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Monitoring and managing of a micro-smart grid for renewable sources exploitation in an agro-industrial site

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ABSTRACT

The development of smart grids is a strategic goal at both national and international levels and has been funded by many research programs. At the same time, an increasing interest is rising about local energy systems using renewable energy sources (RES). In this paper, the creation of a monitoring and managing procedure of an electricity micro-smart grid in a small agro-food enterprise is presented. Scopes of the procedure are both the minimization of the energy exchange between the local grid and the public utility grid and the optimization of the exploitation of renewable sources. To achieve that, it was necessary to match energy demand and supply in as short as possible time steps, trying to create a self-sufficient small district. The two objectives above can also generate financial savings due to the reduction of the electricity purchase from the grid. The agro-industrial test site is a *prosumer* (both a producer and a consumer of energy) and it was equipped with wireless networks of smart meters and devices, monitoring generators and loads, a data acquisition tool and a user interface that shows the monitoring results and suggests the optimization strategies of the smart grid to be undertaken.

1. Introduction

Even though the smart grid concept is widespread, currently there is not a common definition of it, but in general, according to literature, smart grid has to combine two different aspects that can be summarized into the kilowatt-hours and the bytes (Ardito, Procaccianti, Menga, & Morisio, 2013).

In this sense, a definition was given by the Smart Grids European Technology Platform (2010), where smart grid is an electricity network in which the actions of users connected to it are intelligently integrated. It is therefore possible to deliver electricity efficiently and in a sustainable, economic and secure way. A smart grid employs innovative products together with technologies for the monitoring, control and communication.

Another relevant definition was given by U.S. Government (2007) that characterizes the smart grid as a list of achievements, for example the use of digital information (for guaranteeing reliability, security and efficiency), the presence of smart technologies (useful for metering, communicating and automating) and the integration of distributed resources and generation.

By the previous definitions is possible to understand that a standard system becomes "smart" when it is able to sense, communicate, exercise control and give feedback (Gellings, 2009). This is possible by using ICT technologies. By the definitions that were reported, it is also possible to understand how smart grids are responding to the challenges of designing and building power systems of the future (El-Hawary, 2014). The current grid, in fact, can be considered a relic of the past. It was designed to meet the needs of a different industry in a past era with outdated technologies that, nowadays, are not able to meet the current requirements (Sioshansi, 2012) and were not developed considering the increasing use of renewable power generation (Gellings, 2009).

For this reason, a smart grid responds to new needs relying on the implementation of communication systems, sensors, metering systems and intelligent devices for the improvement of the energy management (Moura, López, Moreno, & De Almeida, 2013). Their development can lead to many different benefits such as the secu-

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Nomenclature

Δt	Time step
a	Number of permanent loads
A_{gr}	Relative grid interaction amplitude
b	Number of permanen loads
c	Number of permanen loads
D	Delivered energy
DB	DataBase
E	Net exported energy
EMN	Enegy meter node
F	Feed-in energy
γ	Load cover factor over period t
G	Generator
h	Number of permanent loads
i	Generic time step t
j	Number of mandatory loads
k	Number of shiftable loads
L	Load
m	Number of generators
m, mand	Mandatory
MG	Mesh gate
MN	Mesh node
n	Number of loads
NOSQL	Not only structured query language
p, perm	Permanent
$P_{E\approx 0}$	No grid interaction probability
q	Number of time step t within period T
shift	Shiftable
T	Total time period
WSN	Wireless sensor network

rity of energy supply, the possibility of the utilities to handle new operational scenarios and the new consumption models of smart buildings and cities (Darby, Strömbäck, & Wilks, 2013).

One of the key drivers for the smart grid development is that a more intelligent grid can counter-balance the intermittent and fluctuating energy availability of renewable energy sources that strain the existing networks (Amin, Moussa, & Mohammed, 2012; Arif, Javed, & Arshad, 2014; Maknouninejad, Lin, Harno, Qu, & Simaan, 2012). Many problems arise from the characteristics of energy generators that are not reliable as far as the production continuity and predictability. Among renewable energy generators, the ones that show worse predictability figures are also the ones that can give a larger amount of power (solar and wind). Other kinds of green generators – like biomass ones – are man-activated sources and are therefore controllable, but in the current days they have not yet a widespread diffusion due to the not easy installation and maintenance procedures and to the difficulty of supplying the primary source.

Smart grid is not only a technical concept that relies on new technologies, because the energy use management that can be realized into a smart grid also plays an important role. According to Gellings (2009), the energy use management includes three different methodologies: DER (Distributed Energy Resource), DSM (Demand-side Management) and DR (Demand-Response). DER consists in the use of energy sources (often renewable ones, as previously said) sparsely distributed on the territory and generally near the final use sites. These energy sources are useful because they reduce the dependence from the grid.

DSM and DR are related to the control of energy consumptions of the grid customers. In fact, consumers are seen as an active part of the same smart grid and this interaction and responsiveness of the customers are one of the key issues of the system (Gellings & Samotyj, 2013; Siano, 2014). DSM is not