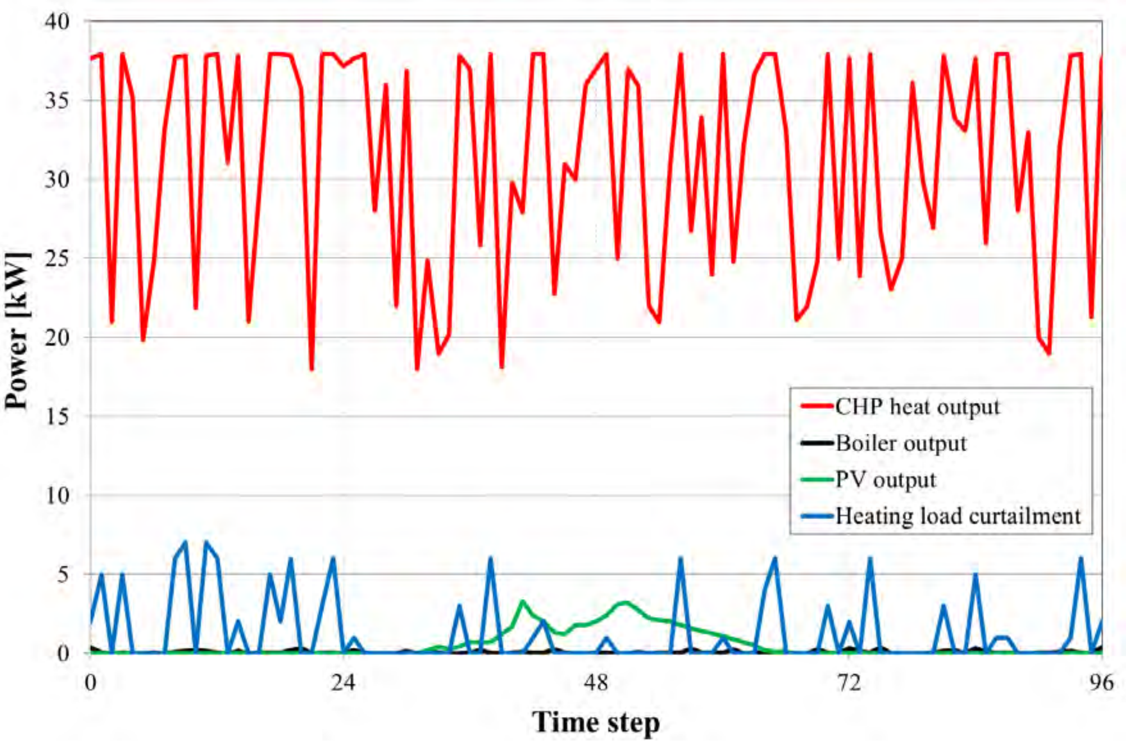


Figure 95 - Output for the algorithm CHP thermal-led with load curtailment experiment (winter, 2nd run)

The comparison between the two outputs, in terms of energy supply costs of the plant, shows that no differences can be appreciated (Figure 96).

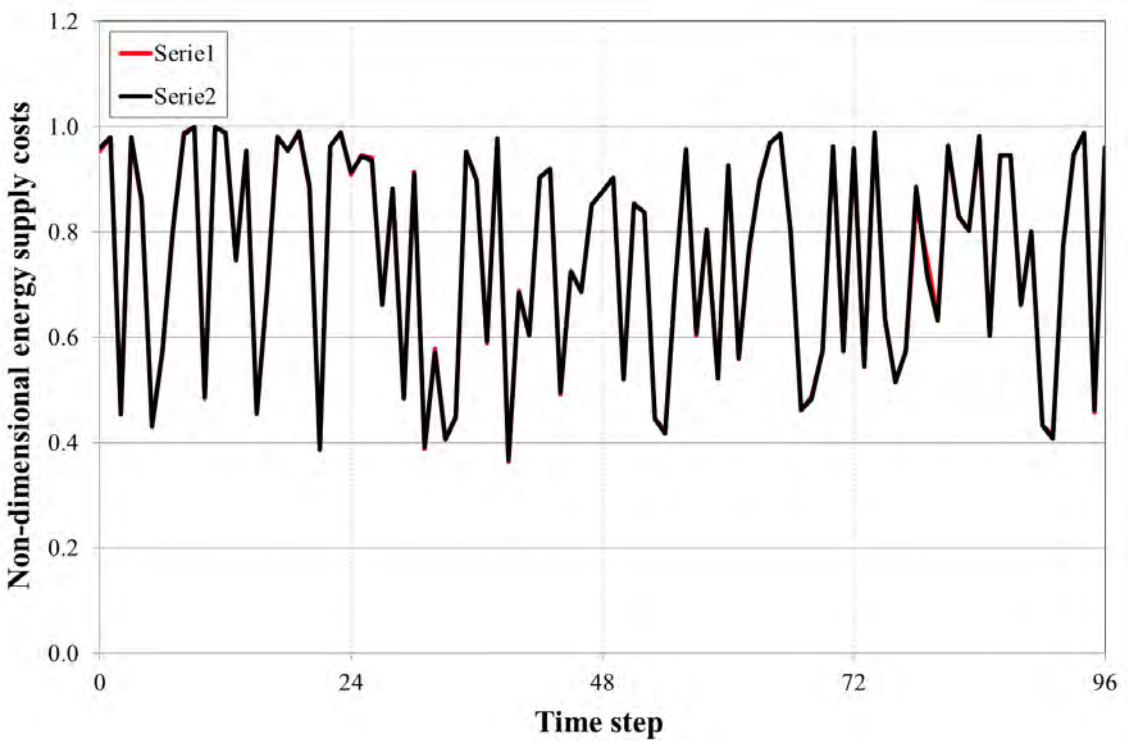


Figure 96 - Cost comparison between the 1st and 2nd run results for the algorithm CHP thermal-led with load curtailment experiment (winter)

Similar experiments are carried out considering the “summer” configuration of the thermal plant, when the heat from the CHP feds the absorption chiller and the heating load is null. In this case, if no load curtailment potential is considered, the considered input parameters variation and the load curves are shown in and , respectively.

Parameter	Value
Natural gas purchase cost (generation use)	1 €/Sm^3
Electricity selling cost to the grid	0 €/kWh$_e$

Table 12 - Input variation for the algorithm CHP thermal-led experiment (summer)

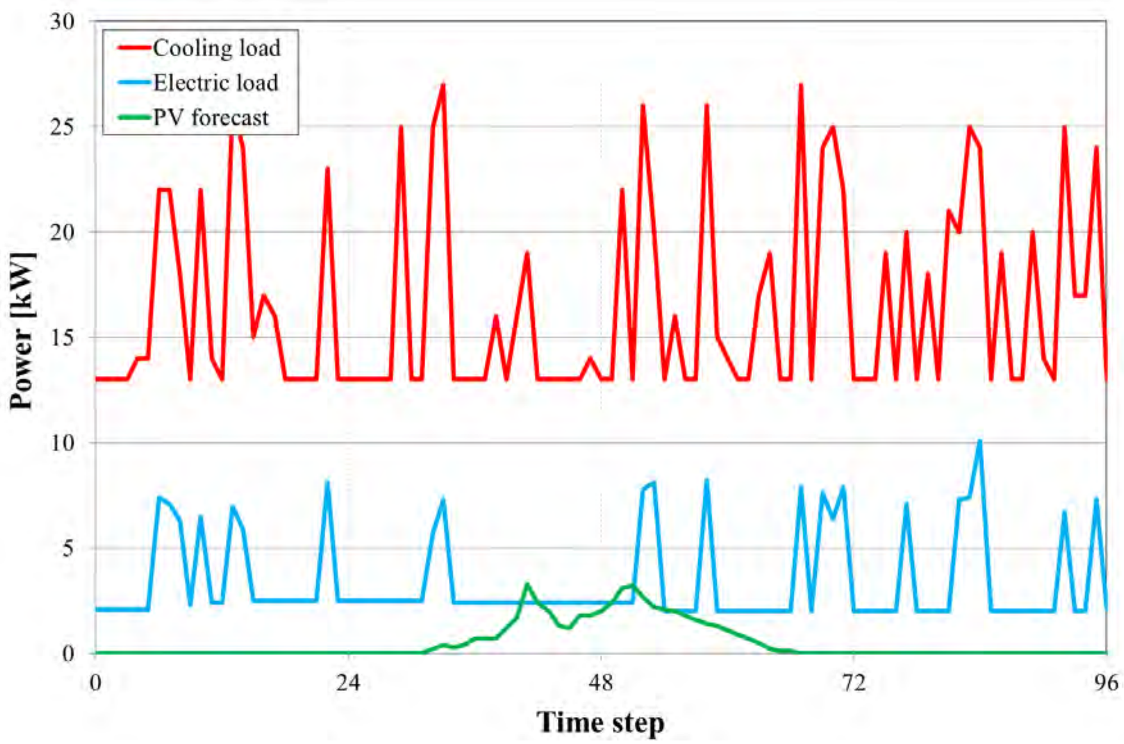


Figure 97 - Load curves for the algorithm CHP thermal-led experiment (summer)

Similarly to what previously done, the cooling load is randomly determined, with the constraint not to exceed the operational range of the absorption chiller. In addition, in order to prevent the electricity supply of the factory loads from the grid, the energy price, which is variable with an hourly frequency, is considered 1.5 times the actual one. The outputs of the 1st run of the algorithm are shown in Figure 98.

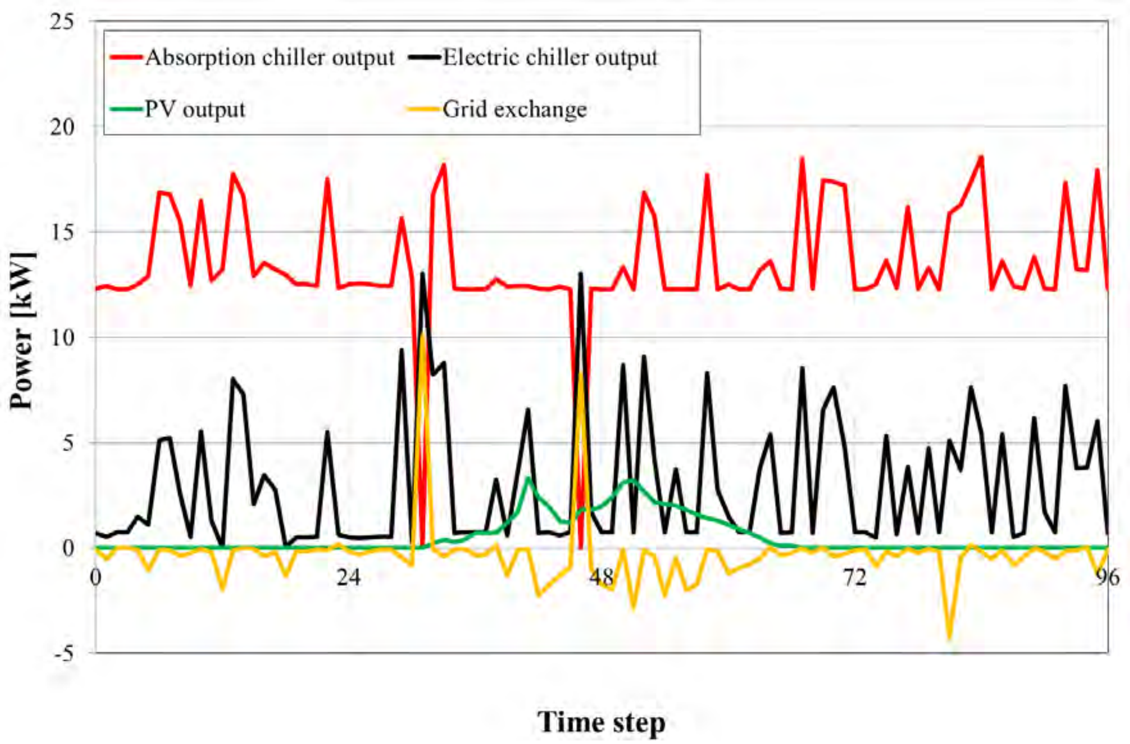


Figure 98 - Output for the algorithm CHP thermal-led experiment (summer, 1st run)

From a perusal of the figure, it is evident how the cooling loads are not completely satisfied by the absorption chiller, with a remarkable intervention of the electric chiller. Nevertheless, this result must not be interpreted as an error for the algorithm: indeed, the electricity for the auxiliary cooling unit is produced by the CHP, as testified by the analysis of the power exchange with the grid, which is in most of the cases negative (the power flow goes from the SU plant to the grid) or null, avoiding the external electricity supply: The result can thus be considered as if the plant has a "virtual" larger absorption chiller than the physical one, which is supplied by the electric output of the CHP. A similar result is confirmed by the 2nd run of the optimizer (Figure 99).

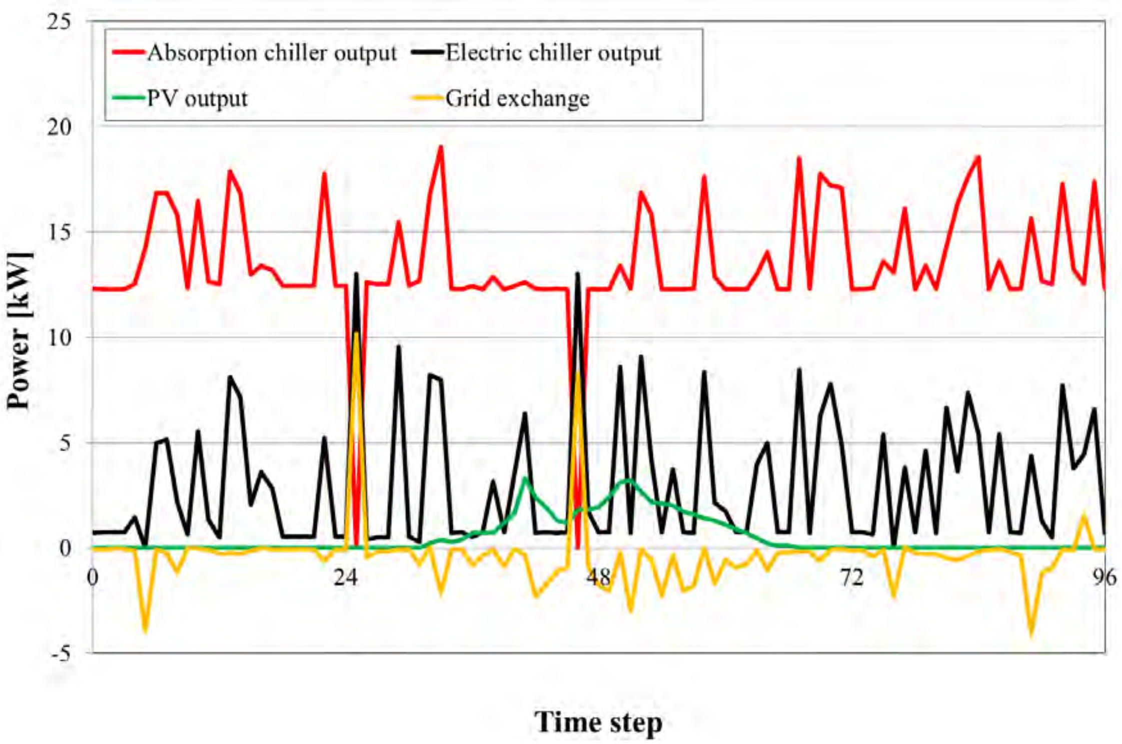


Figure 99 - Output for the algorithm CHP thermal-led experiment (summer, 2nd run)

When a cooling load exceeding the technical upper limit of the absorption chiller is considered, together with the possibility for the cooling load to be curtailed (Figure 100), the optimizer output results as in Figure 101.

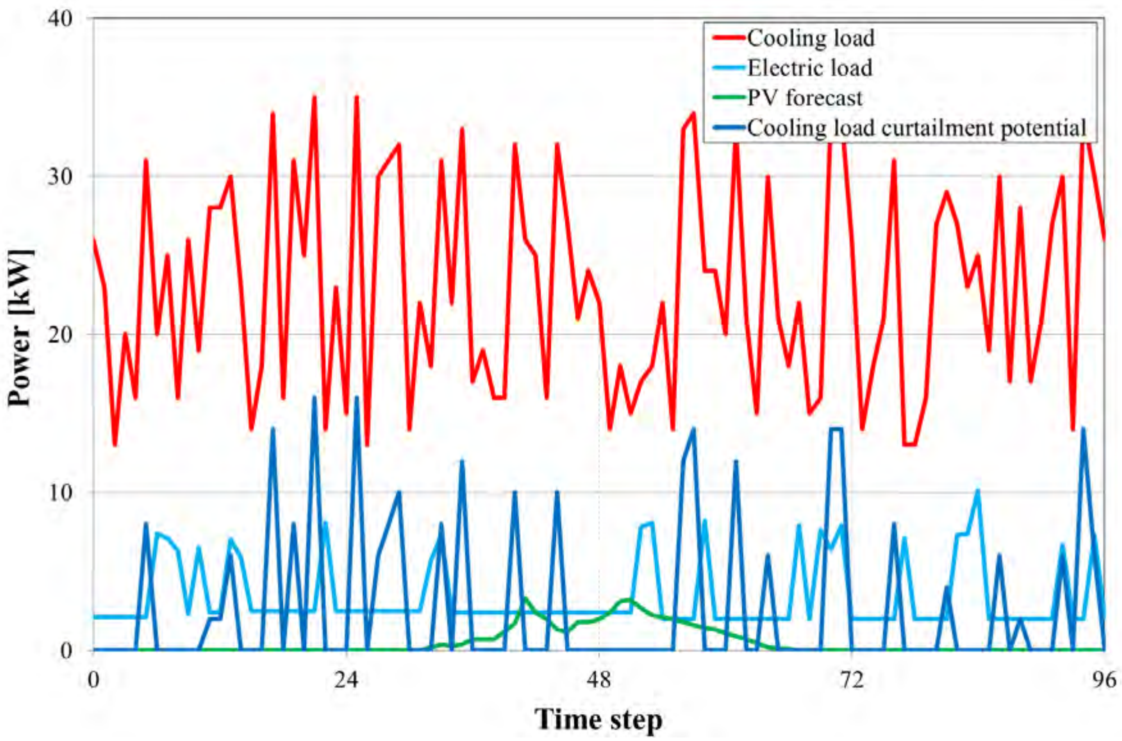


Figure 100 - Load curves for the algorithm CHP thermal-led with load curtailment experiment (summer)

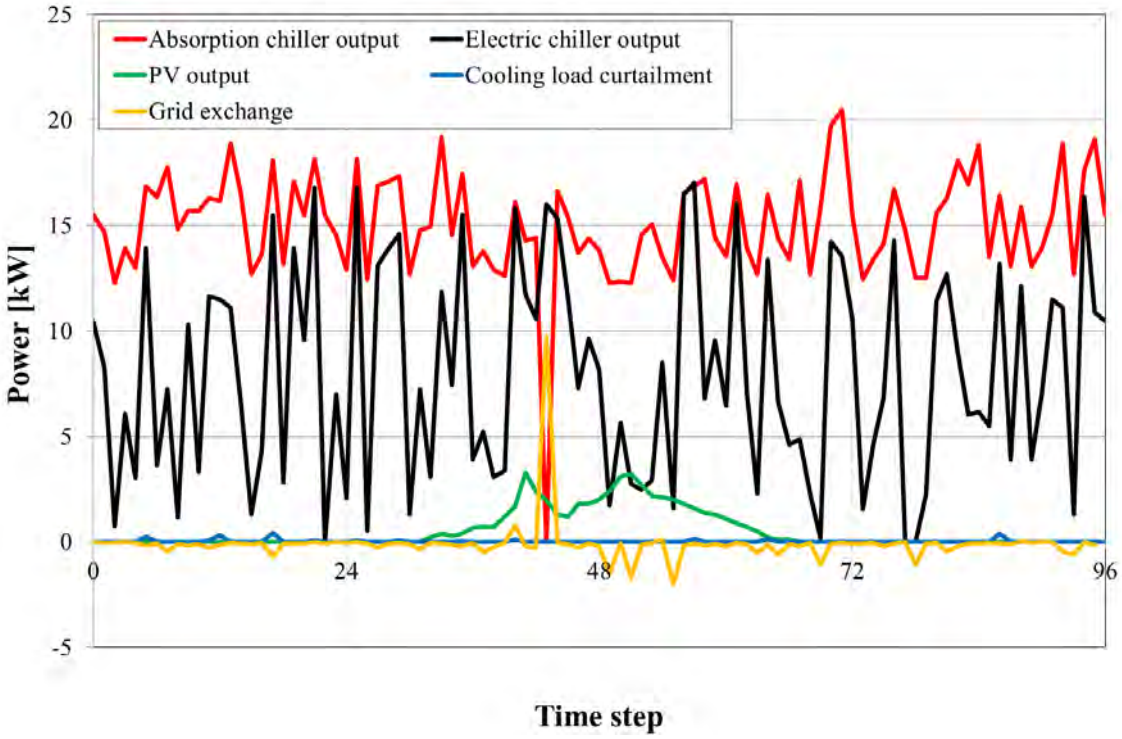


Figure 101 - Output for the algorithm CHP thermal-led with load curtailment experiment (summer, 1st run)

Also in this case, there is a sensible contribution of the electric chiller for the satisfaction of the cooling loads, even not negatively influencing the plant supply costs (the electricity exchange with the grid is in most cases negative or null), because its electricity input is produced by the CHP. The obtained result is substantially confirmed by the 2nd run of the optimization algorithm, as shown in Figure 102.

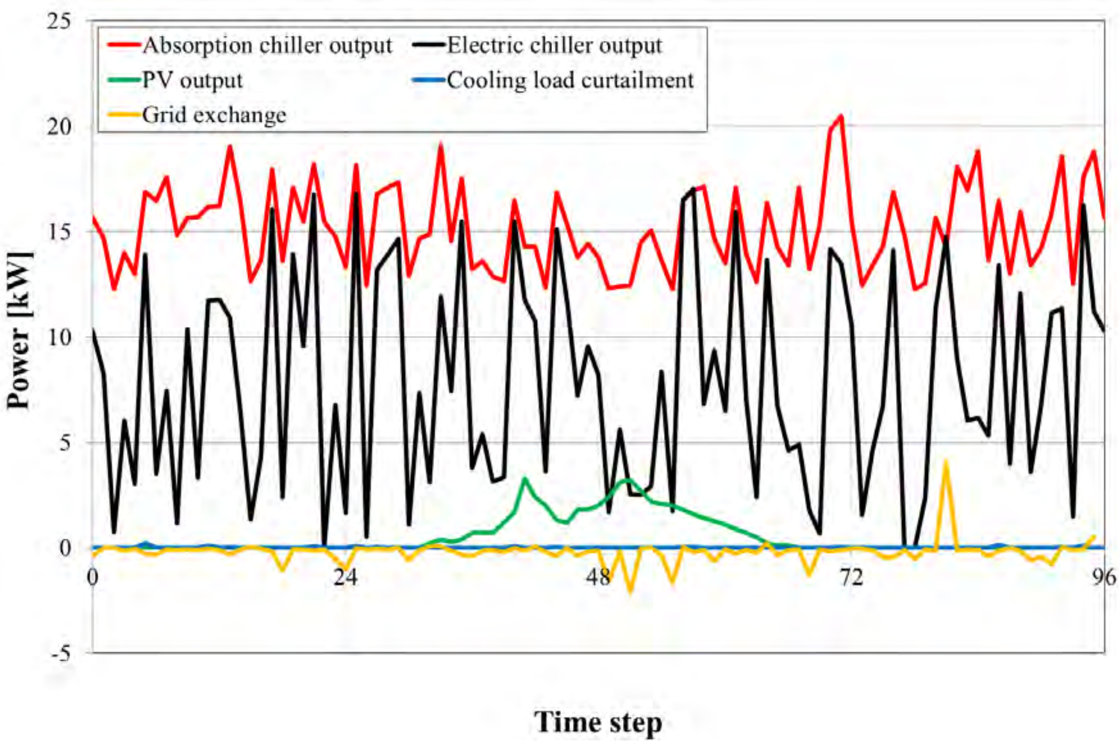


Figure 102 - Output for the algorithm CHP thermal-led with load curtailment experiment (summer, 2nd run)

After the thermal-led management trial from the optimization algorithm, the power-led output strategy of the CHP by means of the modification of some algorithm parameters is investigated. Thanks to the good results obtained with the previous experiments, only the "winter" configuration of the plant, including the possibility to curtail the electric loads, is considered. Both the electric and the heating load curves are randomly chosen, considering as constraints the technical operational limits of the CHP for the heating, and only the minimum power if considering the electricity output of the ICE (Figure 103). As before, the electric load curtailment potential is chosen as twice the value which allow the rated power output of the CHP.

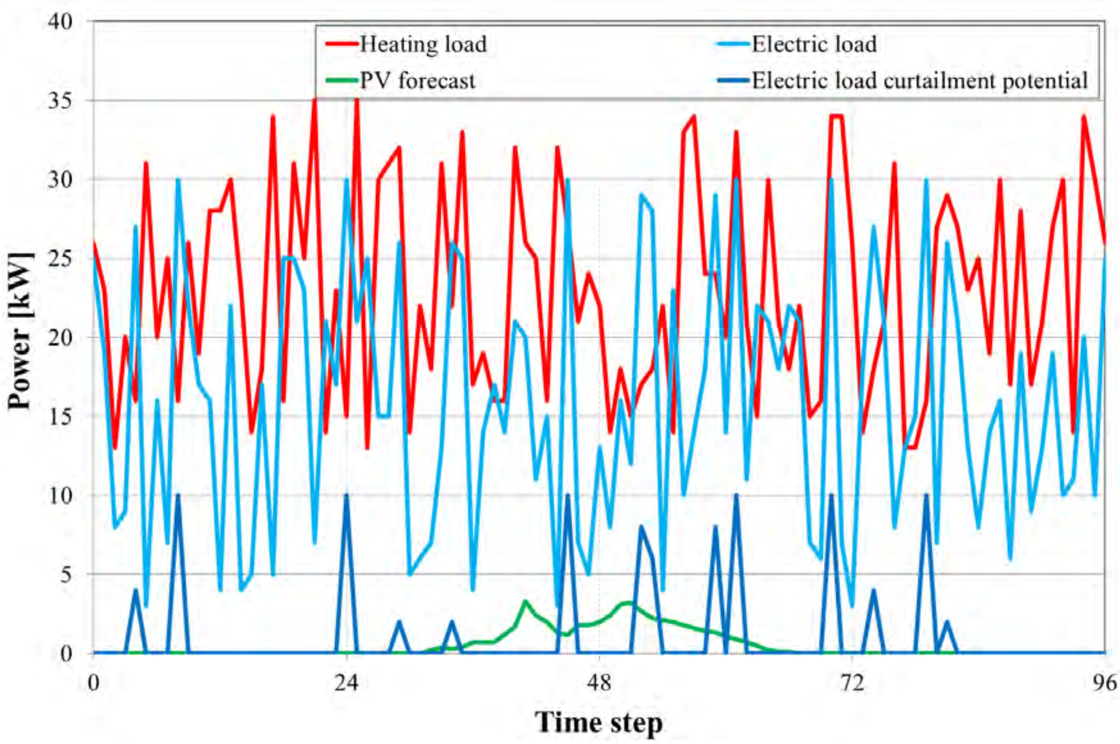


Figure 103 - Load curves for the algorithm CHP power-led with load curtailment experiment (winter)

In order to prevent the electricity supply by means of the purchase from the grid, the price of the electricity is considered as 1.5 times the actual one, with a cost fluctuation of hourly frequency. The other fixed relevant parameters changed respect to the real values are reported in .

Parameter	Value
Natural gas purchase cost (generation use)	0.4 €/Sm^3
Natural gas purchase cost (civil use)	0.4 €/Sm^3
Electricity selling cost to the grid	0 €/kWh_e
Electric load curtailment penalty	0.2 €/kWh_e

Table 13 - Input variation for the algorithm CHP power-led experiment (winter)

Figure 104 shows the results of the algorithm optimization.

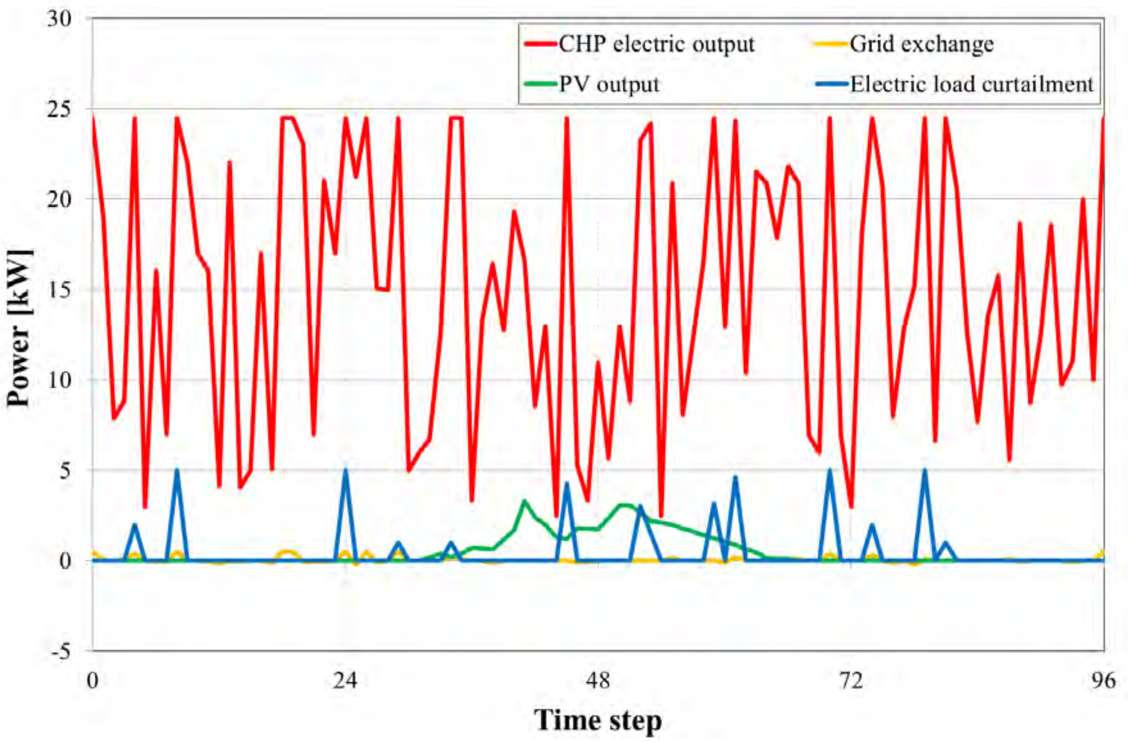


Figure 104 - Electric output for the algorithm CHP power-led with load curtailment experiment (winter, 1st run)

It is easy to see how the CHP schedule of the algorithm is specular to the electric load request, with some exceptions correspondent to the load curtailment when the electric load exceeds the ICE rated power and when the PV contributes to the loads supply: the energy exchange with the grid is nearly zero anytime. The heat production is shown in Figure 105. In this case the CHP production exceeds the load request: part of the heat is stored in the water tank until it comes to its upper temperature limit: above that energy level, the heat is no longer recovered and the thermal output is considered wasted.

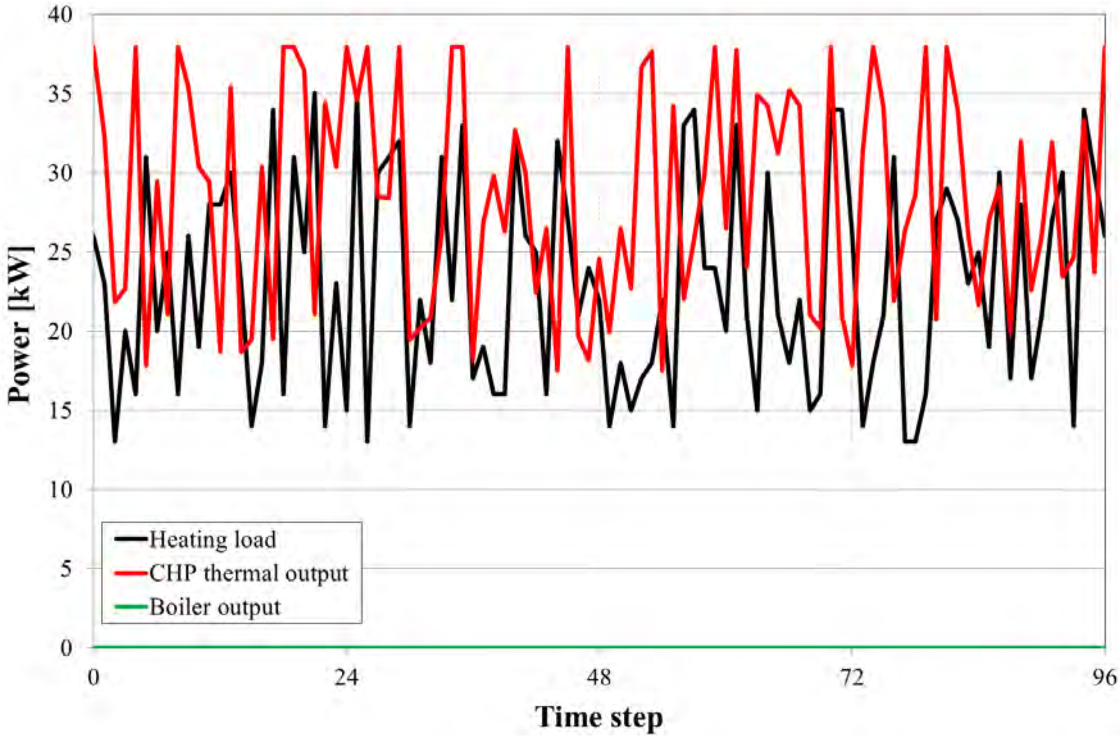


Figure 105 - Thermal output for the algorithm CHP power-led with load curtailment experiment (winter, 1^{st} run)

The presented trend is confirmed by the 2^{nd} run of the algorithm with the same input, with the CHP output following the electric load request (Figure 106).

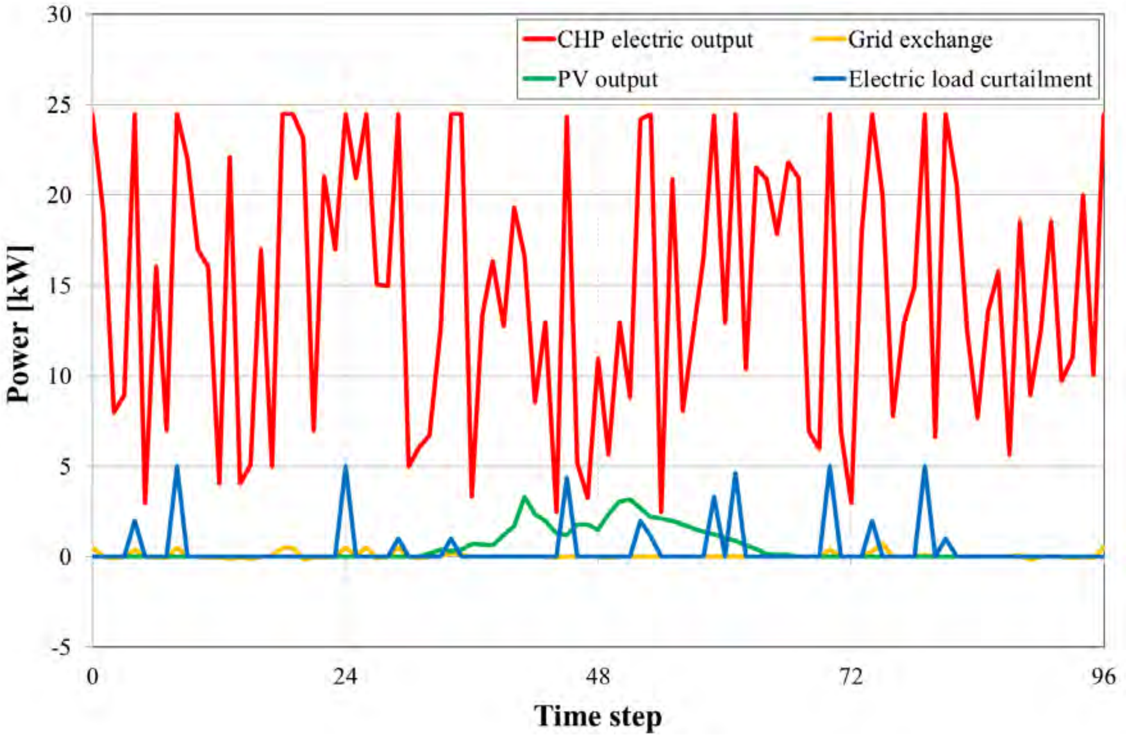


Figure 106 - Electric output for the algorithm CHP power-led with load curtailment experiment (winter, 2nd run)

As last, the input parameters of the optimization algorithm are modified to favor the Smart User plant to be supplied in a "conventional" manner, with the purchase of the electricity from the grid and the satisfaction of the thermal loads by means of the auxiliary devices (i.e. the gas boiler and the electric chiller).

Considering the "winter" configuration of the thermal plant, when the cooling request is null and the heat energy for room heating is needed, the modified input parameters are the price of the natural gas for both the CHP and the auxiliary boiler, and the selling price to the grid of the exceeding electricity produced by the ICE, as reported in . The electricity purchase price from the grid is not modified compared to the MGP values. In addition, no curtailment for the loads is considered.

Parameter	Value
Natural gas purchase cost (generation use)	0.6 €/Sm^3
Natural gas purchase cost (civil use)	0.2 €/Sm^3
Electricity selling cost to the grid	0 €/kWh$_e$

Table 14 - Input variation for the algorithm "conventional" experiment (winter)

As previously done, the loads curve are randomly chosen, with the constraints to lie in the operational range of the CHP ().

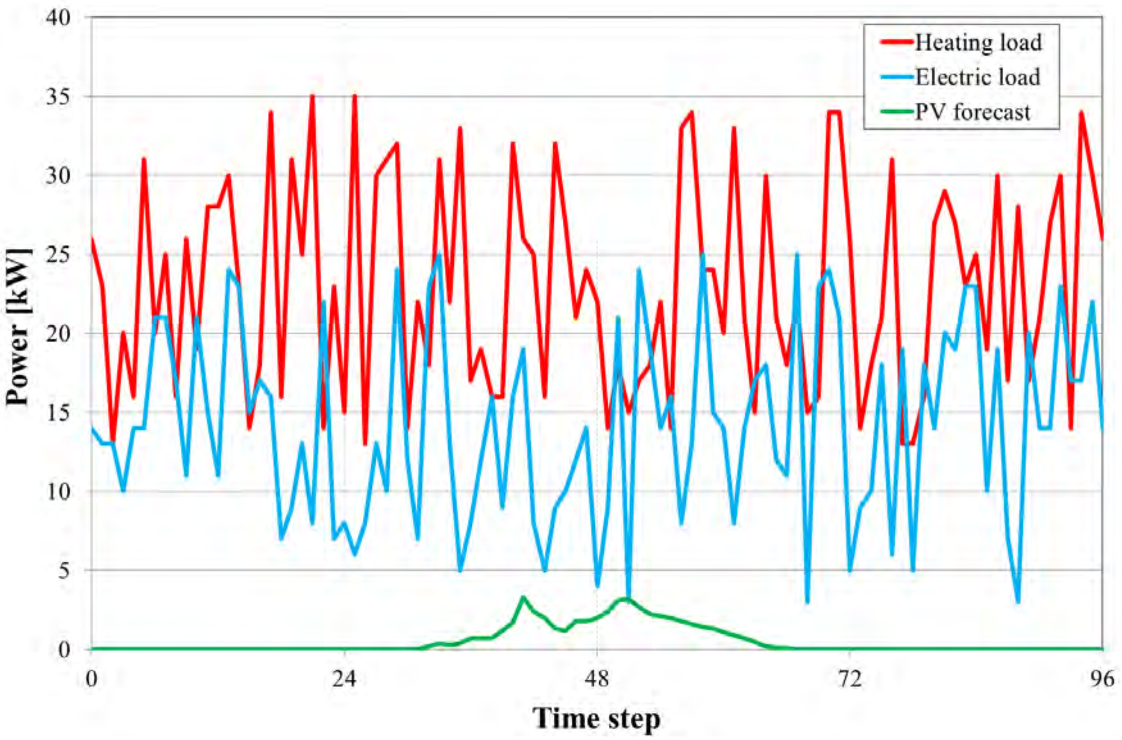


Figure 107 - Load curves for the algorithm "conventional" experiment (winter)

The schedule output of the optimization algorithm is shown in Figure 108.

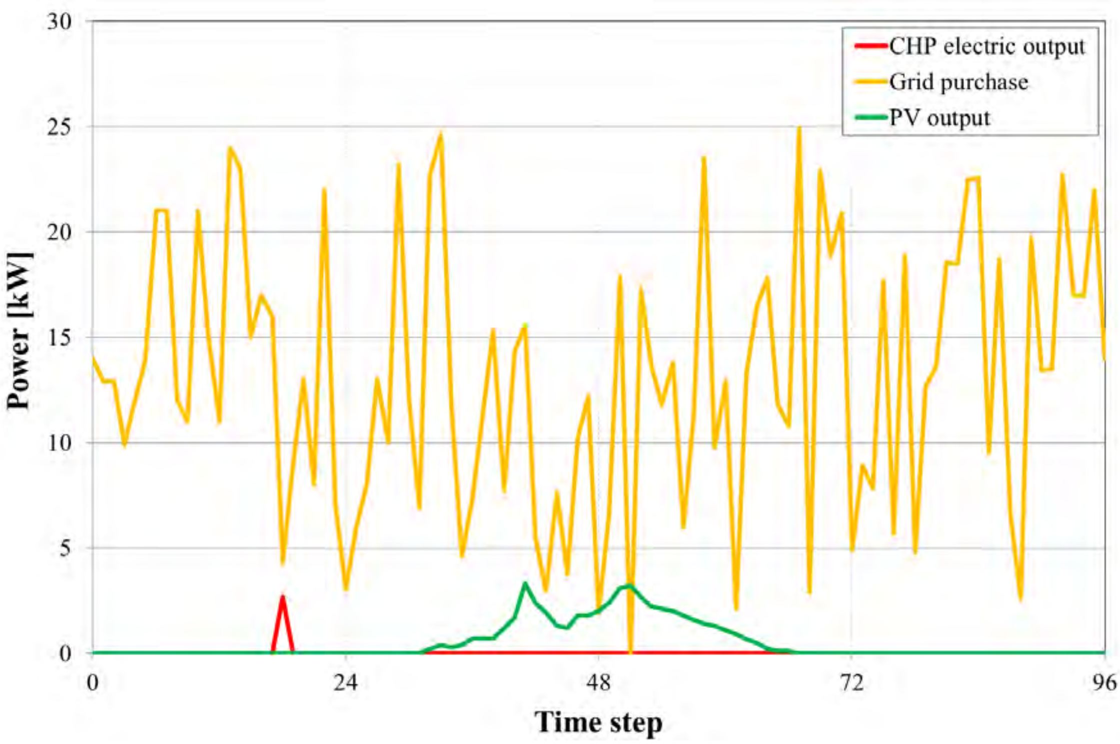


Figure 108 - Electric output for the algorithm “conventional” experiment (winter, 1st run)

From a perusal of the figure, it is evident how the CHP is continuously deactivated, with all the electric load request satisfied by the energy purchase from the external power grid. Of course, the same result is obtained for the heating load, completely supplied by the gas boiler (Figure 109).

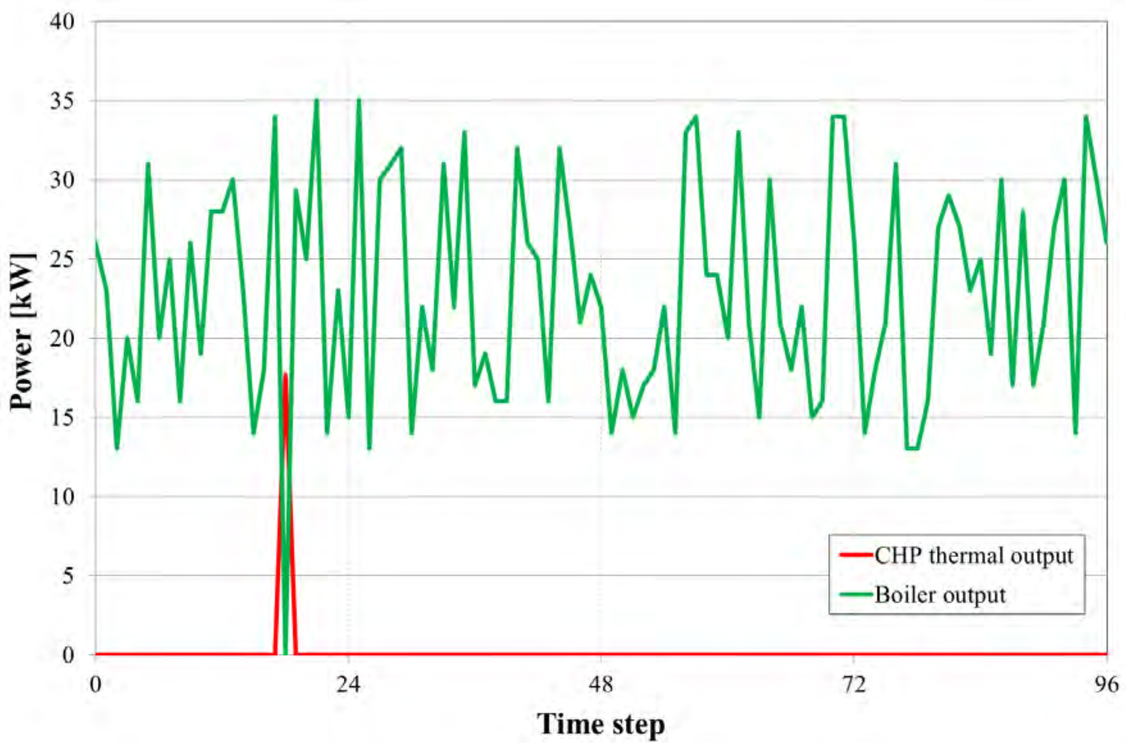


Figure 109 - Thermal output for the algorithm “conventional” experiment (winter, 1st run)

The presented results are very close to the output of the 2nd run of the optimizer with the same input parameters, confirming the robustness of the implemented algorithm (Figure 110 and Figure 111).

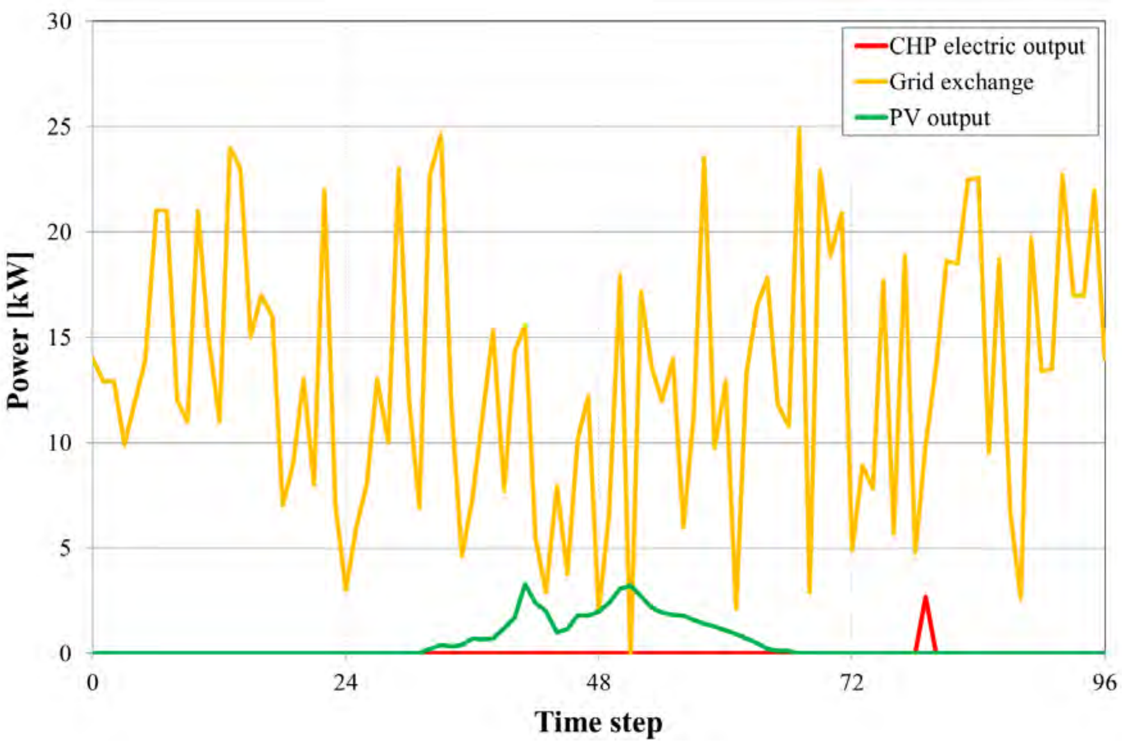


Figure 110 - Electric output for the algorithm "conventional" experiment (winter, 2nd run)

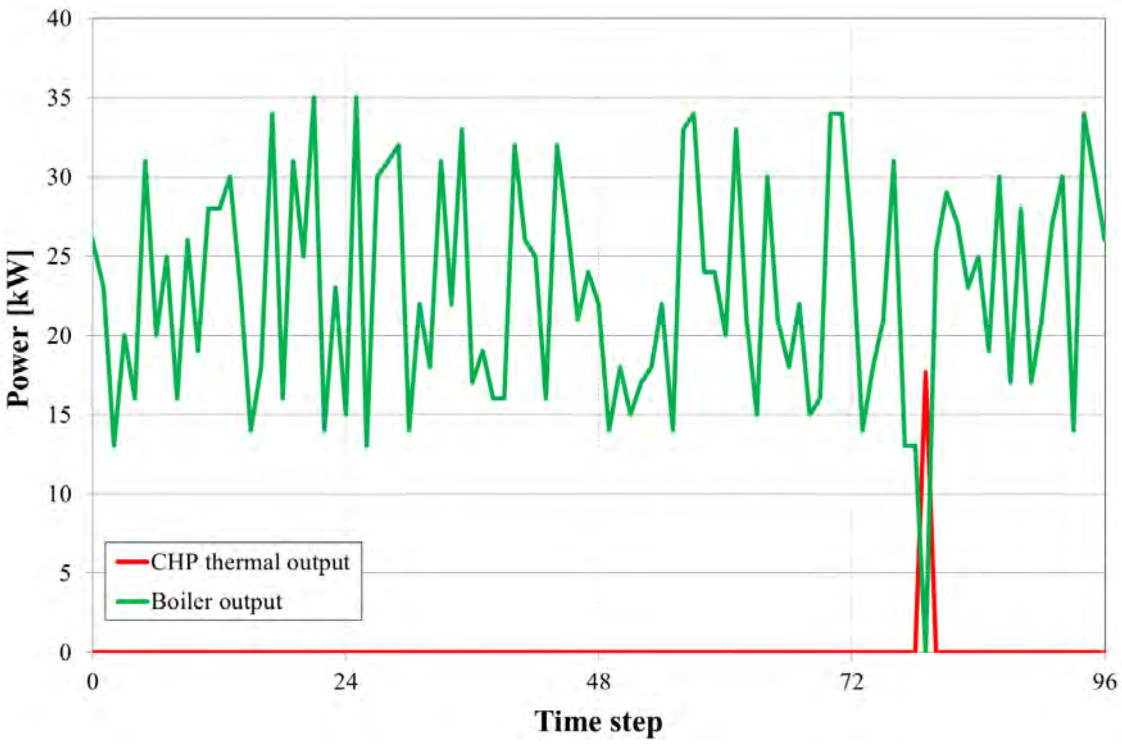


Figure 111 - Thermal output for the algorithm "conventional" experiment (winter, 2nd run)

A similar experiment is carried out considering the heating load as null and imposing a random curve for the cooling loads, as shown in .

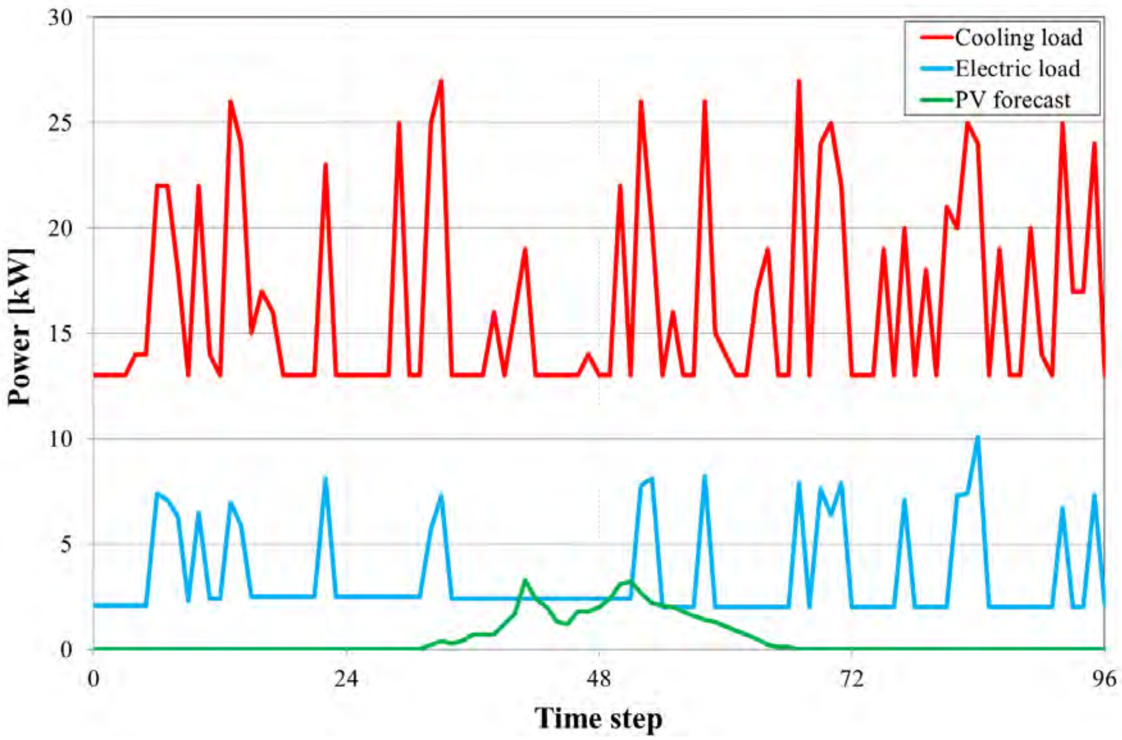


Figure 112 - Load curves for the algorithm “conventional” experiment (summer)

The scheduled optimizer results are shown in Figure 113.

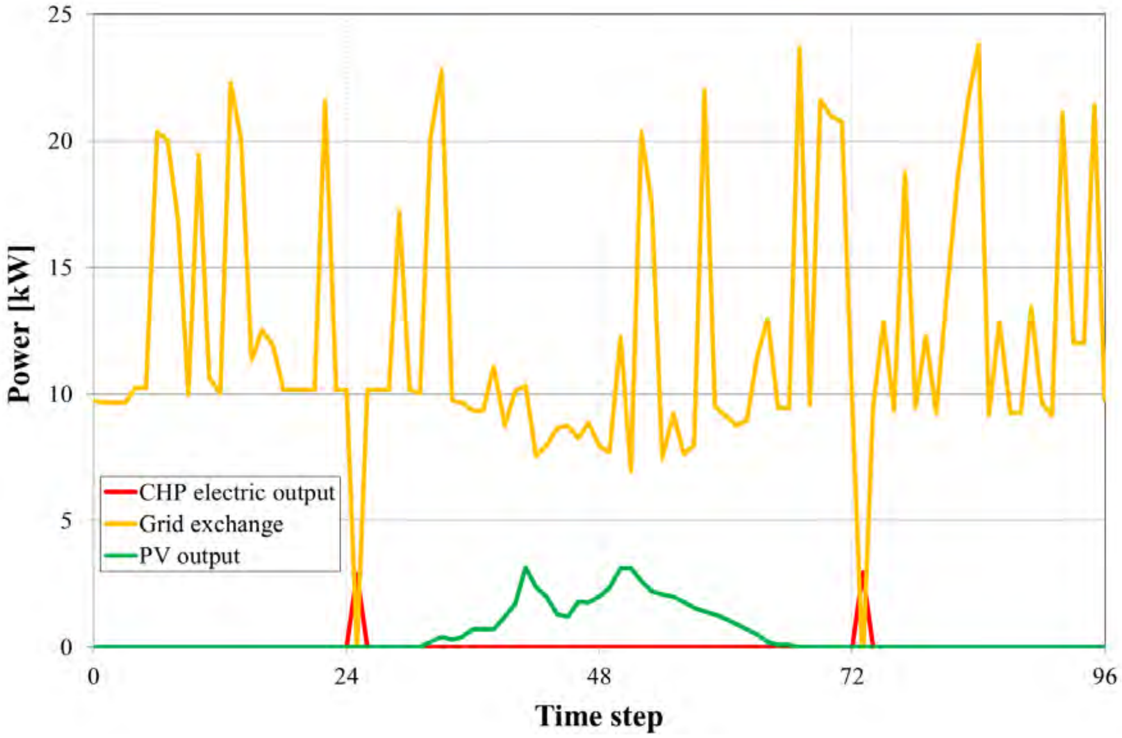


Figure 113 - Output for the algorithm “conventional” experiment (summer, 1st run)

Once again, the intervention of the CHP is mostly avoided, with the electric load supply carried out by the external power grid. As usual, the PV production is fully exploited by the plant. The robustness of the solution is confirmed by the analysis of the results of the 2nd run of the algorithm with the same input conditions (Figure 114), which shows a scheduling very close to one obtained by means of the 1st run of the optimization algorithm.

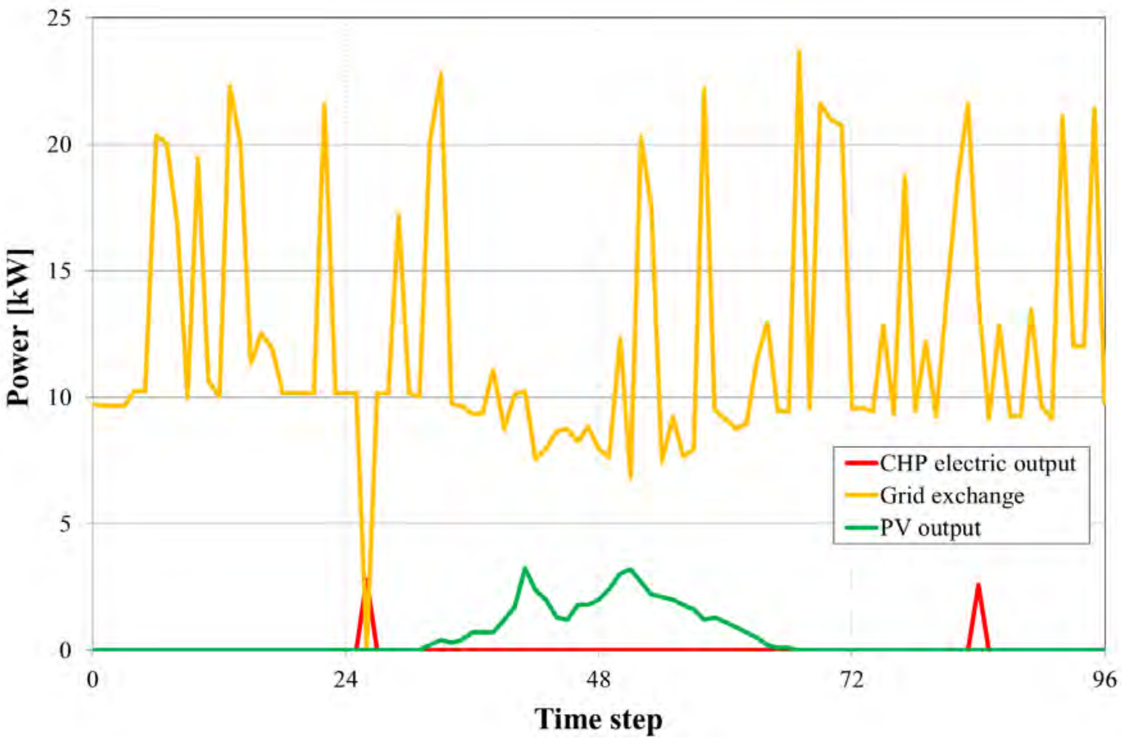


Figure 114 - Output for the algorithm "conventional" experiment (summer, 2nd run)

5.3.2 Design Of Experiments analysis

Before the implementation of the algorithm within the SCADA system for the experimental management on the real plant, a Design Of Experiments (DOE) analysis is carried out for the individuation of the most relevant economic parameters affecting the final result, in collaboration with the researcher of ENEL Ingegneria e Ricerca, being one of the partners of the research project.

First of all, the experimental field for the analysis of the most influent parameters on the objective function is defined: two configurations of the SU plant are considered in this case, corresponding to the "winter" and to the "summer" configuration. In both cases, some parameters are considered as independent, while some others are considered as fixed constraints, as summarized in Table 15 and Table 16, respectively for the "winter" and "summer" operations of the system.

WINTER		
Independent Parameter	**Variation range**	**Unit**
Electric loads	0 - 8.7 - 21.5 - 34.3 - 43	kW_e
Heating loads	0 - 4.1 - 10 - 16 - 20	kW_{th}
Cooling loads	0 - 20.3 - 50 - 79.7 - 100	kW_c
PV generation	0 - 2.8 - 6.8 - 10.8 - 13.6	kW_e
Wind turbine generation	0 - 0.6 - 1.5 - 2.4 - 3	kW_e
"Hot" storage temperature	60 - 65.1 - 72.5 - 79.9 - 85	°C
Electricity purchase price	0 - 0.06 - 0.14 - 0.22 - 0.27	€/kWh_e
Electricity selling price	0 - 0.04 - 0.10 - 0.16 - 0.20	€/kWh_e
Hypotheses	**Value**	**Unit**
"Cold" storage temperature	16	°C
Natural gas price	0.60	€/Sm^3
O&M costs	-	€

Table 15 - DOE parameters for SU "winter" configuration

SUMMER		
Independent Parameter	**Variation range**	**Unit**
Electric loads	0 - 8.7 - 21.5 - 34.3 - 43	kW_e
Cooling loads	0 - 20.3 - 50 - 79.7 - 100	kW_c
PV generation	0 - 2.8 - 6.8 - 10.8 - 13.6	kW_e
Wind turbine generation	0 - 0.6 - 1.5 - 2.4 - 3	kW_e
"Cold" storage temperature	4 - 6.4 - 10 - 13.6 - 16	°C
Electricity purchase price	0 - 0.06 - 0.14 - 0.22 - 0.27	€/kWh_e
Electricity selling price	0 - 0.04 - 0.10 - 0.16 - 0.20	€/kWh_e
Hypotheses	**Value**	**Unit**
"Hot" storage temperature	40	°C
Heating loads	0	kW_{th}
Natural gas price	0.60	€/Sm^3
O&M costs	-	€

Table 16 - DOE parameters for SU "summer" configuration

The loads values are selected on the basis of the measured minimum and maximum values during the data acquisition, while RESs generators production vary from their rated power output value to their switching off. The temperature range of the storages is set considering the technical limits of the back-up generators, and when their use is not considered in the analyzed configuration, the temperature is fixed in order to achieve the null energy value.

The regression model chosen for the DOE analysis is a quadratic polynomial model with interactions, allowing to understand the effect of the parameter variation on the response variable and on the others, and characterized by the equation:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i,j=1, i\neq j}^{n} b_{ij} x_i x_j$$

where *b* coefficients represent the regression factors which are to be estimated by running the optimization algorithm for a single time-step.

The parameters constituting the variables to the model are summarized in Table 17 and Table 18, respectively for the “winter” and the “summer” SU configuration.

WINTER	
Variable	**Parameter**
x_1	Electric loads
x_2	Heating loads
x_3	Cooling loads
x_4	PV generation
x_5	Electricity purchase price
x_6	“Hot” storage temperature
x_7	Wind turbine generation
x_8	Electricity selling price

Table 17 - DOE variables for SU “winter” configuration

SUMMER	
Variable	**Parameter**
x_1	Electric loads
x_3	Cooling loads

x_4	PV generation
x_5	Electricity purchase price
x_6	“Cold” storage temperature
x_7	Wind turbine generation
x_8	Electricity selling price

Table 18 - DOE variables for SU “summer” configuration

The experimental design of the DOE is structured as a Central Composite Circumscribed (CCC) one, which allow to the coefficient list to be determined in accordance with the considered variables, with each point of the design corresponding to an experiment, and considering 5 values level per each variable (Figure 115).

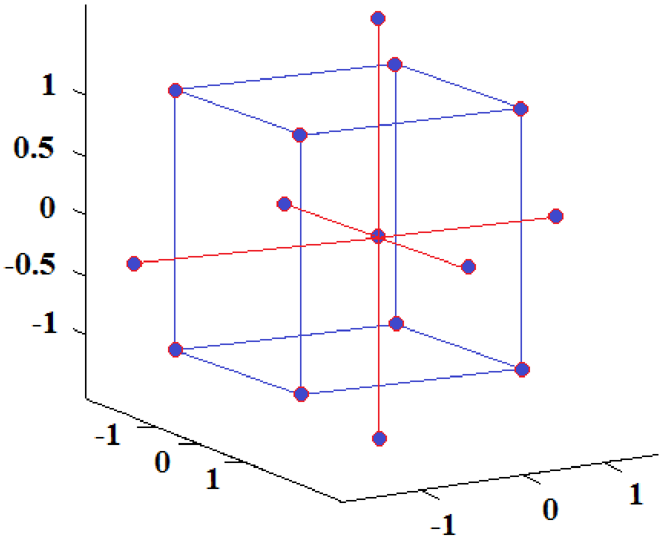


Figure 115 - Central Composite Circumscribed design

This typology of DOE allows a significant decrease in the experimental test which have to be performed to characterize the influence of each variable in the global cost function: e.g. considering the SU “winter” configuration, the needed experiments for the 5 levels of the 8 indicated variables would be 5^8 = 390,625; with this technique the number of test which have to be carried out is reduced to 275.

The coefficient estimation obtained by the experimental tests performed with the “winter” configuration are shown in Figure 116.

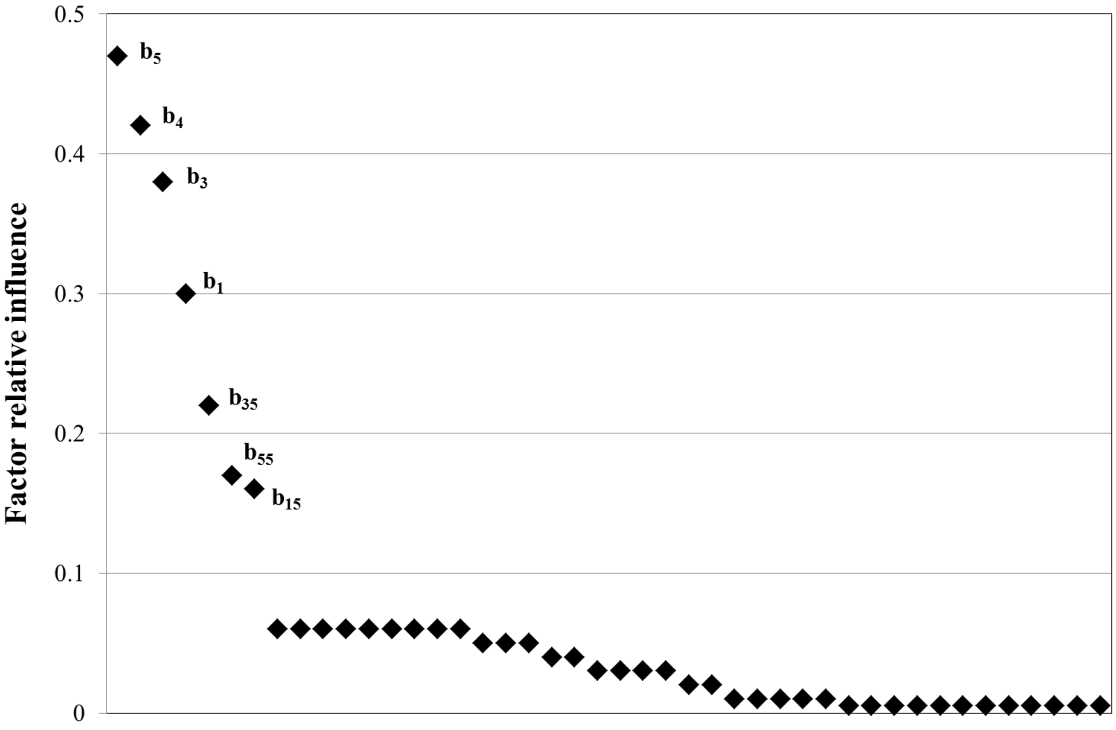


Figure 116 - Results of DOE analysis for SU "winter" configuration

The higher the value, the higher the influence of the parameter on the cost objective function. From the perusal of , it can be seen how the most relevant parameter for the hypothesized configuration results to be the electricity purchase cost, followed in decreasing order by the cooling loads, the PV plant production, and the electric loads amount; other parameters show a limited influence on the final result. The detail of the analysis, in terms of *b* coefficient values, is reported in Table 19.

WINTER	
Coefficient	**Value**
b_5	0.4726
b_3	0.4187
b_4	0.3845
b_1	0.2992
b_{35}	0.2274
b_{55}	0.1686
b_{15}	0.1578

Table 19 - Most influent *b* coefficient values for SU “winter” configuration

On the basis of the results of the DOE analysis on the **“winter” configuration**, the cost function can be approximated by the reduced model defined by the equation:

$$COST = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7 + b_8 x_8 + b_{15} x_1 x_5 + b_{35} x_3 x_5 + b_{55} x_5^2$$

The comparison between the tests and the equation is shown in Figure 117.

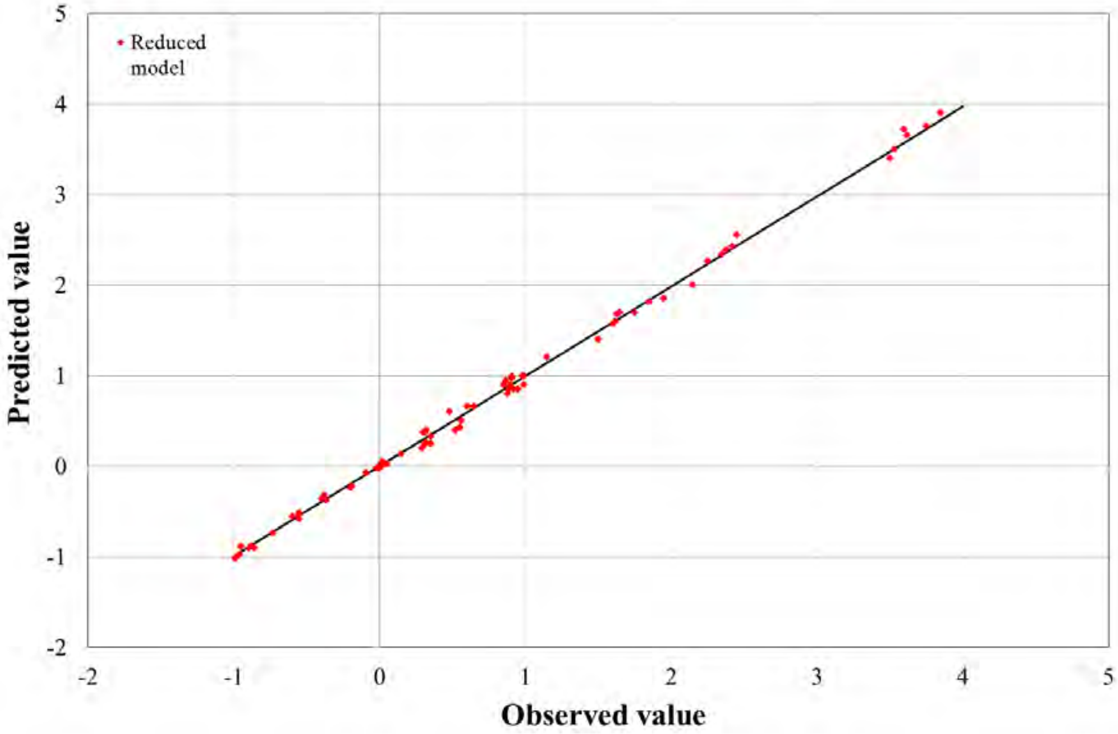


Figure 117 - Comparison between the DOE experiments in “winter” and the obtained reduced model

By the analysis of the results, it follows that there is a linear dependency of the SU costs on both the electric loads and the PV production, whilst it results non-linear on the electricity purchase price, as shown in Figure 118.

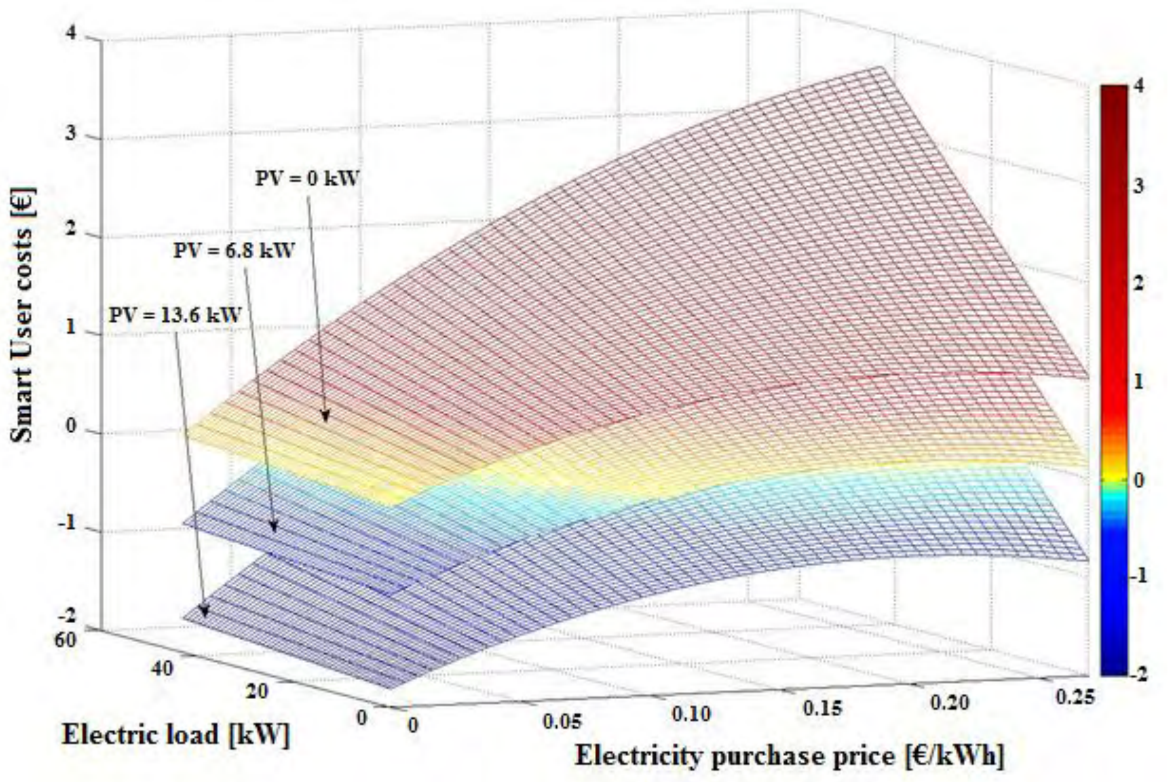


Figure 118 - SU cost dependency on the electric loads, PV production, and electricity purchase price (winter)

As expected, the higher the electricity purchase price, the higher the influence of the electric loads on the plant cost result. In addition, due to the high value of the "Conto Energia" incentive, there is a remarkably high influence of the PV electric production on the final result: e.g. given the cooling loads of 50 kW_c, the SU plant has a null or negative supply costs (earnings) when the PV plant production is at its rated power (Figure 119).

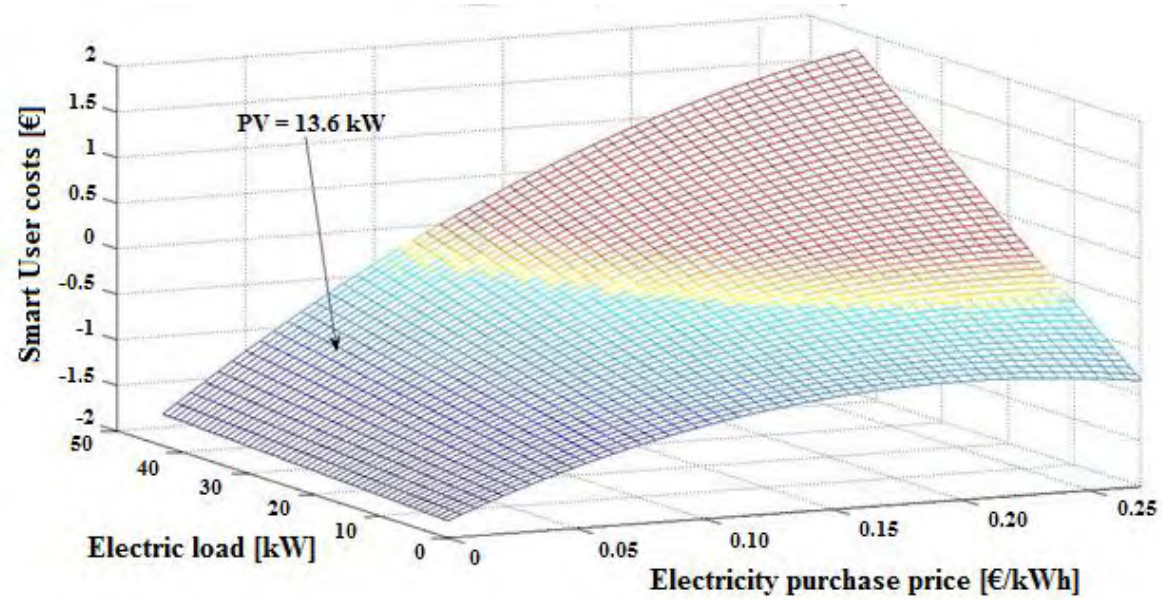


Figure 119 - Economic plant result with PV @ rated power output (winter)

If considering the case in which the cooling loads are in a range between their full power and half of that, the SU plant result is positive (no earnings) independently by the PV production or the electric loads values, as shown in Figure 120.

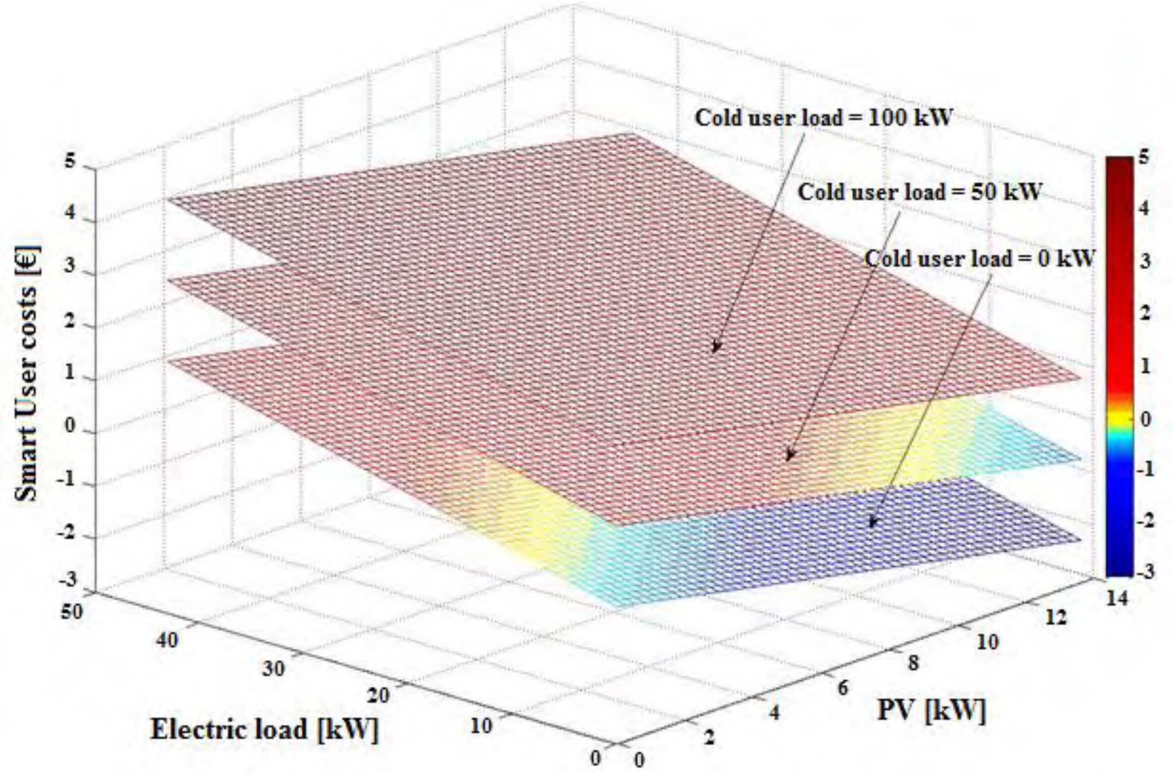


Figure 120 - SU cost dependency on the electric loads, PV production, and cooling loads (winter)

When considering the results of the DOE analysis during **“summer” operations** of the SU plant, a slightly different trend can be individuated: in this case, the most relevant cost parameter results to be the PV production, followed in decreasing order by the electric loads, the electricity purchase price, the temperature of the “cold” storage, and the cooling loads, as shown in Figure 121 and detailed in Table 20.

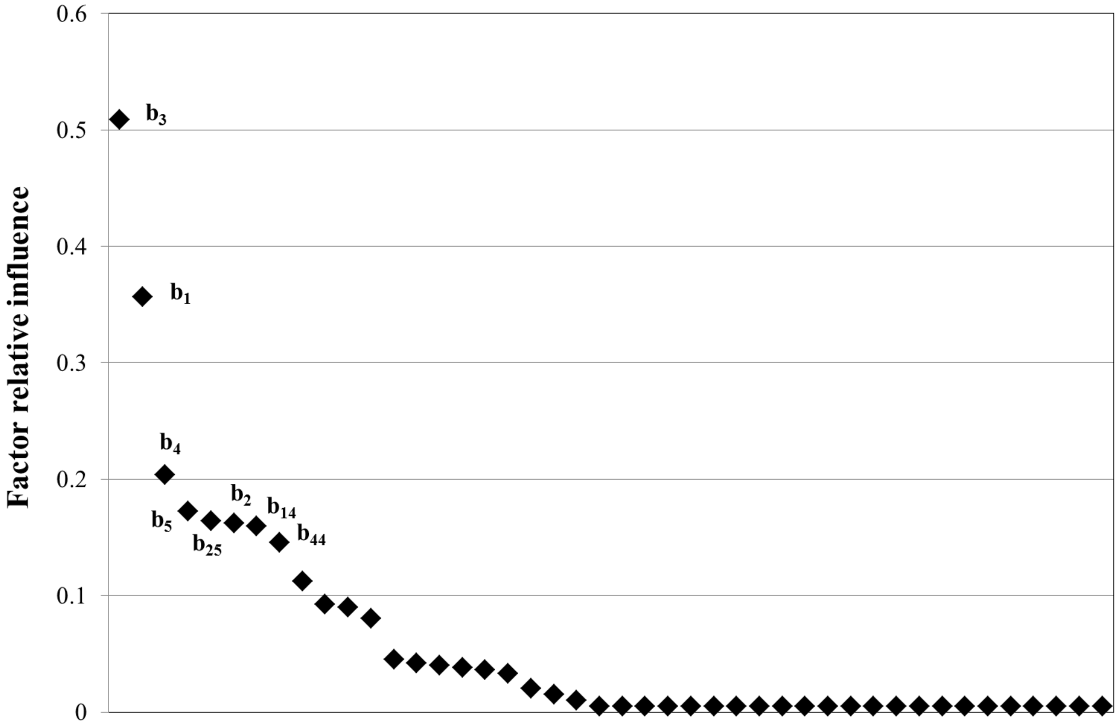


Figure 121 - Results of DOE analysis on SU "summer" configuration

SUMMER	
Coefficient	**Value**
b_3	0.5087
b_1	0.3569
b_4	0.2040
b_5	0.1723
b_{25}	0.1643
b_2	0.1623
b_{14}	0.1597
b_{44}	0.1455

Table 20 - Most influent *b* coefficient values for SU “summer” configuration

On the basis of these results, the reduced function cost can be written as:

$$COST = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7 + b_{14} x_1 x_4 + b_{25} x_2 x_5 + b_{44} x_4^2$$

The comparison between the test data and the reduced function is shown in Figure 122, where the scarce prediction capability is evident.

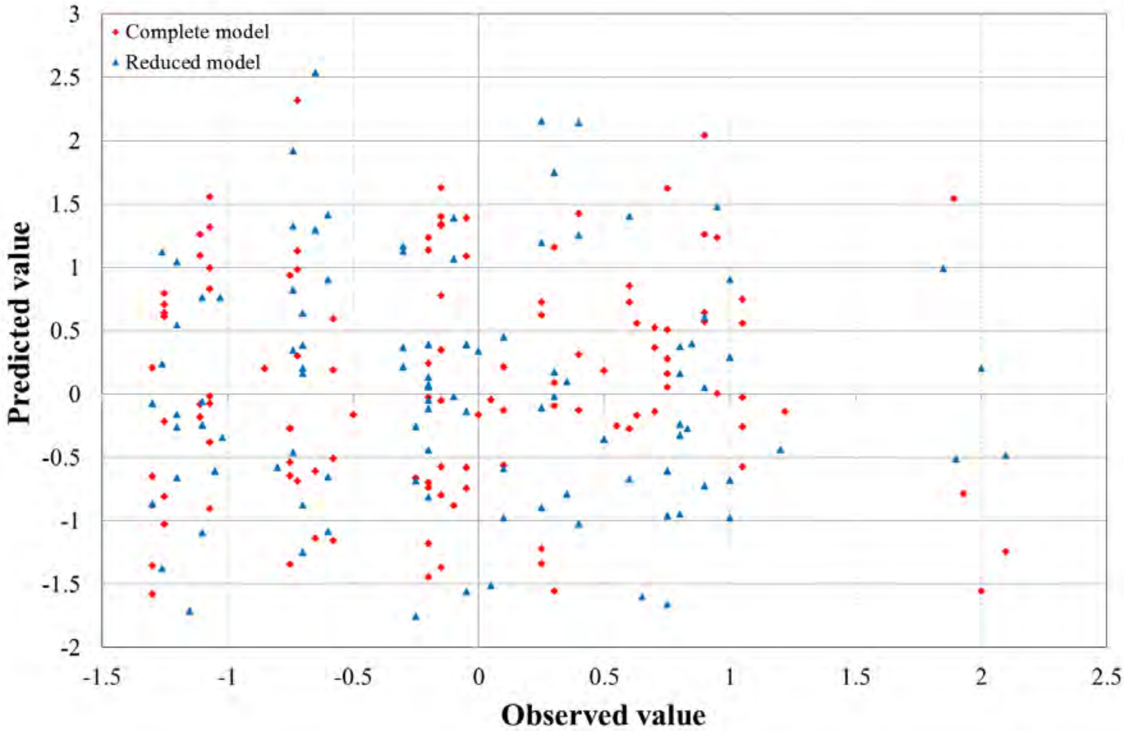


Figure 122 - Comparison between the DOE experiments in "summer" and the obtained reduced model

The main reason of the mismatching between experiments and prediction is due to the fact that the non-linear dependence of the costs by the electricity purchase price is not correctly represented by the quadratic term. The introduction of a cubic term for the correlation of the electricity price with the cost function shows a better result, as reported in Figure 123.

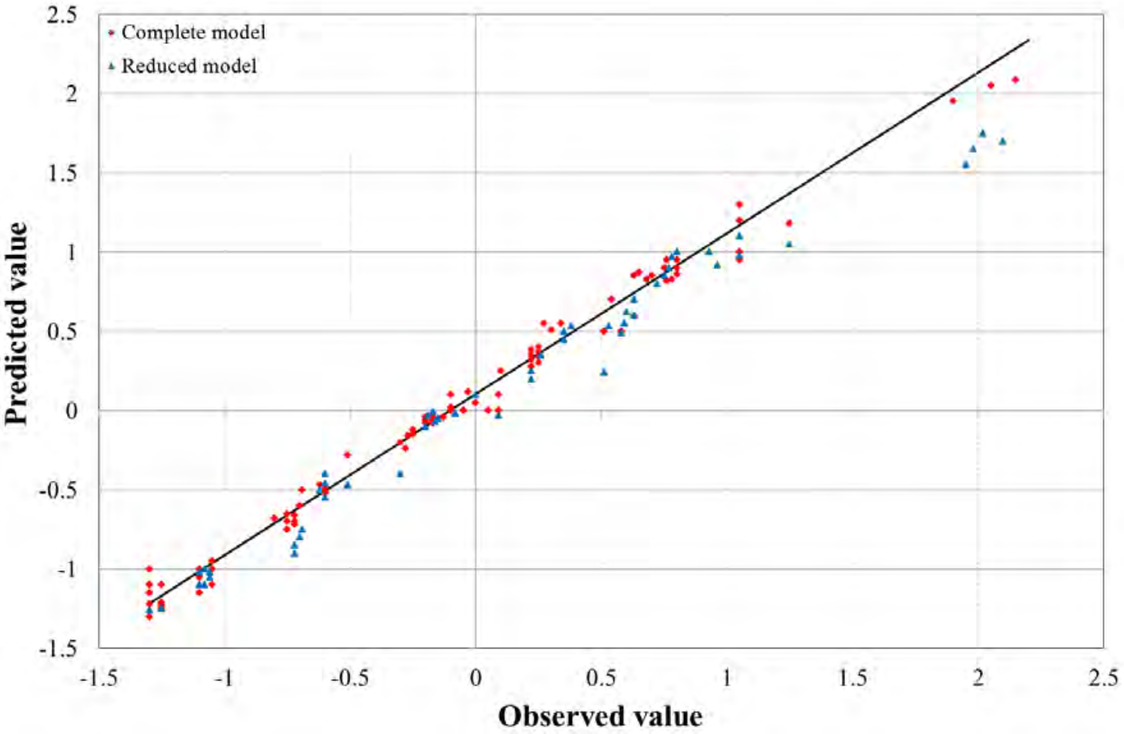


Figure 123 - Comparison between the DOE experiments in "summer" and the obtained reduced model with the cubic term for the electricity purchase price

The correspondent cost equation for the reduced model can be written as:

$$COST = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7 + b_{14} x_1 x_4 + b_{25} x_2 x_5 + b_8 x_4^3$$

The tests show a linear dependency of the cost function on the electric loads and the PV production, and a non-linear dependency on the electricity purchase price; in addition, an interdependence between the electric loads and the electricity price can be easily found, as expected (Figure 124).

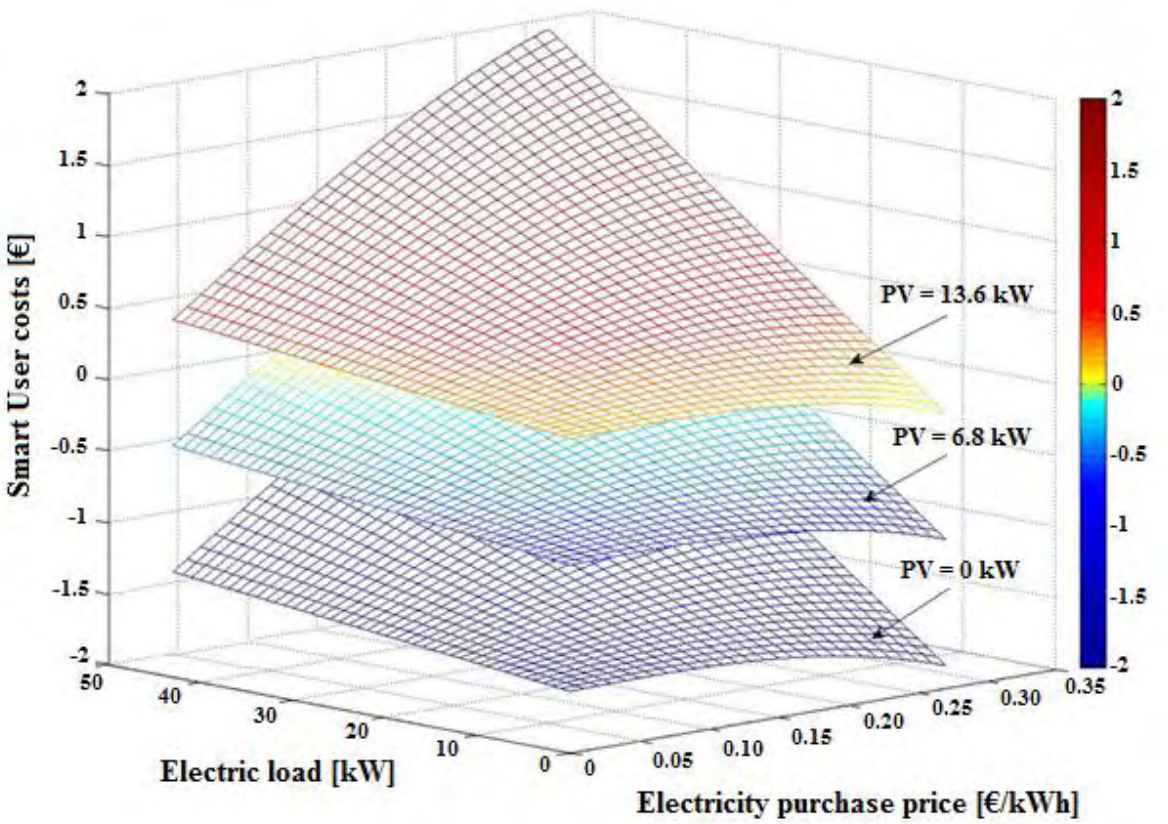


Figure 124 - SU cost dependency on the electric loads, PV production, and electricity purchase price (summer)

The cross-correlation between the electricity purchase price and the electric loads is relevant, especially when both values are relatively high, as shown in Figure 125.

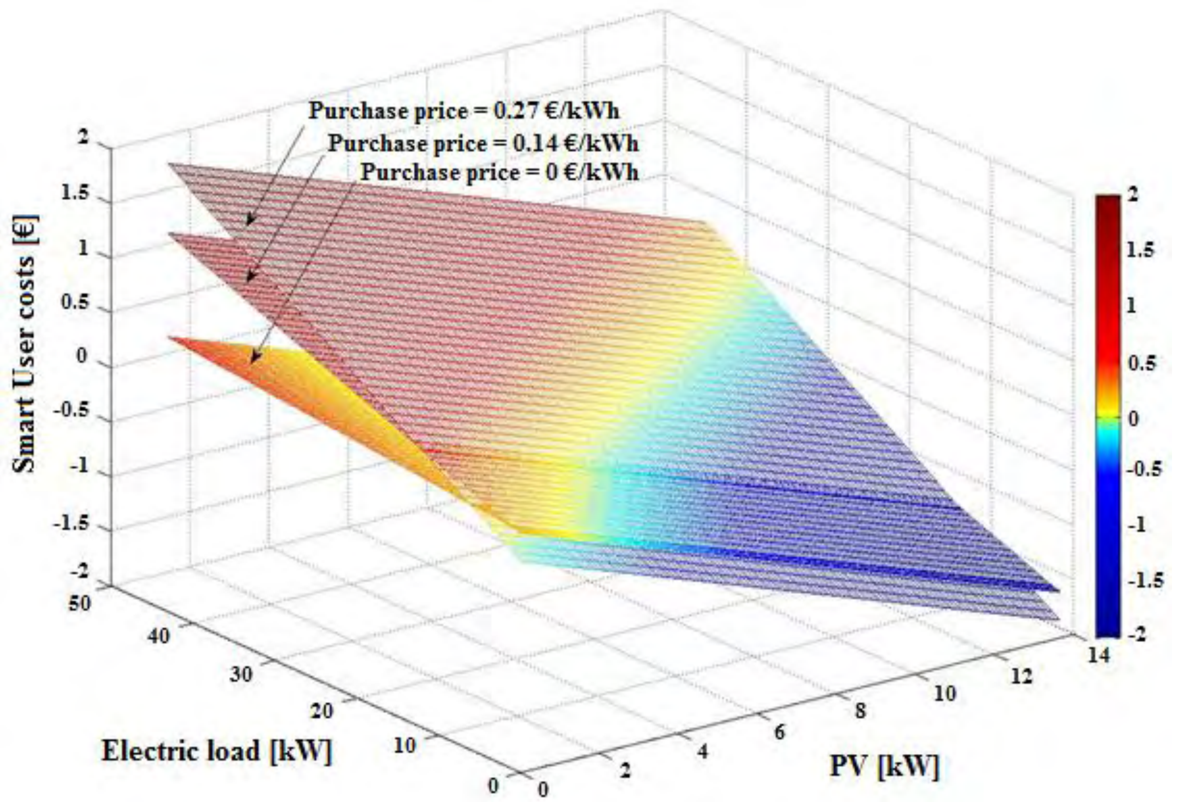


Figure 125 - SU cost dependency on the electric loads, PV production, and electric loads (summer)

The SU system costs also present a linear dependency on the cooling loads and the “cold” storage temperature, whilst a non-linear dependency on the electricity purchase price is experienced (Figure 126).

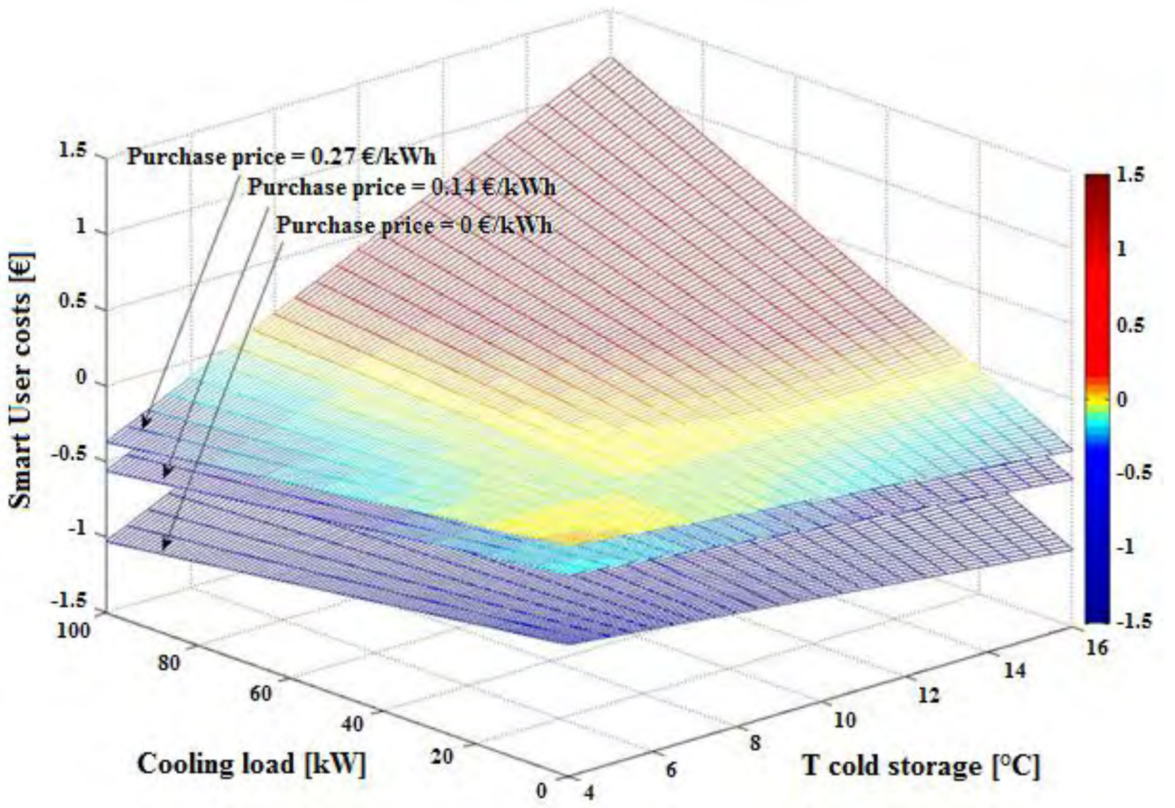


Figure 126 - SU cost dependency on the cooling loads, "cold" storage temperature, and electricity purchase price (winter)

In case of high cooling loads, the cost result of the SU system is heavily affected by the "cold" storage temperature: the lower it is, the lower is the cost supply, thanks to the energy recovered for free in the considered time-step. Conversely, when the cooling loads are relatively low, the final result is slightly affected by the initial storage energy level.

5.4 Experimental calibration of the equipment parameters

After the installation of the plant and of the SCADA monitoring system and before the implementation of the GA within it, on the basis of the field data all the performance of the generators have been measured and analyzed, in order to correctly calibrate in the algorithm the parameters characterizing the pieces of equipment.0

5.4.1 CHP

The cogeneration unit performance curve has been characterized by comparing the heating power and the electric power production.

The experimental results are reported in Figure 127, together with the CHP performance declared by the producer and the curves approximating the experimental data. The considered measured data for the analysis are selected considering both high and low ambient temperatures, in order to avoid estimation errors due to seasonal weather conditions.

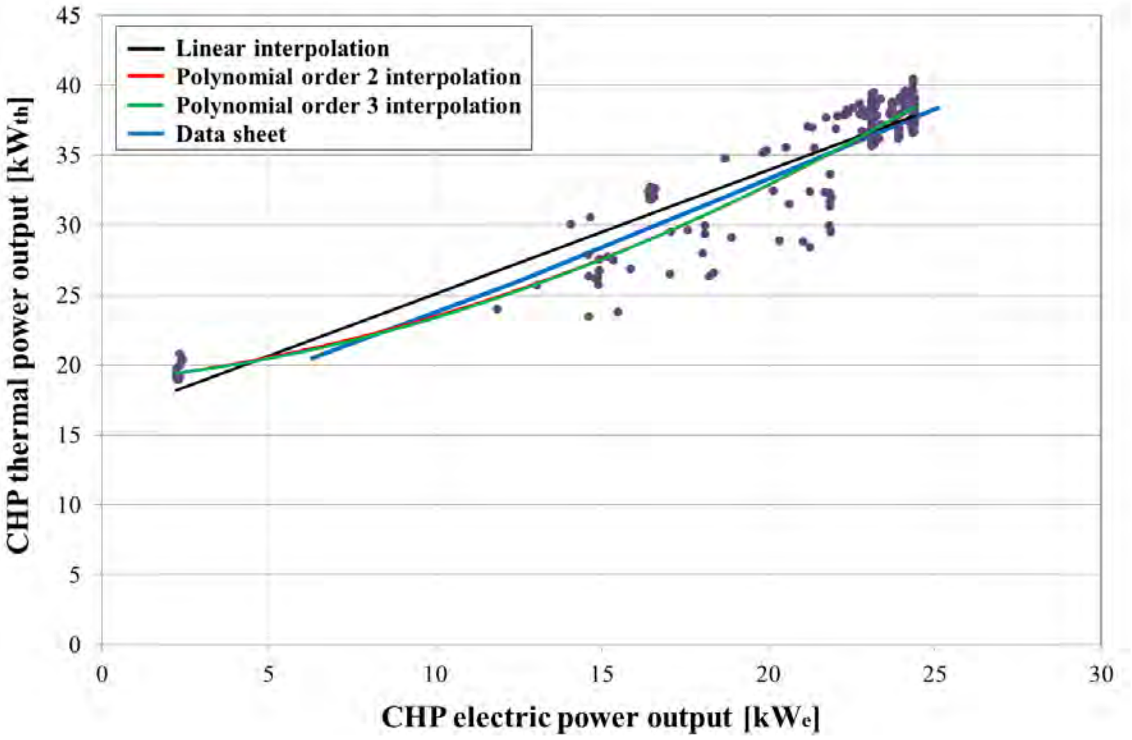


Figure 127 - CHP performance experimental data, approximation curves, and data sheet values

From a perusal of Figure 127, the data sheet parameters are similar to the measured performance, and very poor correction of the parameters has been carried out. The interpolation curves presented in the figure show how the linear approximation (black) and both the polynomial functions (red and green) bring to similar performance estimation, especially these latter two are overlapped in all the operative CHP range. As a consequence of all these considerations, the chose approximation curve for the CHP performance is the polynomial of order 3, whose equation can be written as:

$$P_{th,CHP} = 18.8990 + 0.1692 \cdot P_{e,CHP} + 0.0292 \cdot P_{e,CHP}^2 - 0.0001 \cdot P_{e,CHP}^3$$

In a similar fashion, the ICE consumption characteristic can be estimated, by comparing the electrical output with the gas consumption measured by the smart gas meter. The result of the acquisition campaign is shown in Figure 128.

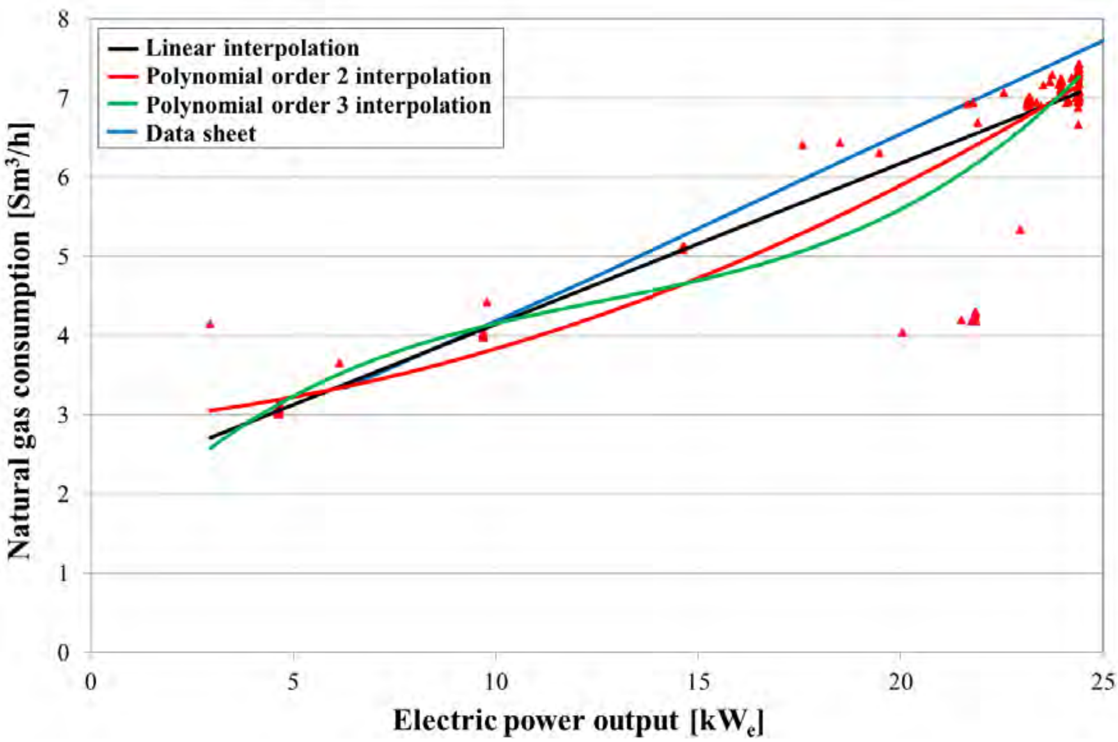


Figure 128 - CHP consumption experimental data, approximation curves, and data sheet values

The measured performance are compared with the data sheet values, and also the linear and polynomial approximation curves are shown. Data sheet performance are given by the producer in terms of total input power: for allowing the comparison in terms of gas consumption, a LHV of 34,600 kJ/Sm^3 for the natural gas is considered. The comparison between the experimental measurements and the fitting curves shows how both the polynomial of order 2 and 3 seem to approximate with insufficient precision the measurements: the order 2 polynomial seem to under-estimate the ICE consumptions, being lower also than the data sheet curve, while the order 3 polynomial appears to match with a good accordance the gas consumptions for the lowest power output of the engine, but remarkably under-estimate the gas consumptions when the CHP load is large. The linear approximation shows the best according with the experimental measurements and the producer data sheet values, for these reason is the approximation considered within the algorithm estimations. The equation of the adopted line can be written as:

$$GAS = 2.1093 + 0.2034 \cdot P_{e,CHP}$$

5.4.2 Absorption chiller

The characterization of the performance of the absorption chiller requires the knowledge of three critical parameters: the heating power supplied from the CHP, the temperature of the hot water flow from the CHP, and the temperature of the cooling water flow coming from the cooling tower dedicated to this piece of equipment. In particular this latter parameter results the most critical one: by the analysis of the experimental measurements, the performance of the absorption chiller does not have a monotone behavior with the temperature variation, which can be explained only considering the internal operation performed by the absorber. Indeed, when the cooling water temperature is too low (and, in any case over 18 °C, temperature under which the absorption chiller is automatically switched off for security reasons), the efficiency of the chiller, in terms of COP, is poor due to the high portion of Lithium Bromide evaporating in the solution with water; on the contrary, when the temperature of the water coming from the cooling tower is relatively high (indicatively over 24 °C), the process efficiency is decreased because the solution is too rich in Lithium Bromide. An efficient way for keeping this temperature within an acceptable range, and thus improving the chiller efficiency, is the realization of a by-pass system which allow to throttle the water passing through the cooling tower (Figure 129), with the temperature output driving the opening of the three-way valve. In addition to that, also the thermo-regulation of the cooling tower fan operation would help to achieve this purpose.

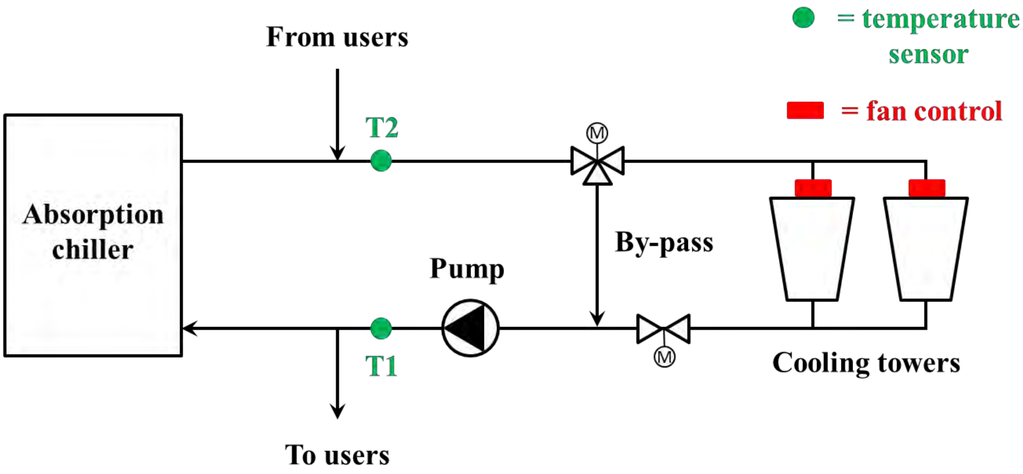


Figure 129 - Cooling tower-absorption chiller optimal layout

Unfortunately, these interventions could not be carried out, also due to the presence of two cooling towers in parallel which must also satisfy some cooling users, whose performance could be badly affected by such layout. For this reason, any attempt to characterize the performance of the chiller failed. Indeed, no coherent behavior cannot be identified, as shown in Figure 130, where the COP of the absorber is reported considering the same condition in terms of power and temperature of the water flow from the CHP.

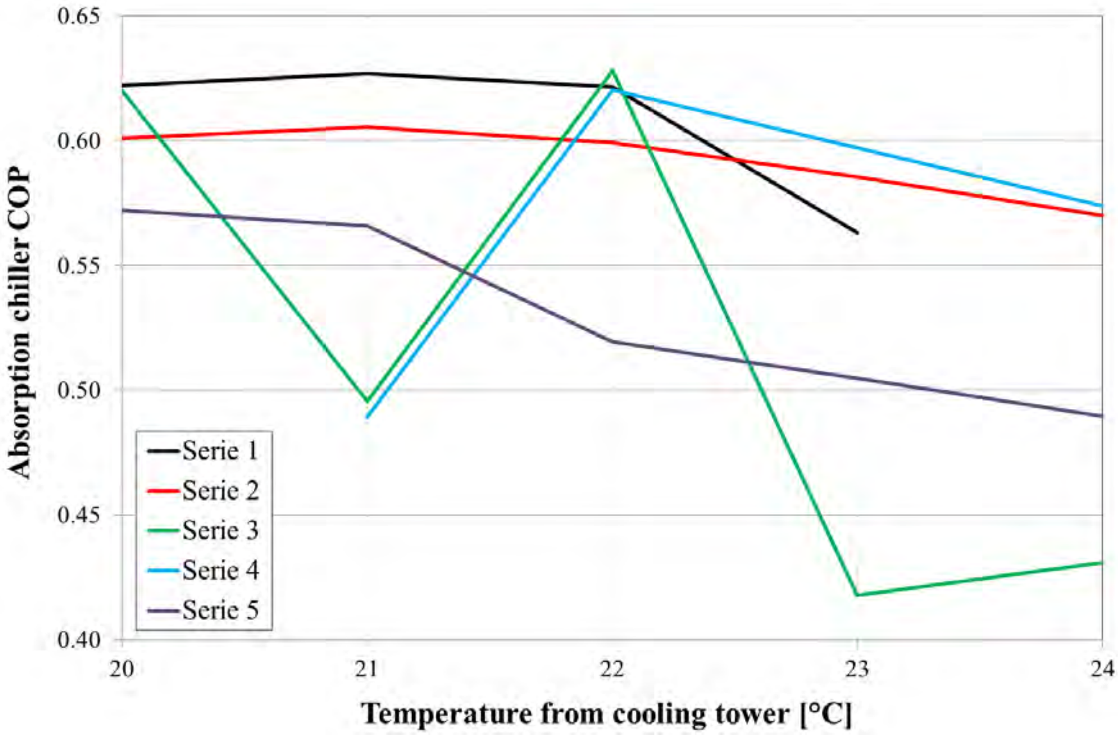


Figure 130 - Absorption chiller COP measured data (fixed P and T from the CHP)

For the exposed reason, the performance parameters considered in the algorithm are the values in data sheet of the producer: in Figure 131 the cooling output of the absorber is shown on the basis of the temperatures of both the hot water flow from the CHP and the cooling water flow from the towers.

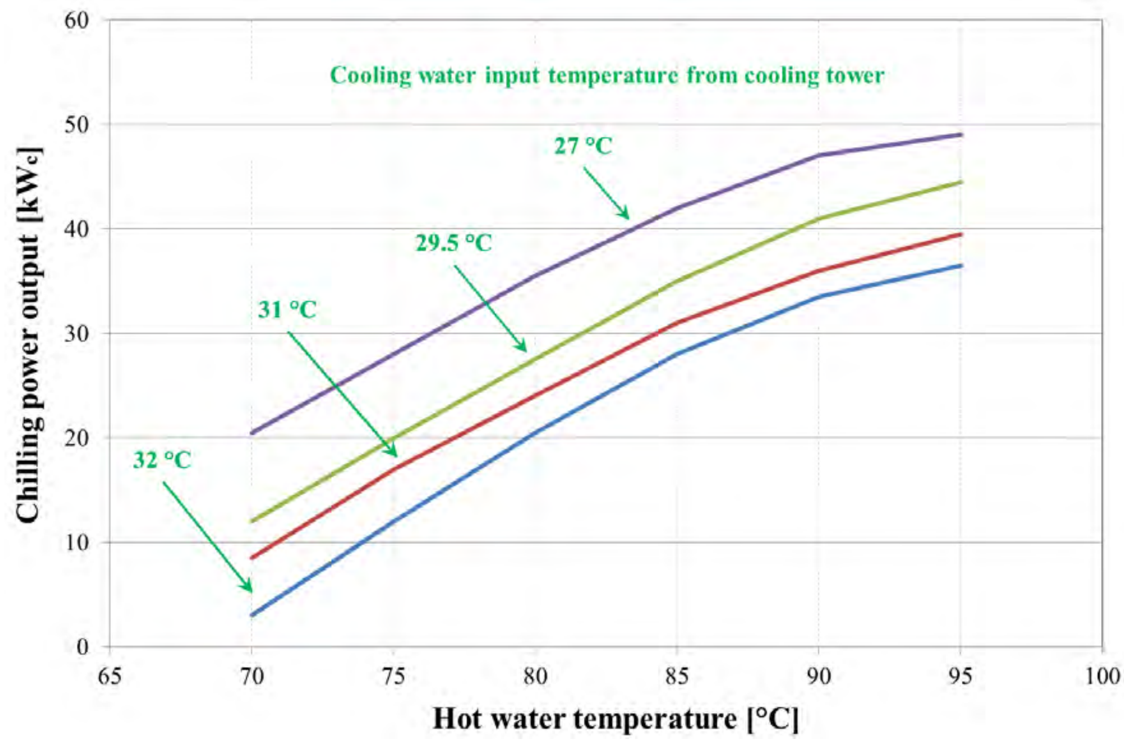


Figure 131 - Absorber cooling output vs. hot and cooling water temperatures [147]

The heating power required by the absorption chiller when the hot water and the cooling water temperatures are changed is reported in Figure 132.

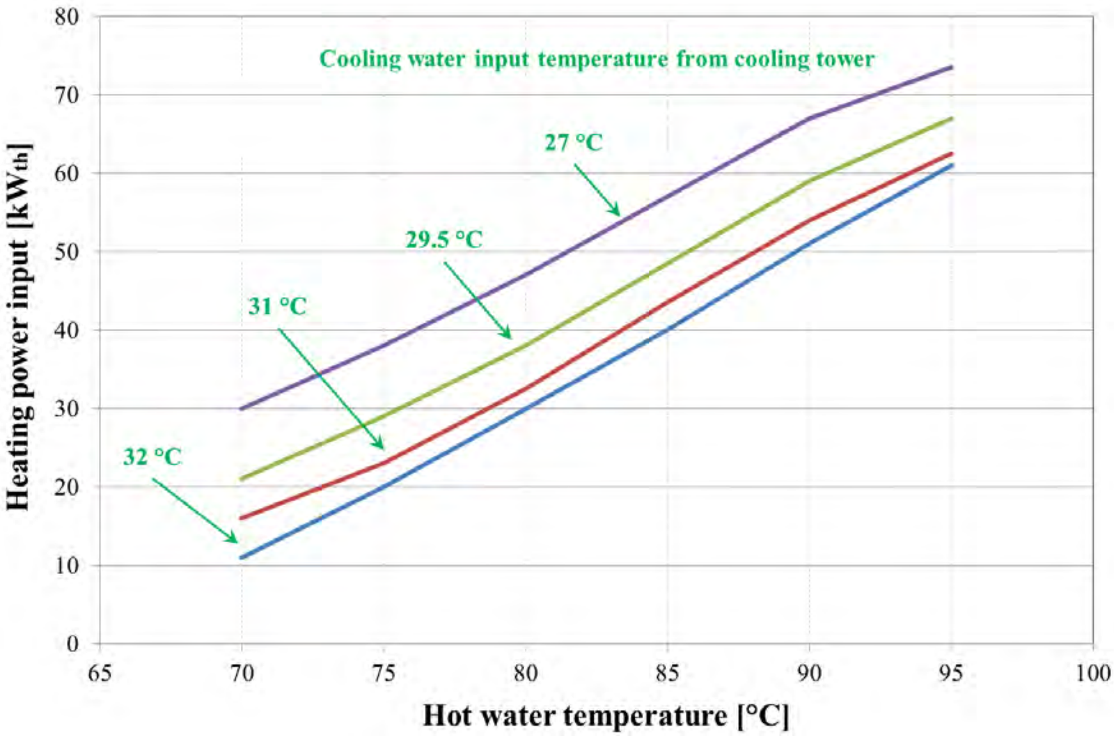


Figure 132 - Absorber requested input vs. hot and cooling water temperatures [147]

Finally, Figure 133 shows the decrease ratio of the COP compared to the rated value when the hot water flow rate is decreased.

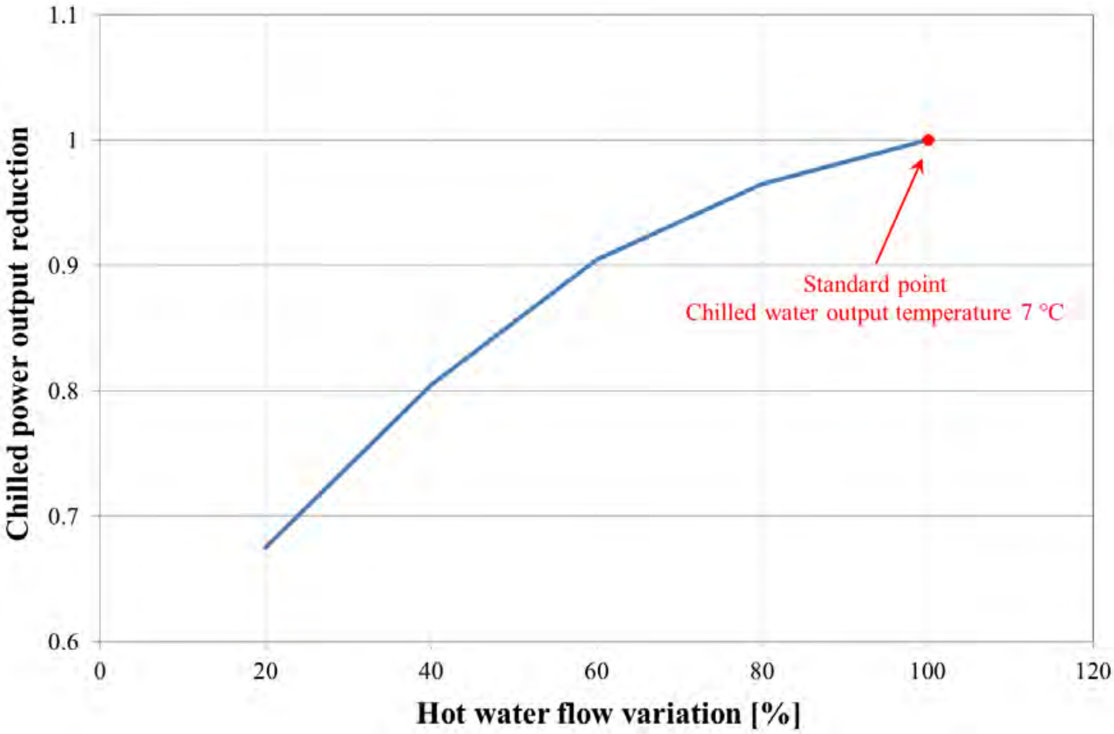


Figure 133 - COP relative variation with the hot water flow decrease [147]

5.4.3 Electric chiller

For the electric chiller the data sheet with the performance curve was not available, only the COP at rated power conditions can be estimated (the producer declares a 59.5 kW_c rated cooling output with an electric input of 23.4 kW_e, with a resulting COP of approximately 2.5): for this reason the experimental characterization is essential for the good prediction capabilities of the optimization algorithm.

The measured data, together with the respective interpolating curve, is shown in Figure 134, considering three different interpolating curves: linear (black), polynomial of order 2 (red), and polynomial of order 3 (green).

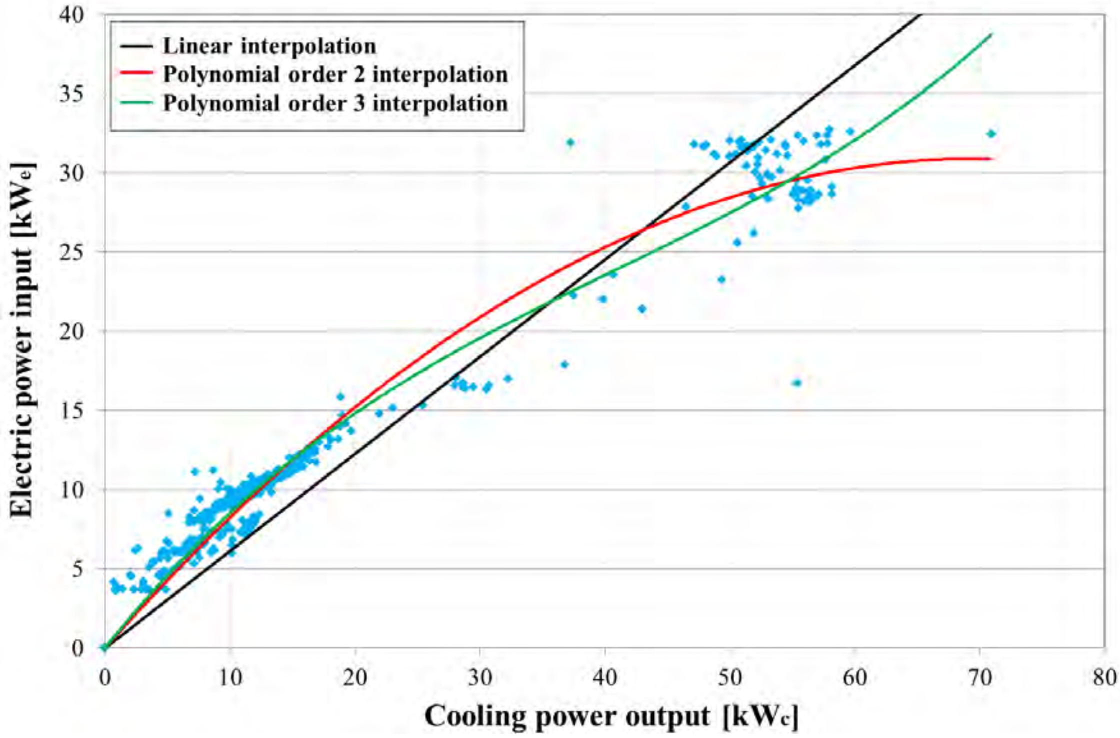


Figure 134 - Electric chiller performance experimental data and approximation curves

From a perusal of Figure 134, it can be seen how the linear data approximation is not satisfactory in any condition: the electric consumption are under-estimated for low cooling power output, whilst in the opposite side of the operation field, for high cooling power requests, the electricity consumption is remarkably over-estimated, leading to possible misleading results. The polynomial curve having order 2 seems to allow a good enough approximation of the experimental data, with a satisfactory trend both for low and high cooling power output. The approximating polynomial of order 3 presents a better behavior than the other curves for low energy output, but when the cooling request is high the electric consumption of the chiller could be over-estimated, even with a better approximation than the linear curve.

For this reason the polynomial of order 2 was selected, characterized by the equation:

$$P_{e,chiller} = 0.8869 \cdot P_{c,chiller} - 0.0063 \cdot P_{c,chiller}^2$$

giving the electric chiller energy consumption when a generic cooling power is requested.

5.4.4 Gas boiler

The gas boiler presents an on/off operation strategy: as a consequence there is no need to estimate its performance curve, only the efficiency at rated power conditions is sufficient to our purposes. The considered value is 90 %.

5.5 Experimental results

The results taken from the data acquired during the running period of the optimization algorithm are presented. The global results are shown, comparing the economic performance with the estimation carried out considering the previous layout of the case study site and also a tri-generation unit with the “conventional” thermal-led management, in this latter case only when no prescribed energy exchange with the grid is considered. In addition, also the performance in terms of CO_2 emission are compared.

Then, the economic result of the optimization will be compared with the actual result, with the target to analyze the influence of the error of the loads and weather forecast on the final economic result. Also the different management procedures of the SU plant will be compared: in particular, the results from the “advanced dispatching” are compared with the same output generated by the “next-day” optimization, and finally the performance of the “real time” procedure will be critically analyzed.

All the experimental data involving the optimization algorithm management have been collected in the period going from July 17th 2013 until the date of writing of the thesis: they do consider both the “summer” configuration of the SU plant, with the heat from the CHP supplied to the absorption chiller, and the “winter” layout, with the thermal energy recovered from the ICE directly exploited by the heating users, thus giving a complete understanding on the management system behavior.

5.5.1 “Next-day” management

The results of the experimental campaign obtained during the optimization algorithm functioning are measured in a time period of about 4 months, both in the “winter” and “summer” configuration, respectively exploiting the heat recovered from the CHP directly for the heating loads and for supplying the absorption chiller.

In order to understand the performance of the plant managed by means of the optimization algorithm, some comparison are carried out with the previously installed plant (i.e. without the CCHP system, with only the PV panels supplying a small part of the electric needs of the factory), and with the correspondent plant without the advanced management software. By doing so, the advantages of an optimized scheduling of the plant devices can be considered in an absolute value, if compared with a “conventional” plant layout, and in a relative value, helping to understand the added value of such a kind of management.

During the operation of the Smart User plant in “summer” configuration, with the heat from the ICE feeding the absorption chiller, compared to an energy supply solution consisting in purchasing the power from the grid to feed the electric users and the electric chiller, the average measured decrease in the energy cost is about 63.4 %. Nevertheless the excellent result, most of the benefit is attributable to the tri-generation system only: the thermal-led management solution for the CCHP is estimated to bring a decrease in the energy purchase amount of about 61.5 %, with a difference with the optimization algorithm scheduling of the plant devices of about 5.3 %, corresponding to a decrease of about 3 € per day. This latter result is mainly attributable to the unfavorable cooling load request, often being larger than the absorption chiller maximum technical power output. Considering such kind of cooling curves, the worst measured performance of the optimization algorithm is experienced all the times the cooling load is continuously exceeding the absorption chiller maximum technical limit: in those cases, the advantage of the optimization algorithm compared to a thermal-led operation strategy is null, due to the fact that the CHP output is the same: always full-load. However, this result can be considered as a confirmation of the reliability of the implemented algorithm.

Considering the best result for the algorithm in the SU plant management, the measured load curves (only electricity and cooling, because heat is required just for room heating) and the PV power production are shown in Figure 135.

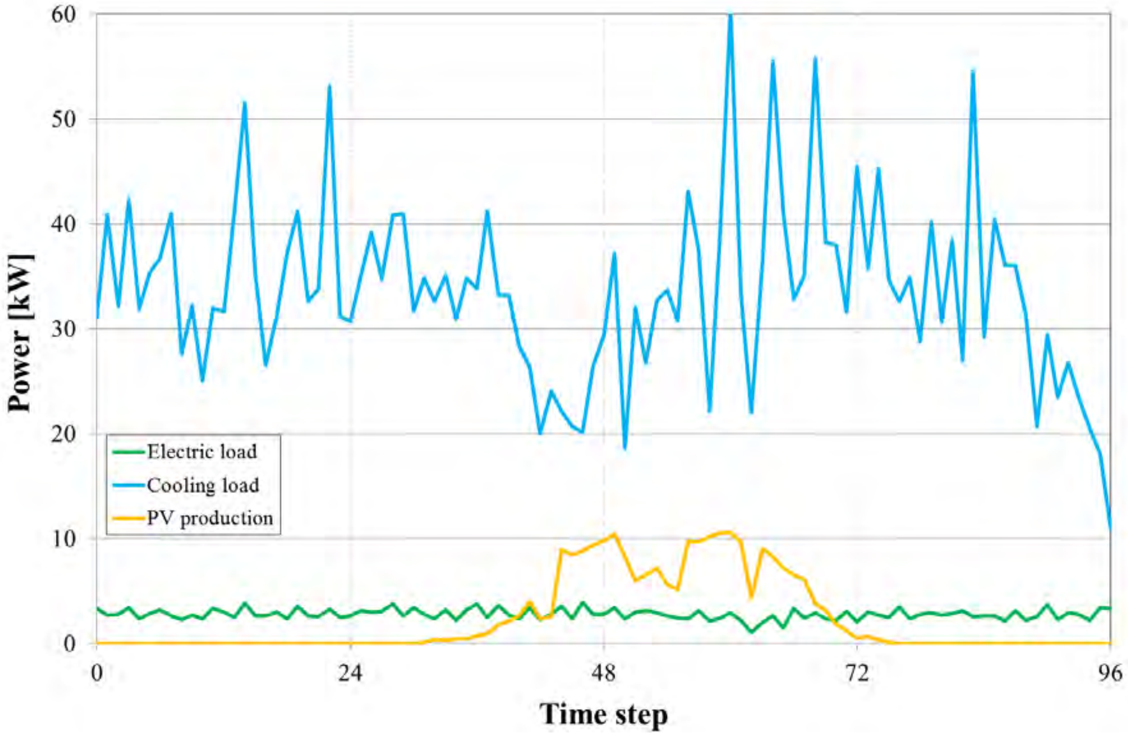


Figure 135 - Load curves and PV production for the considered "summer" day

From a perusal of the figure, it is evident how the average cooling request is relatively high, calculated in about 33.9 kW$_c$, value largely exceeding the technical maximum output of the absorber (27 kW$_c$). The measured minimum and maximum cooling request are respectively 18.1 kW$_c$ and 60.6 kW$_c$: also the minimum load value exceeds the minimum technical limit of the absorption chiller. On the contrary, the electric loads request is relatively low, with a measured average value of 2.8 kW$_e$, very close to the minimum technical limit of the CHP (2.5 kW$_e$), with a range variation during the whole day between the minimum value of 1 kW$_e$ and the maximum one of 3.8 kW$_e$, which in the central part of the day could be satisfied by the PV plant production. Even if the large difference between the electric and cooling loads ratio compared to the CCHP system capability represents a good testing condition for the optimization algorithm, the high average of the cooling request during the whole day does not allow good experiments for the system optimization characteristics. Indeed, the daily economic result shows that the decrease is mostly attributable to the tri-generation system presence (- 74.8 %), with a slight contribution of the optimization software (- 83.2 %), as shown in Figure 136.

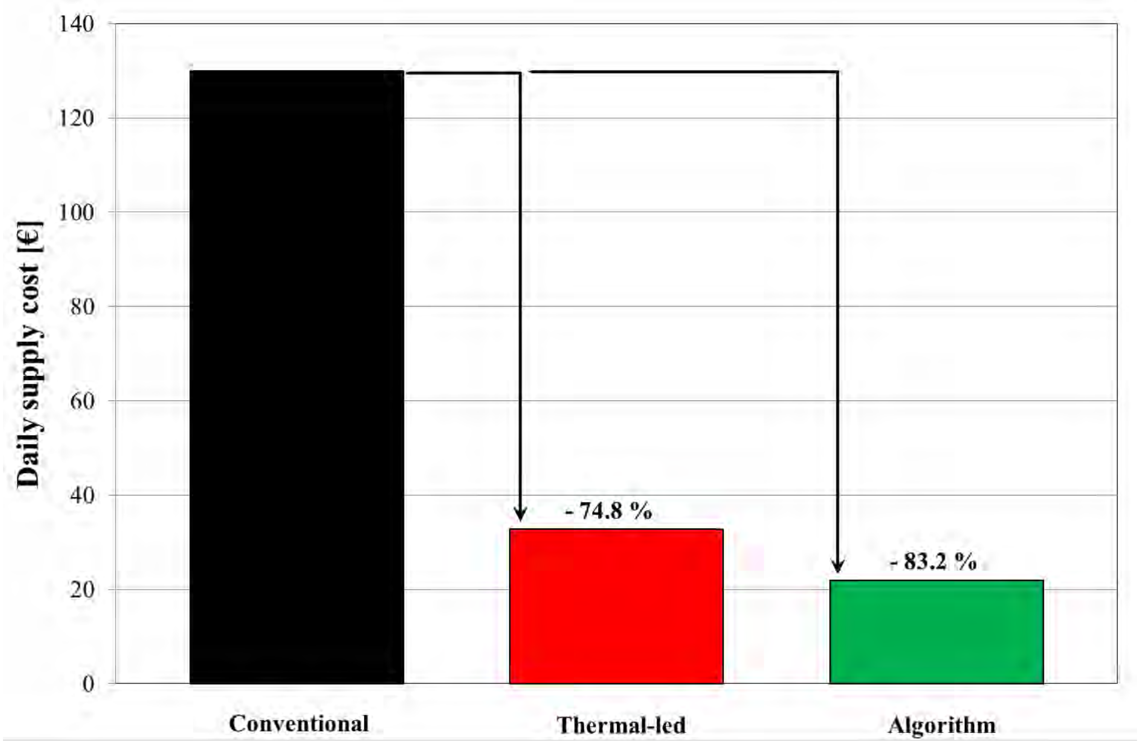


Figure 136 - Daily energy cost comparison for the considered "summer" day

This kind of result is possible thanks both to the high electricity prices (Figure 137) for the considered day and to the low COP of the electric chiller: considering the calibration curve reported in §5.4.3, coupled with the large cooling request variation between successive time steps (thus an intrinsic scarcely efficient behavior of the piece of equipment), the average efficiency of the chiller is estimated in about 1.92.

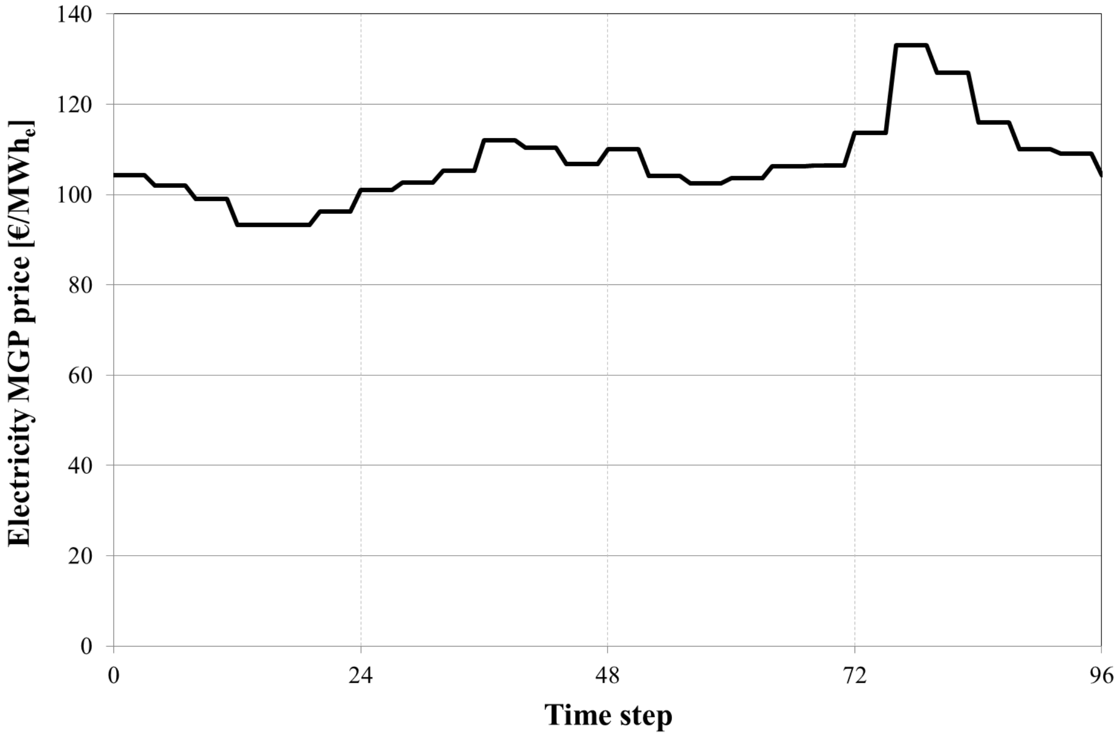


Figure 137 - Electricity MGP price for the considered "summer” day

The scheduling of the CHP from the optimization algorithm, compared to the estimation of its operation in thermal-led mode, is shown in Figure 138.

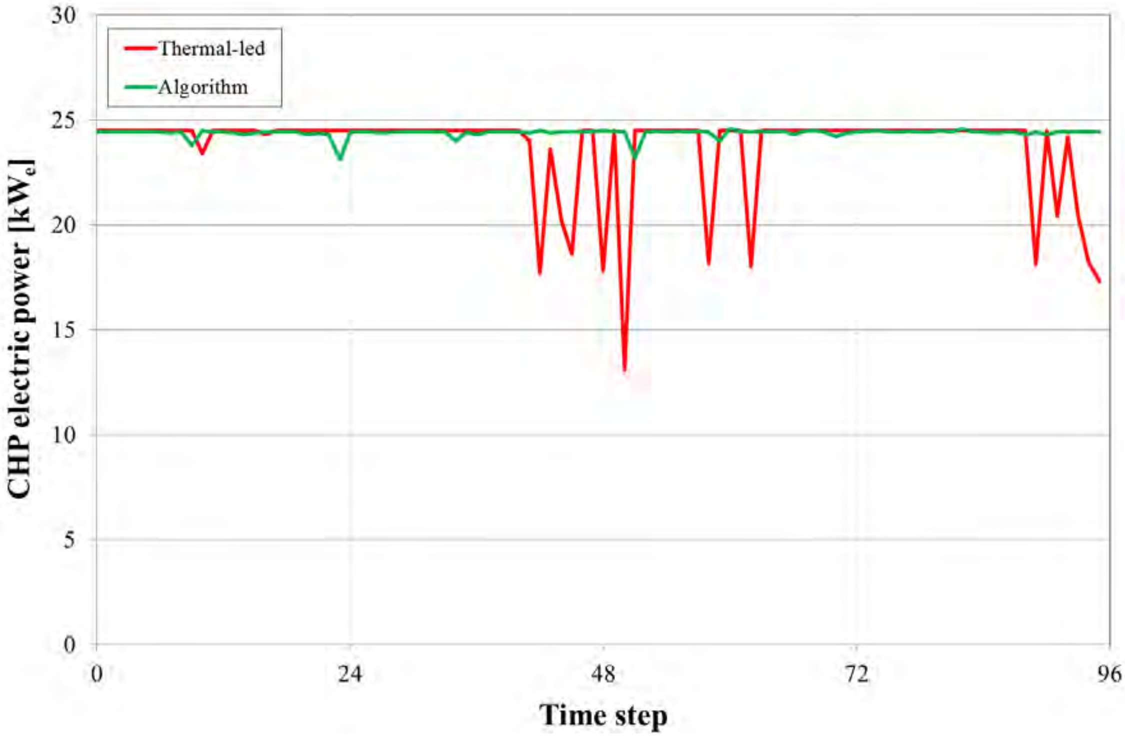


Figure 138 - CHP management for the considered "summer" day

It is evident how the ICE is operated at nearly full-load conditions also when the cooling request is under the limit of the absorption chiller: by doing so, the exceeding produced power from the CHP is sold to the grid, and contemporarily the exceeding cooling energy output for the absorber is stored in the “cold” tank, allowing to exploit the CAR incentive for the reduction of the taxes on the natural gas, coupled to the higher efficiency of the engine if operated at rated power output.

The “winter” experimental activity of the Smart User plant shows more satisfactory results than the previous one, thanks to the more favorable experienced loads: in those cases the heating loads result more varied, and with an average value being consistently lower than the rated heat power output of the CHP, allowing the optimization algorithm to efficiently schedule the pieces of equipment and manage the storage. Indeed, the average measured percentage in the energy cost decrease is about 40 % compared to a “conventional” energy supply, with a remarkably lower contribution of the CHP only in determining that kind of result: the average advantage of the co-generation system considering a thermal-led management is estimated in about 17.9 %, with a relative decrease of the energy costs of the algorithm management being estimated in about 28 %. The worst obtained result when comparing the “conventional” and the “smart” plant supply is measured in about 22.5 %: in that occasion the thermal-led management of the engine bring to a decrease in the energy costs of 8.1 %.

The best results of the Smart User algorithm management compared with the “conventional” energy supply is obtained with the load conditions shown in Figure 139.

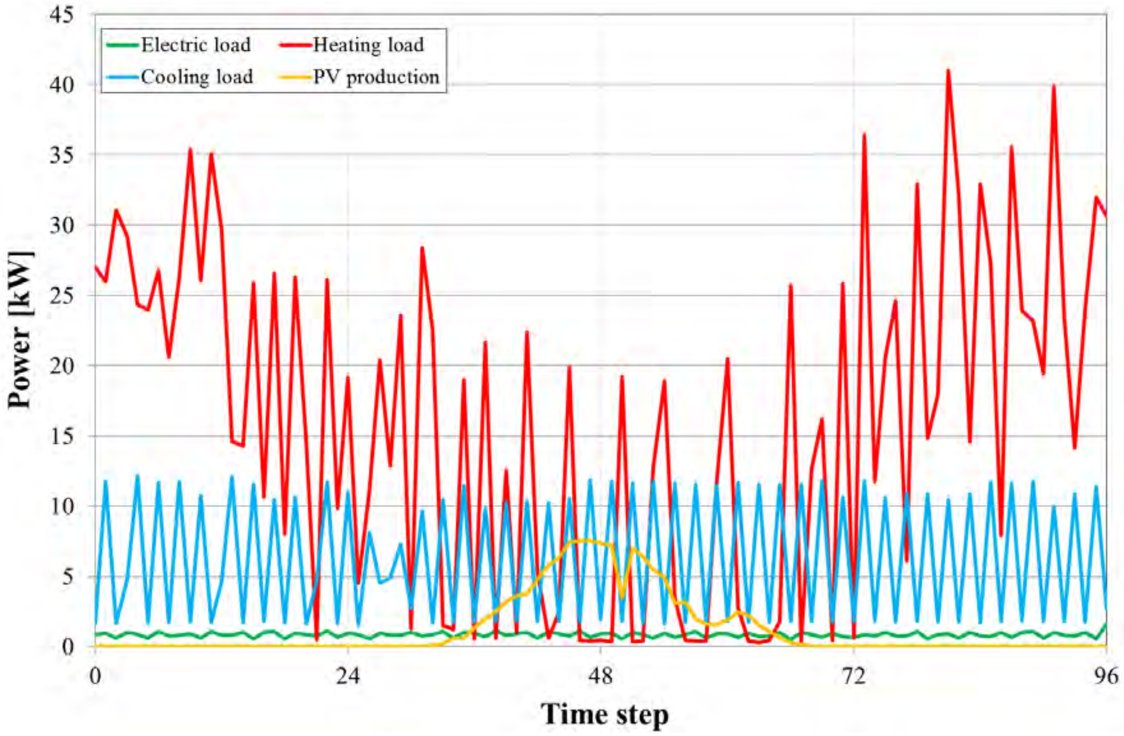


Figure 139 - Load curves and PV production for the considered “winter” day

The electricity purchase price from the grid, in terms of MGP energy price, is shown in Figure 140.

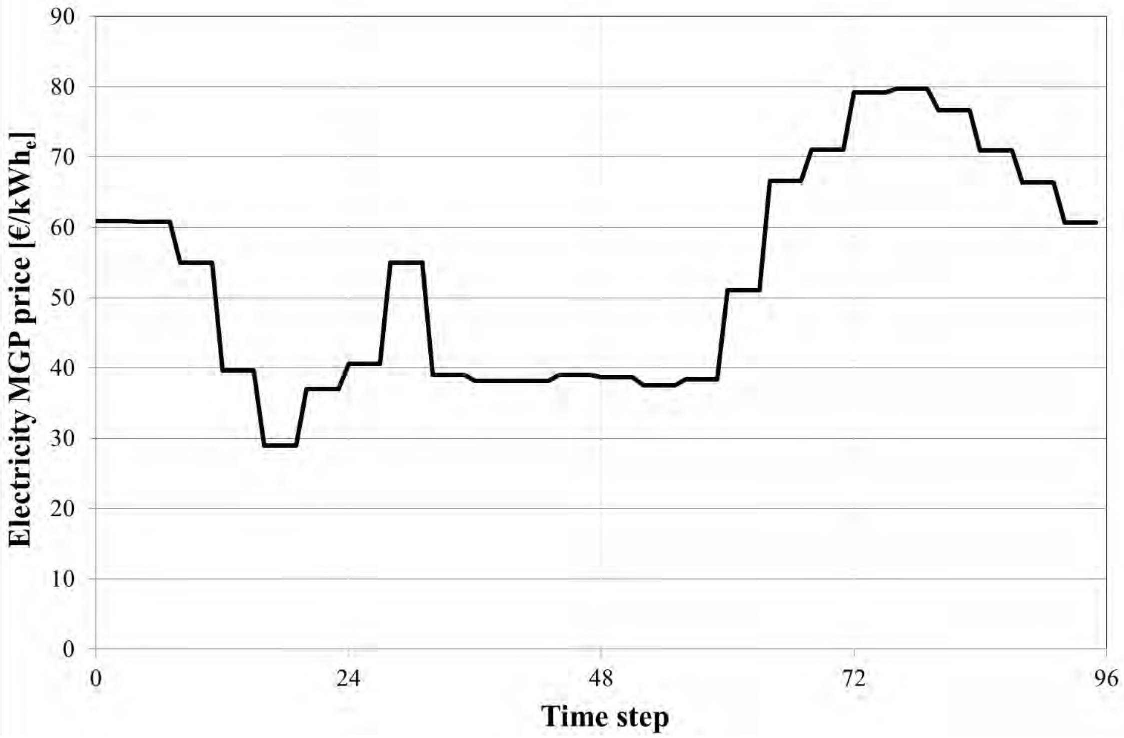


Figure 140 - Electricity MGP price for the considered "winter" day

The daily obtained money saving can be seen in Figure 141, demonstrating how the energy supply cost is reduced of over 58 % compared to the “conventional” energy supply, while the thermal-led management of the CHP would just allow a decrease in the energy purchase of about 17 %.

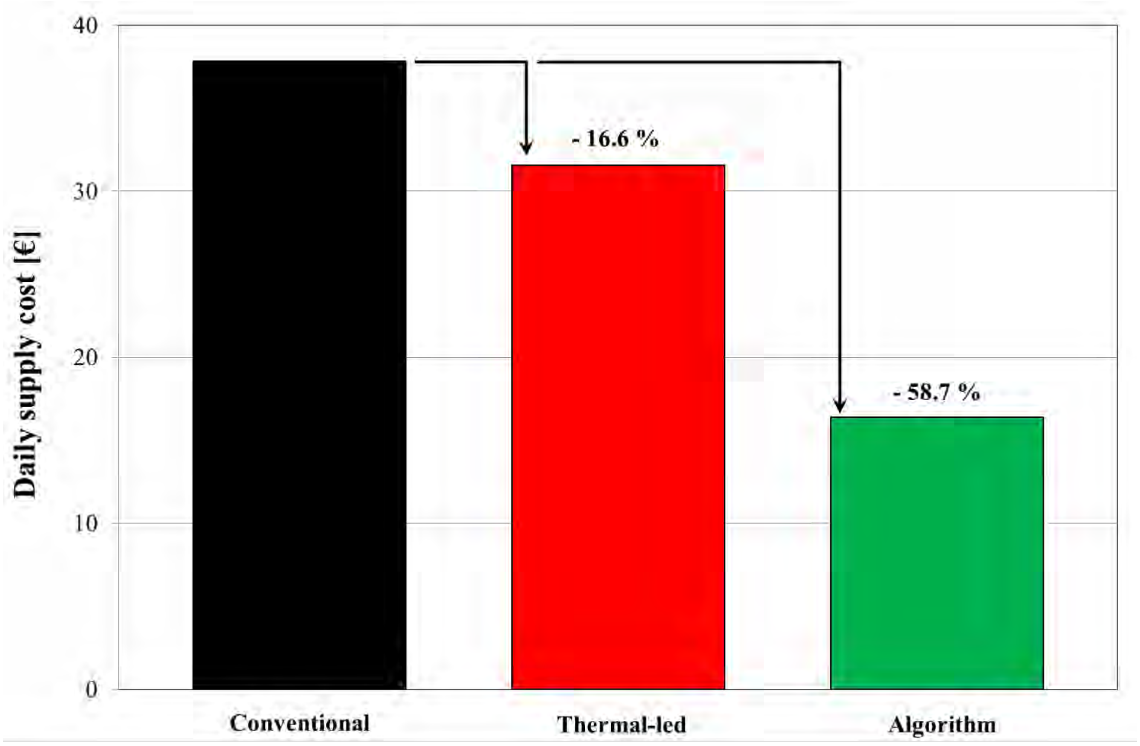


Figure 141 - Daily energy cost comparison for the considered "winter" day

The detailed comparison of the energy supply costs is shown in, where it is evident how the algorithm is mostly under both the other proposed solutions: this behavior, of course, mainly belongs to the different management of the ICE (), which is often run at its full load, with a remarkable increase in its efficiency and, consequently, in the good operations of the whole plant: the recovered heat which cannot be immediately exploited is stored and usefully supplied to the loads, instead of running the ICE at partial load or switching on the auxiliary boiler.

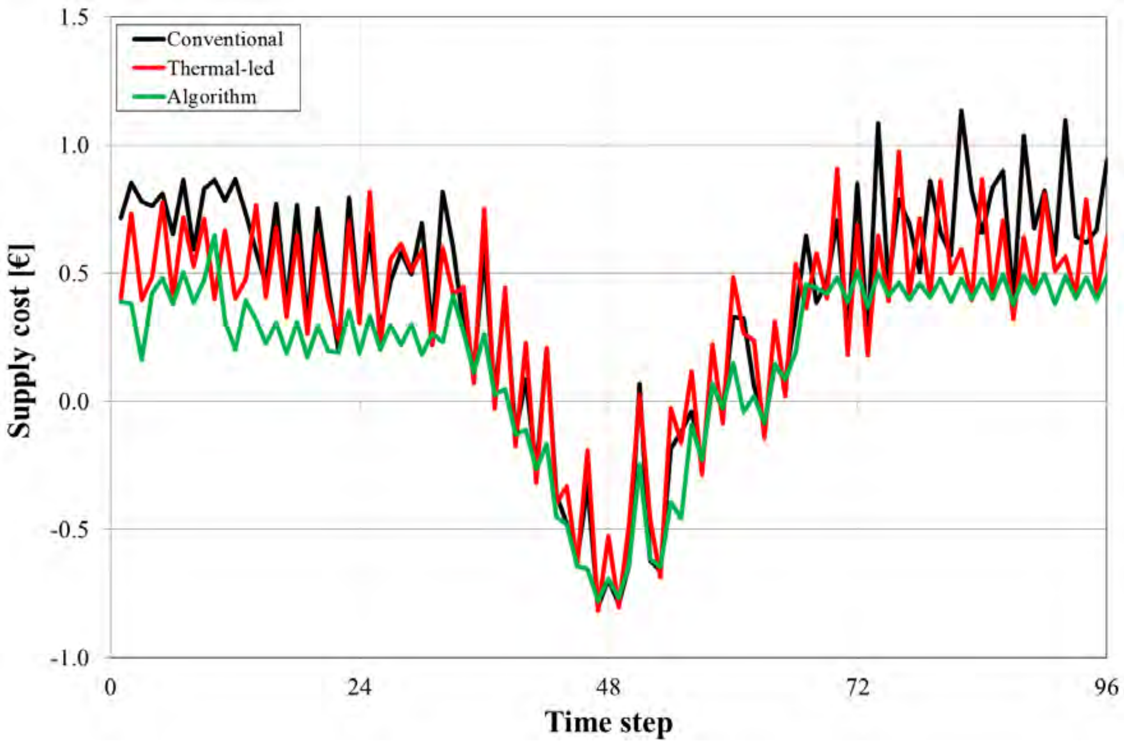


Figure 142 - Detailed daily cost comparison for the considered "winter" day

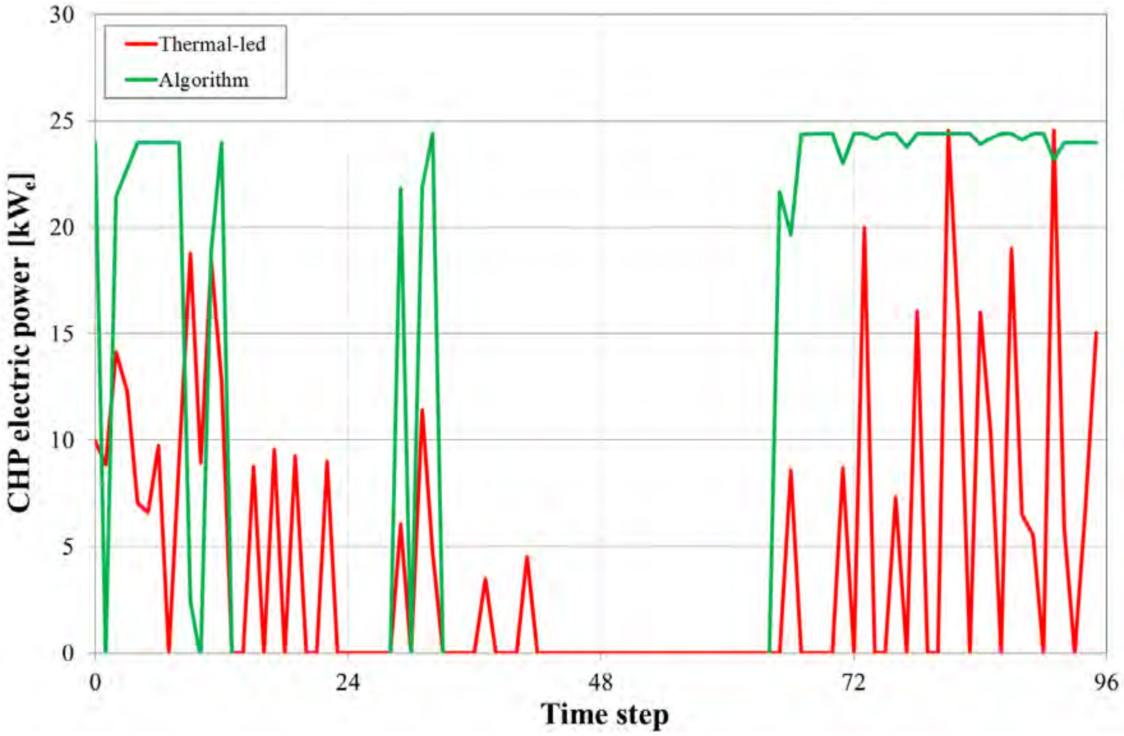


Figure 143 - Comparison of the CHP management for the considered "winter" day

5.5.2 “Advanced dispatching” vs. “Next-day”

The advanced dispatching optimization allow to re-schedule the generators set-point during the day, considering that some conditions can be changed or updated in the meanwhile:

- The loads forecast;
- The weather forecast;
- The storage temperature (i.e. its energy level) at the beginning of the considered time-step.

The advanced dispatching procedure was run considering two different conditions:

1. A free energy exchange profile with the grid;
2. A prescribed electricity exchange profile.

In this latter case, the electric profile with the grid is established on the basis of the day-ahead optimization, which is run with a free exchange constraint: by doing so, the advanced dispatching procedure performs the optimization on the basis of the result of a previous optimization.

If **no prescribed energy exchange** with the grid has to be achieved, the optimization of the advanced dispatching procedure can be remarkably different from what estimated with the day-ahead procedure. To give an example, the day of November 30th 2013 is selected: the most relevant differences between the input of the two procedures are due to the update of the weather forecast (Figure 144), while the “hot” storage temperature at the beginning of the day is very similar (84 °C for the day ahead vs. 85 °C for the advanced dispatching).

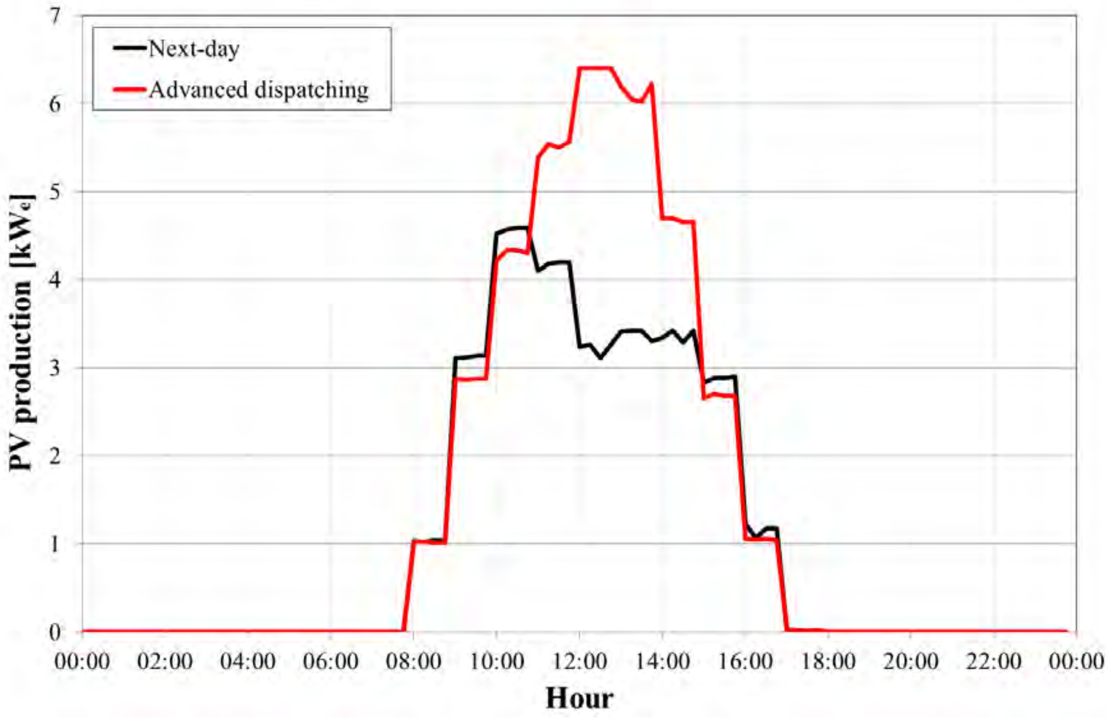


Figure 144 - Difference in PV production between the "next-day" and the "advanced dispatching" due to a change in the weather forecast (free)

This difference brings to a different management of the CHP during the central part of the day, with a consequent different use of the "hot" storage, as shown respectively in Figure 145 and Figure 146.

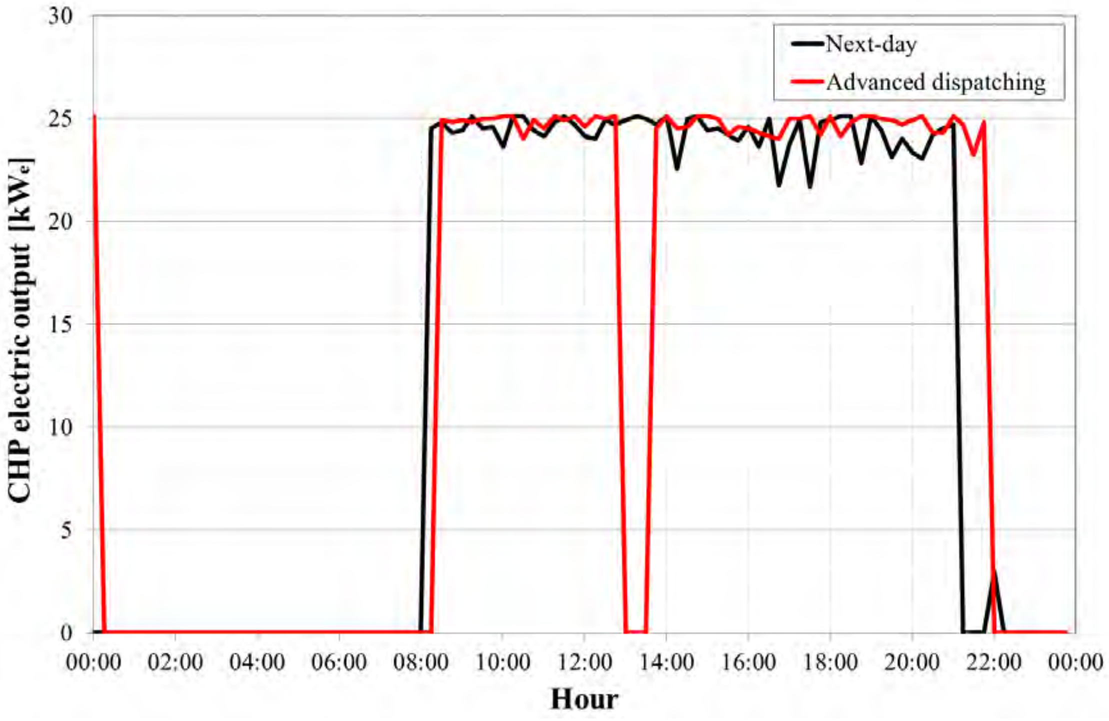


Figure 145 - CHP electric power output difference between the “next-day” and the “advanced dispatching” (free)

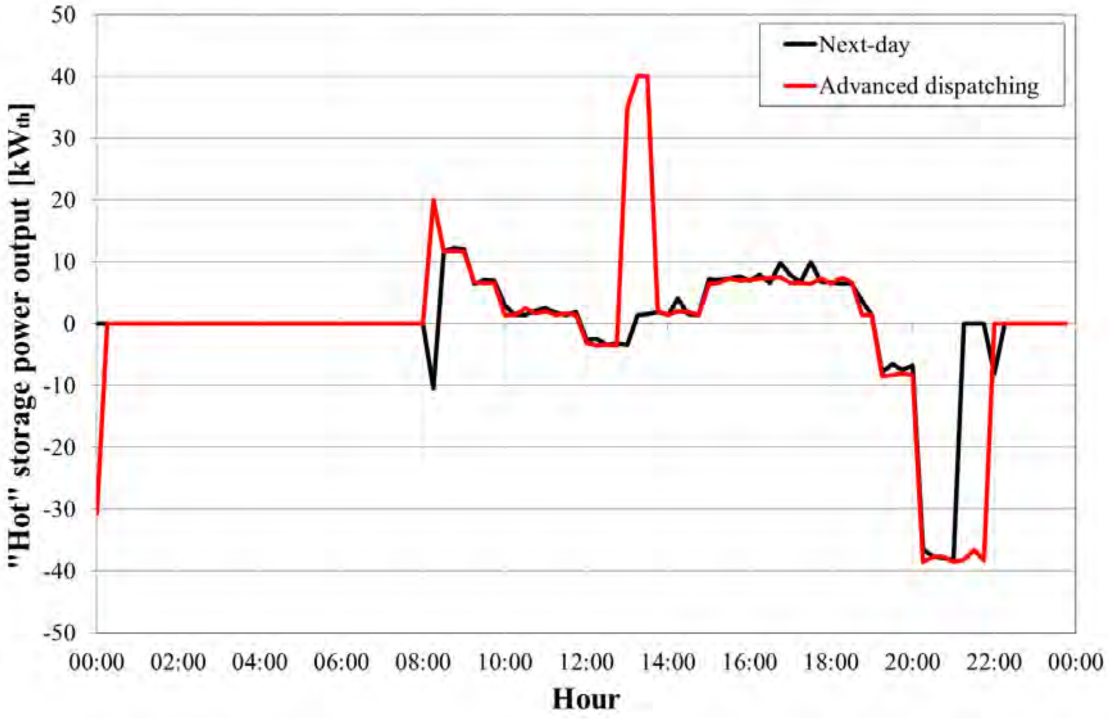


Figure 146 - "Hot" storage power output difference between the “next-day” and the “advanced dispatching” (free)

All these changes bring to a different result for the estimation of the energy supply costs, passing from about 73.1 € of the day-ahead optimization to about 68.9 € of the advanced dispatching, with an absolute and percentage decrease respectively of 4.2 € and 6 %. This result is mainly due to the variation of the energy exchange with the power grid, as shown in Figure 147.

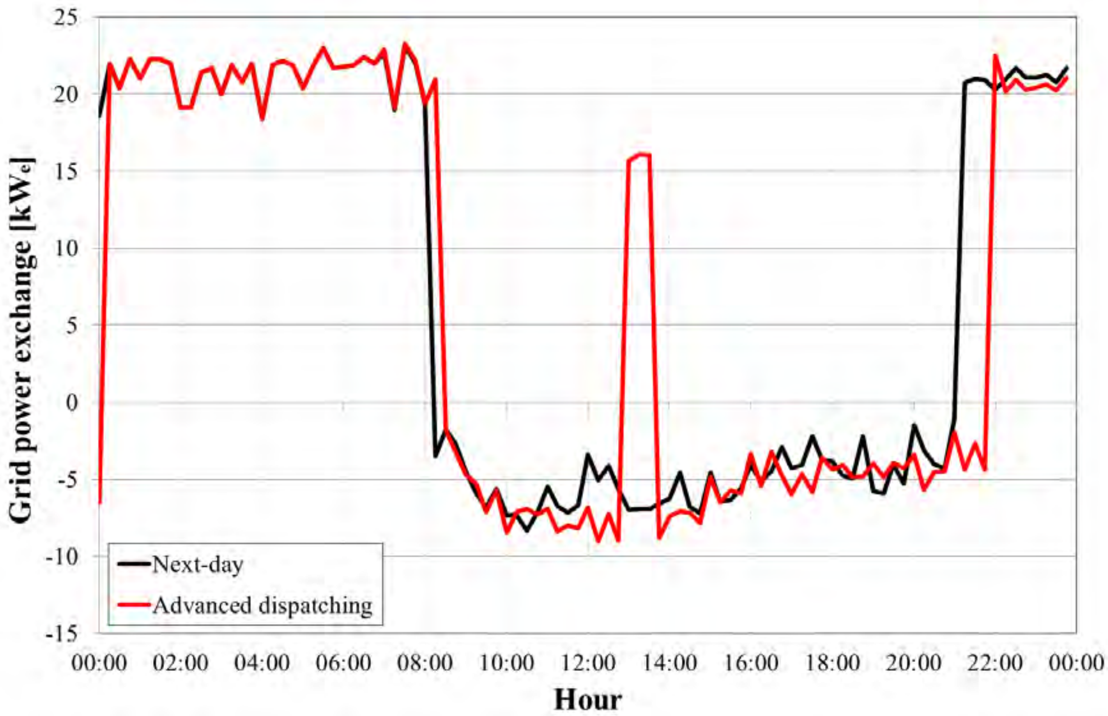


Figure 147 - Grid power exchange difference between the "next-day" and the "advanced dispatching" (free)

When a **prescribed exchange profile** must be followed by the advanced dispatching, the optimization is obviously subjected to an additional constraint, which could bring to an economic result much different (and, in some cases, worse) than the one estimated by the day-ahead optimization. The results for December 14th 2013 are reported: the load forecast is the same for both optimization procedures, only the weather forecast (in particular solar radiation) and the temperature of the storage at the beginning of the day change. In Figure 148 the differences in PV expected production is shown, while in Figure 149 the temperature mismatching of the "hot" storage during the day is reported.

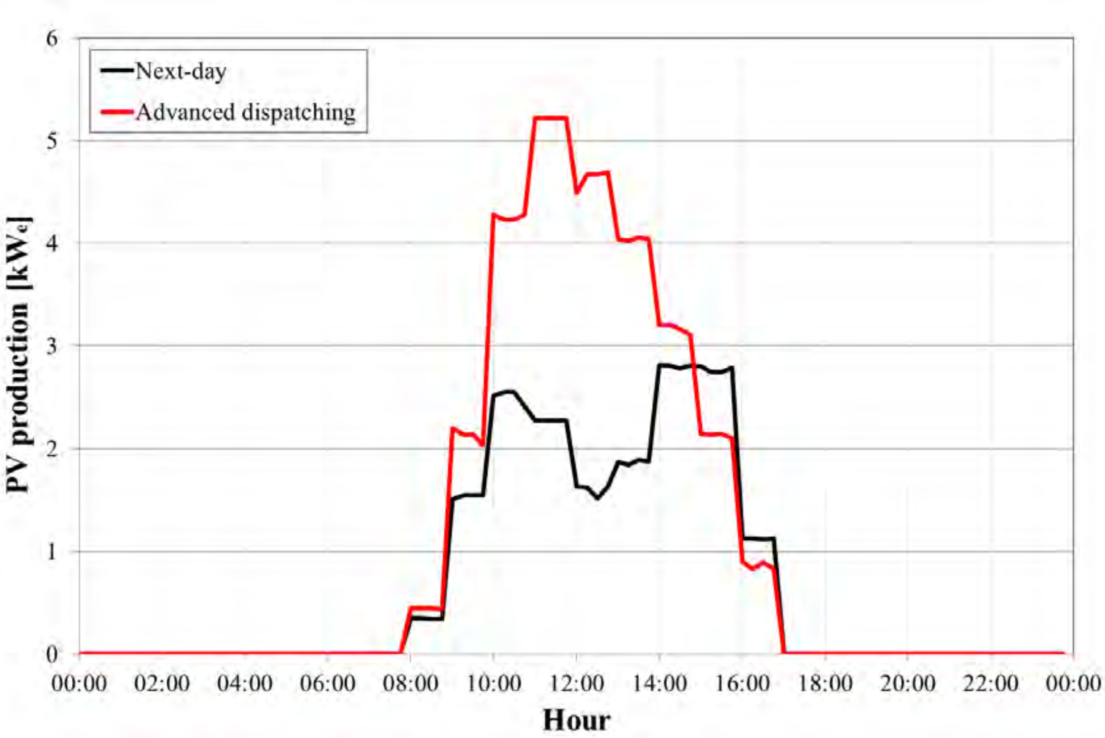


Figure 148 - Difference in PV production between the "next-day" and the "advanced dispatching" due to a change in the weather forecast (balanced)

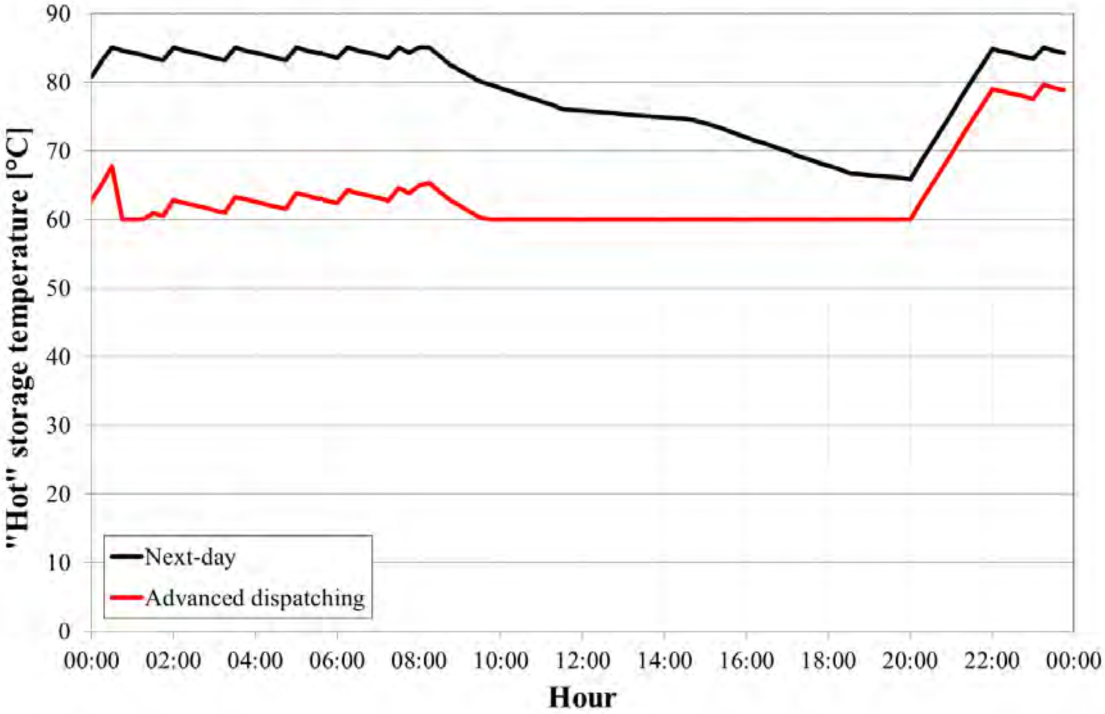


Figure 149 - Difference in the "hot" storage temperature between the "next-day" and the "advanced dispatching" (balanced)

Of course, this latter figure is a function of both the difference in the storage temperature at the beginning of the day and the difference in the daily management of the plant: anyway, it can be seen how the trend, in terms of relative temperature variation, is similar, being the initial mismatch of energy level of the storage (due to a starting difference of about 20 °C) the most relevant parameter.

The shown differences bring to a different management of both the CHP and the storage, as shown respectively in Figure 150 and in Figure 151.

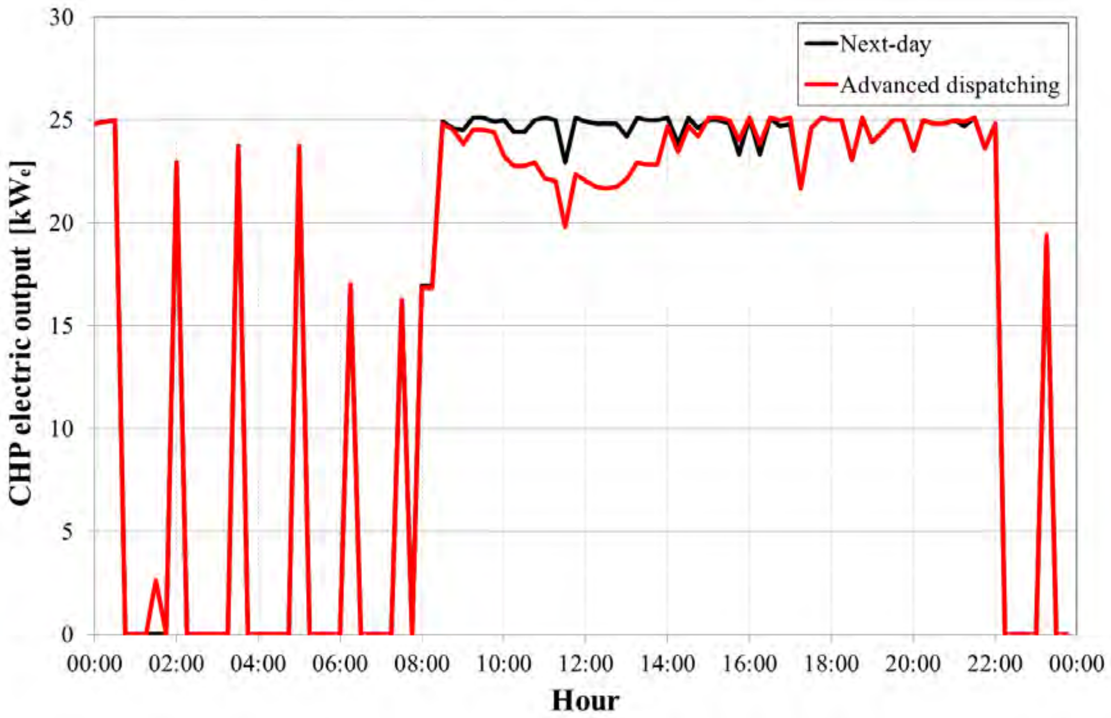


Figure 150 - CHP electric power output difference between the “next-day” and the “advanced dispatching” (balanced)

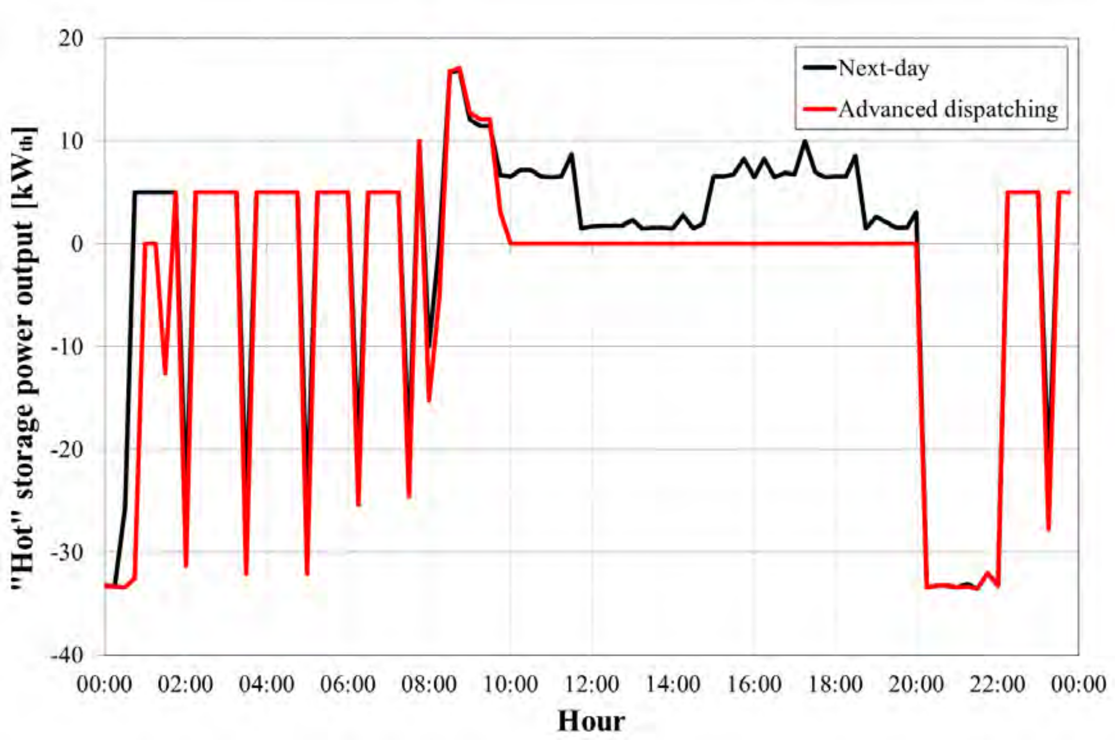


Figure 151 - "Hot" storage power output difference between the "next-day" and the "advanced dispatching" (balanced)

As expected, the most relevant differences are in the central part of the day, due to the need to supply the grid with a prescribed energy exchange and to the contemporarily increased production from PV. Due to the shown change in the management of the plant, the total cost difference for the energy supply of the Smart User system is estimated in about 11.4 €, being the difference from 90.8 € of the advanced dispatching optimization with the 79.4 € of the day ahead, bringing to a percentage increase of about 14 %. Nevertheless, the prescribed energy exchange with the grid is satisfied, as shown in Figure 152.

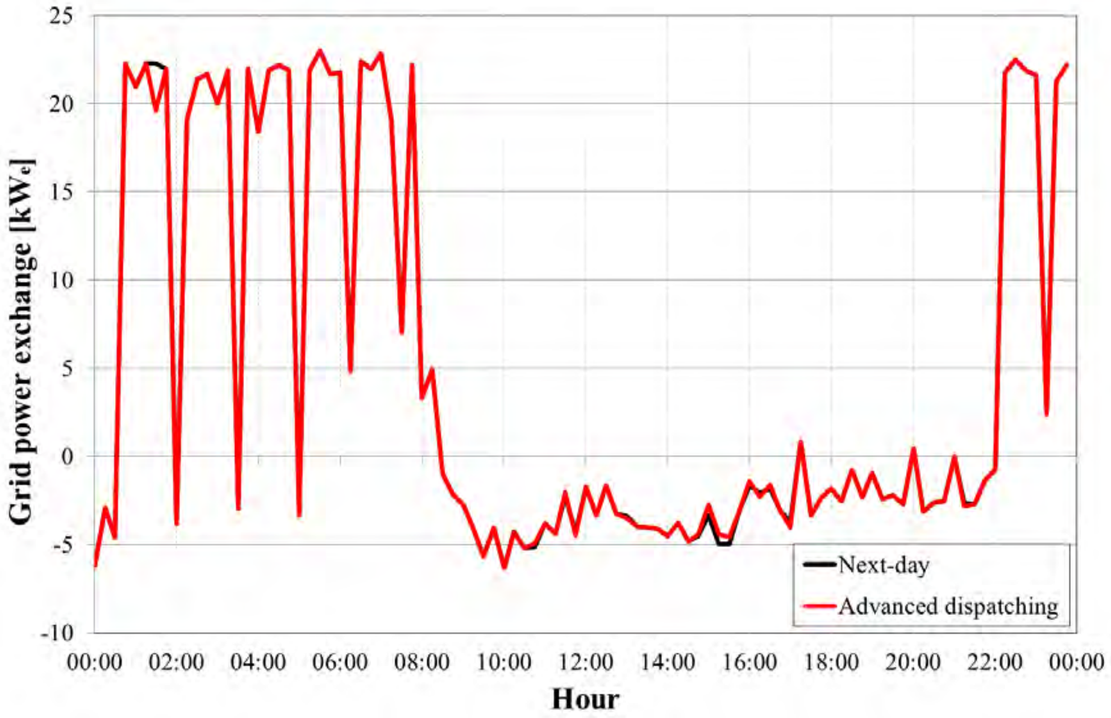


Figure 152 - Grid power exchange difference between the "next-day" and the "advanced dispatching" (balanced)

5.5.3 "Real time" management

The real time procedure, based on a logic algorithm, was implemented within the SCADA system, together with the virtual electric storage. The procedure considers 2 interventions with different time-steps: the shorter one, performed once per second, aiming to balance the mismatching between the prescribed and the actual electric profile with the grid by means of the electric storage, and a longer one, carried out once in a 5-minute time period, with the target of recovering the energy content of the electric storage to its half capacity by varying the set point of the CHP or the amount of the curtailment of the non-privileged electric loads.

In order to better explain the procedure functioning, an example of the on-field operation is presented, relative to the time interval between 9:45 and 10:00 AM of December 12th 2013. In Figure 153 the set point of the energy exchange with grid from the day-ahead procedure compared to the estimated actual exchange profile without the intervention of the electric storage is shown, considering the time interval between data of 1 second.

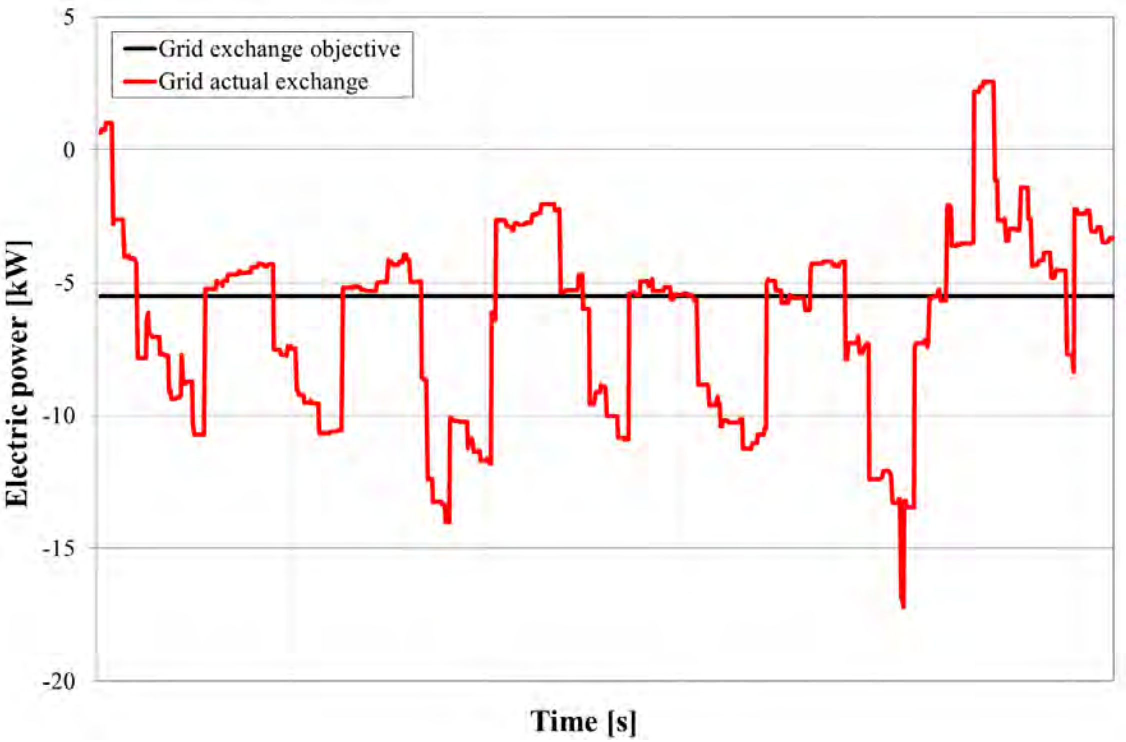


Figure 153 - Grid power exchange: objective vs. actual value

The difference between the curve must be balanced by the electric storage, in case its SOC is sufficiently high or the power request is within its technical limits. For the present application, an electric storage with an energy capacity of 12 kWh_e and maximum discharge and charge power of respectively 22.8 kW_e and 12.3 kW_e is considered: its size is an attempt for the plant, and the optimal dimension are dependent from many considerations, like the rated power of the plant devices (both loads and generators), the time scale considered for its charge recovery with the long-time real time procedure, the accuracy of the loads and weather forecasts, etc.

In Figure 154 the power output of the storage for the balance of the grid exchange mismatching, in addition the variation of its SOC, is shown.

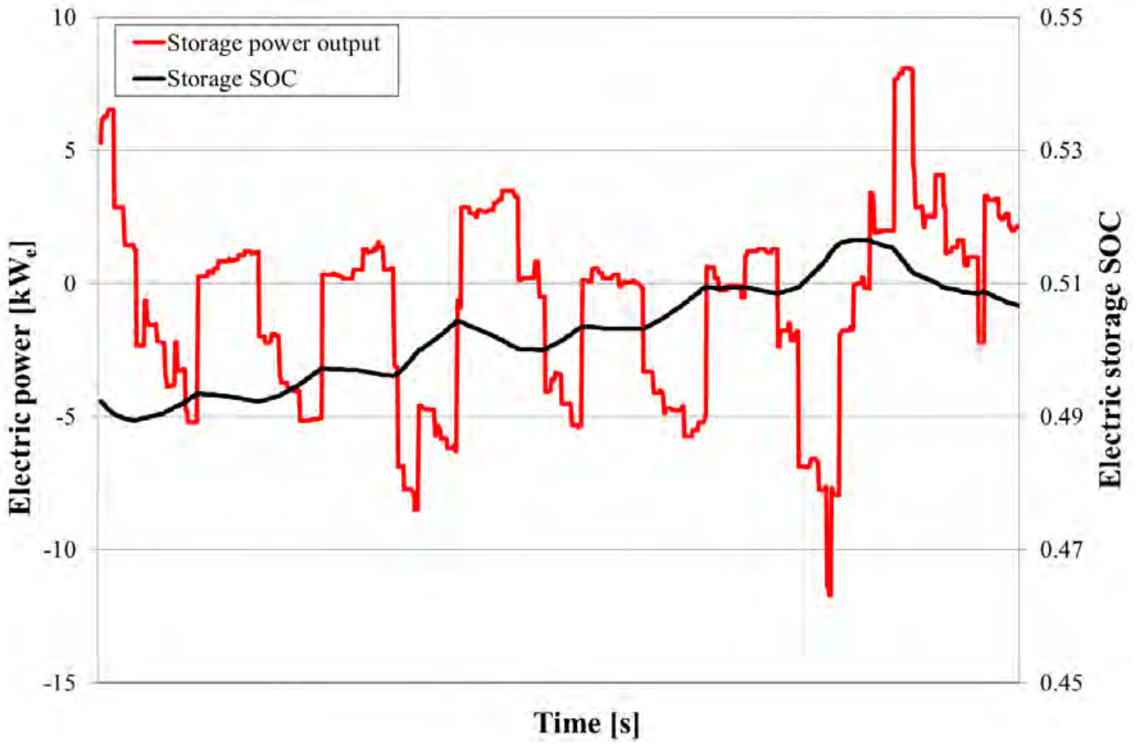


Figure 154 - Power output and SOC of the electric storage in the considered time period

Even with large power output of the storage, its SOC variations are relatively poor, due to the fact that its energy capacity is large and, at the same time, the energy request is remarkably low, because of the limited time interval considered (1 second).

The net result on the imposed algorithm time step (15 minutes) shows how the energy exchange with the grid is achieved: indeed, the difference between the predetermined energy value and the actual one results 0.003 kWh$_e$, which compared to the objective of 1.3766 kWh$_e$ is a mismatching of about 0.2 %.

In the considered time interval, the charge power is sometimes exceeding the technical limit of the storage, as visible in the end of the interval in Figure 154. In addition to that, the analysis of the real time data shows that in some cases delays happened in the communication between the SCADA system and the storage, with the consequence of an instantaneous unbalance of the objective power exchange: this mismatching is taken into account by a purposefully created variable, *DELTAE_REALTIME*. This variable is considered together with the difference between the SOC charge at the beginning of each 5-minute time period and the 0.5 level: the long-time procedure provides to adjust the CHP set-point in order to balance the *DELTAE_REALTIME* value and to restore the 0.5 SOC level of the storage. The effect of the procedure is shown in Figure 155, where the variation of the CHP set-point compared to the day-ahead value and the *DELTAE_REALTIME* value are reported.

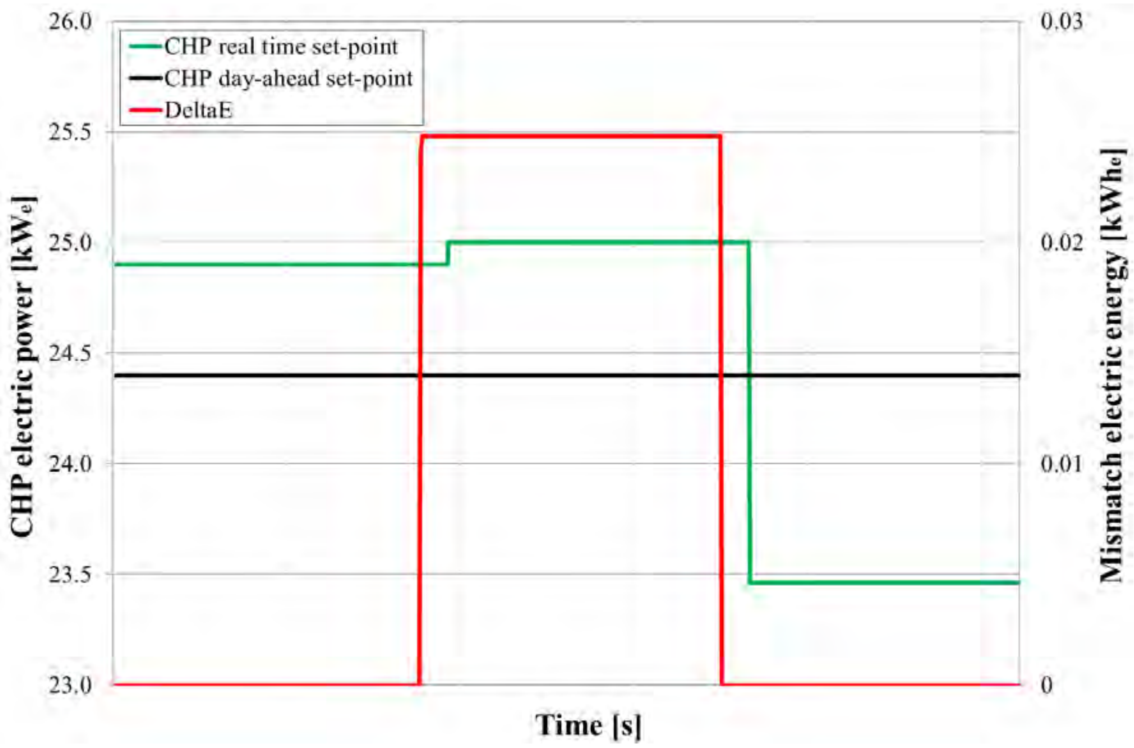


Figure 155 - 5-minute real time procedure: effects on the CHP set-point on 15 minutes

The relatively large difference of the CHP set-point between the end of the second 5-minute interval and the third one (approximately 2.5 kW$_e$) compared to the limited value of the energy mismatching can be explained by the fact that the amount of energy must be recovered in a very short time period; similarly, the recovery of the 0.5 SOC conditions, if “translated” from energy to power, produce the similar effect.

5.5.4 Influence of the forecasts error

The results obtained with the “real time” management show how the forecasts for the next day are not perfect, bring to non-optimized schedule of the algorithm. The influence of the error on both the loads and the weather forecast can be analyzed by running the algorithm with the load and PV production data measured and stored in the SCADA reports: by doing so, a perception of the influence of the error can be individuated, even if it cannot have a real statistical value, due to the fact that it depends on the single analyzed case, in more detail by the load profiles and by their reciprocal ratio.

As an example, the load and PV production forecasted for a selected day are shown in Figure 156, while the actual load are reported in Figure 157.

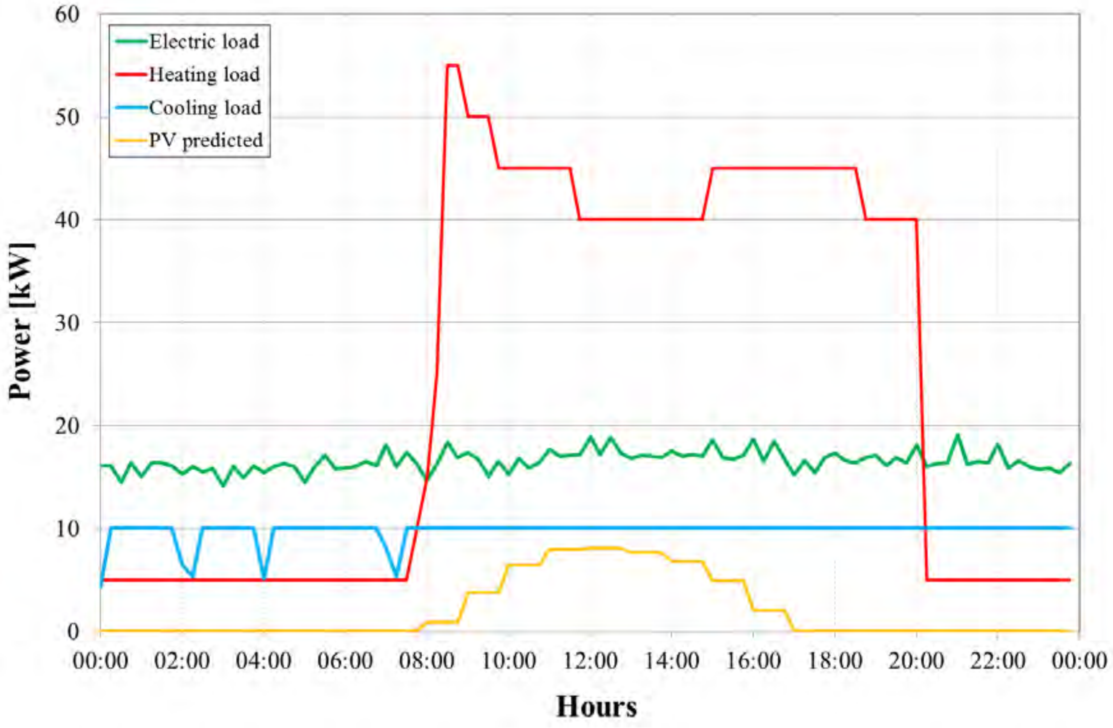


Figure 156 - Predicted loads and PV production for the example day

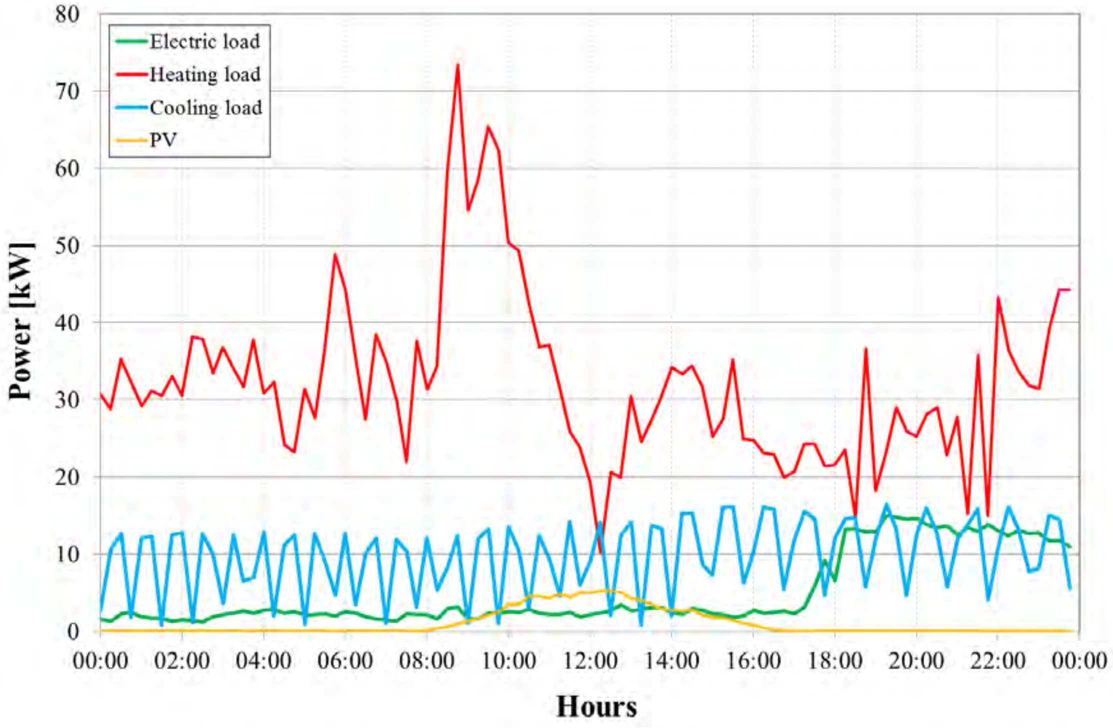


Figure 157 - Actual loads and PV production for the example day

From a perusal of the figures, it is evident how the electric load and the PV production are remarkably different, both in terms of amount and shape, while the cooling and the heating loads have a similar trend, even if the latter one shows a relatively high power difference in the “central” period of the day.

The gross economic comparison is shown in Figure 158, while the detailed energy cost can be seen in Figure 159.

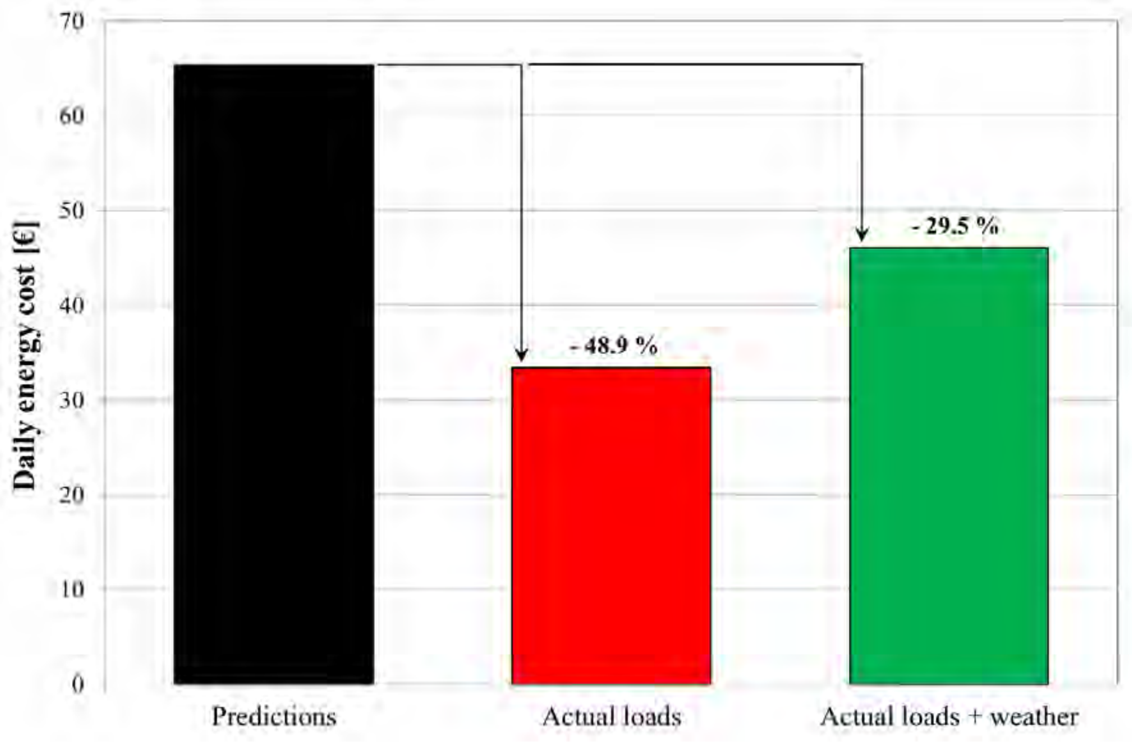


Figure 158 - Daily energy cost comparison

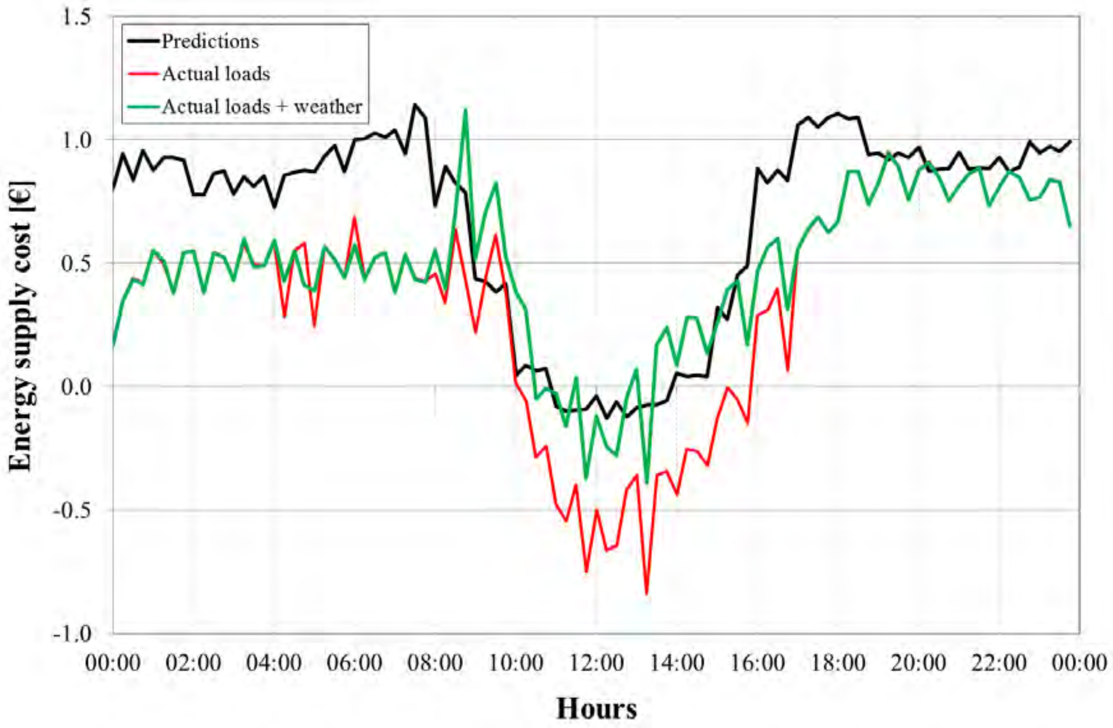


Figure 159 - Detailed energy cost comparison

As expected, the perfect forecast of the loads and the weather conditions bring to better results, due to the fact that the scheduling of the plant devices are managed in a real optimized way. On the contrary, the better daily performance of the algorithm output which only considers the actual loads compared to the overall correct predictions is an apparent non-sense. This can be explained by doing two considerations:

- The weather forecast over-estimated the production from the photovoltaic plant;
- The amount of the “Conto Energia” incentive for the PV production is consistent.

The combination of these factors produce the large difference in the central part of the day, while in the other periods the optimizer results are very similar.

All the errors in the forecast bring to a remarkably different management of the CHP, as shown in Figure 160.

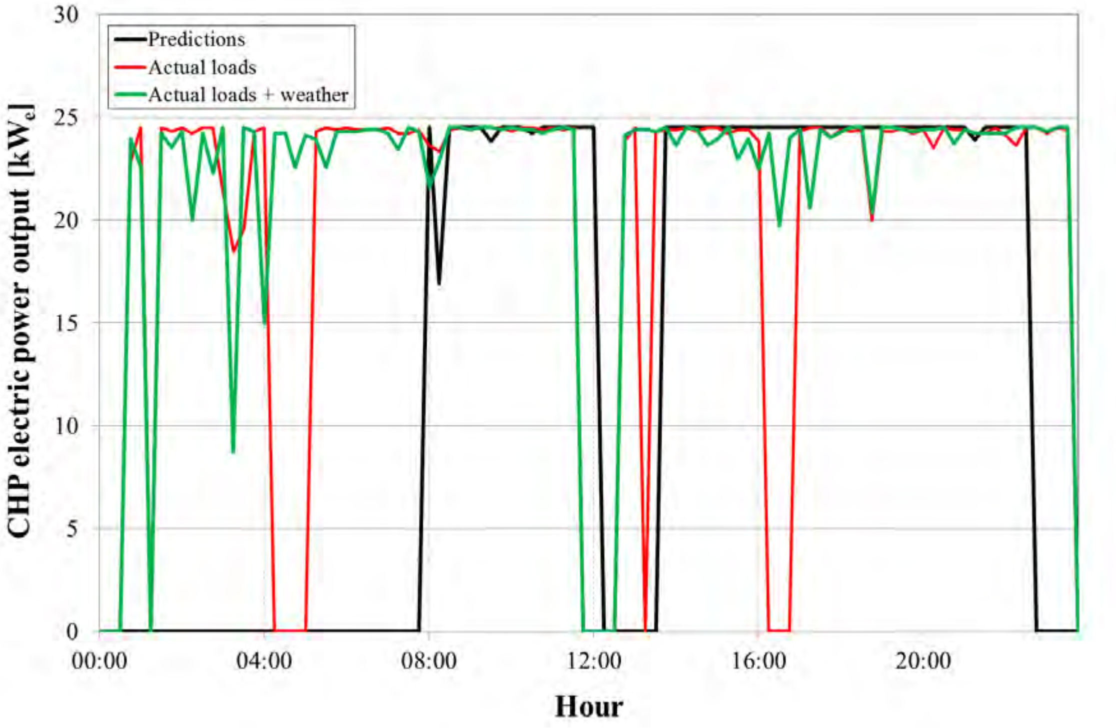


Figure 160 - CHP management comparison for the example day

As a consequence of the previous picture, the electric exchange with the distribution power grid is sensibly different, as visible in Figure 161.

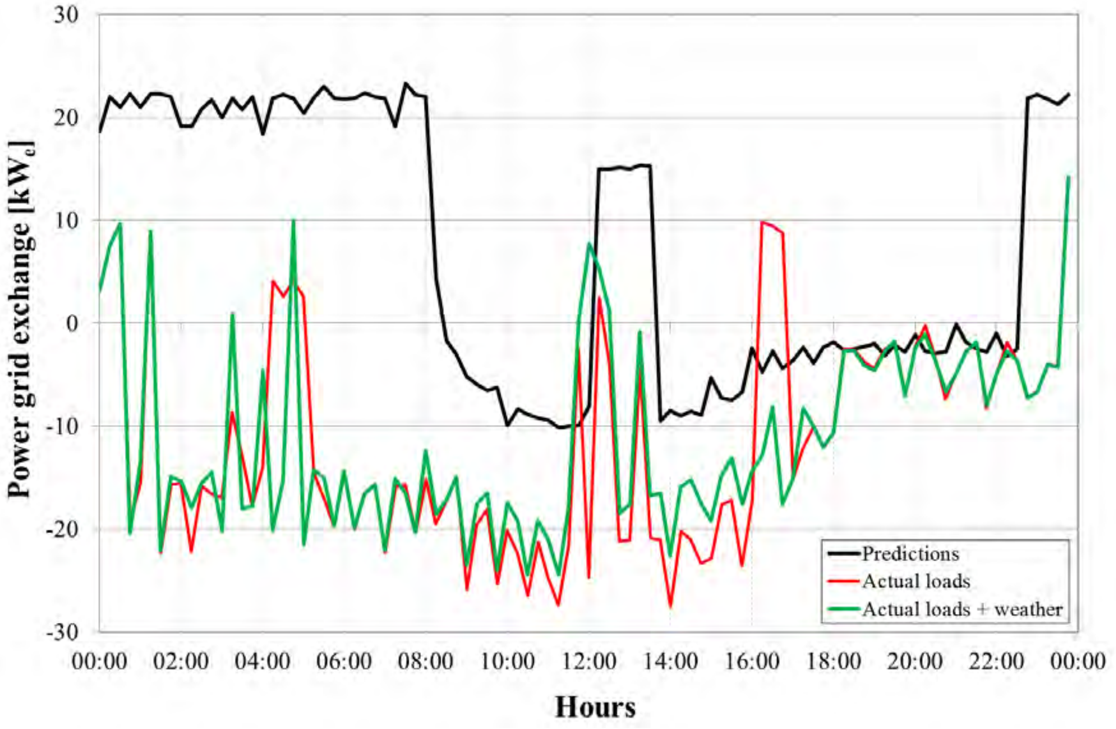


Figure 161 - Comparison of the distribution power grid exchange for the example day

The large decrease in the electricity purchased from the grid (which, in some cases is sold instead of bought) justifies the remarkable difference in the economic result shown in Figure 158, because the auxiliary boiler is never used, thanks to the effective and efficient exploitation of the “hot” storage.

As previously said, no trend analysis can be carried out on the forecast errors, due to the fact that too many parameters have a reciprocal influence one the another, and such a study could bring to misleading results.

6. Conclusions

The PhD project here presented is focused on the study, realization, and experimental analysis of a Smart User system, i.e. a system which could efficiently and reliably manage different energy sources in a small spatial scale context: all the issues related to the implementation of the system and to the performed experimental analyses are described.

In particular, the design process started from a “white paper” condition, giving the possibility to build and develop the system with few fundamental constraints, allowing to conceptualize from the beginning both the plant layout and the computational tools and algorithms best suiting the particular application context.

As first, the issues of the problem were individuated, starting from the considerations that the developed system should be easy to be inserted in the Smart Grid concept. For this reason, a deep and wide range analysis on the next-future energy systems was carried out, focusing both on the large scale systems, such as the mentioned Smart Grid and the Micro Grid, and the smallest contexts, like the Virtual Power Plant, which gave the impulse to create something new with respect to the existing paradigms and at the same time which could be easily coupled with them. The Smart User concept was thus developed, always keeping an eye on the next energy scenarios: on the basis of this latter consideration, one of the fundamental issues is the intelligent coupling between renewable and fossil resources, which have to be integrated in a way not to “feed” the grid with a random and unpredictable power profile, rather than a programmable energy exchange. In addition to that, given the uncertainties on the main direction which the power system could bring and the need for the Smart User system to be easy to install in different World areas, the other fundamental requirement was considered as the flexibility of the system: both the hardware and, above all, the developed software should be as much parametric as possible, in order to be suitable for different regulating constraints.

In a second step, the development of the hardware layout and of the management software were contemporarily carried out: the plant layout driving the implementation of the optimization algorithm capable to efficiently manage all the energy resources of the Smart User, and backwards the computational tool helping to understand the most suitable plant configuration possible, considering different needs, starting from the reliability of the energy supply to the maximization of the cost savings for the final user.

For the development of the optimization algorithm a literature analysis of the existent was carried out, in order to understand the most common features of the research system which could be interesting for the future energy needs of the users and to overcome their most evident limits, with the untold objective of realizing a system as much complete as possible, which could manage different kind of energy needs from different sources. The main target of that was represented by the minimization of the energy costs of the plant and, as a natural consequence of that, the carbon emission connected to it, by efficiently integrating DG and high efficiency systems, fed both from fossil fuels (natural gas micro-CHPs, gas boilers, etc.) and from renewable sources (PV panels, micro-wind turbines, etc.). Of course, the algorithm should be applicable to a variety of context than the tested one, by keeping its main technical characteristics as parametric and easily modifiable.

For all these present reason, the choice of the optimization technique fell on the Genetic Algorithms, which are easily implementable also with a variety of different constraints to be satisfied and, in addition to that, easily modifiable if needed.

The Smart User system was chosen to operate on the basis of three different time-period scenarios: the “Day Ahead” optimization, with a 15-minutes time resolution, based on the loads and weather forecasts (these latter ones for the estimation of the RESs production), could built up an optimized schedule of the plant generators for the whole next day. Due to the unavoidable mismatching between predicted and actual data, an “Advanced Dispatching” procedure was also developed, running during the present day each 15 minutes, which could re-schedule the generators until the end of the day on the basis of the last updates of the loads and weather forecasts. In the end, if an exchange power profile with the external grid had to be achieved, a “Real Time” logic procedure was also developed, exploiting the electric storage with the objective of “dumping” the ripples in the electric grid energy exchange, allowing to satisfy the pre-determined target.

In the end, experimental tests on the realized Smart User plant were carried out, showing satisfying results, sometimes better than expected, with a remarkable decrease in the user energy costs and a related high efficiency of the plant, giving the start to new more contextualized research on the issue and a future industrialization of the developed system by the industrial partners of the PhD project.

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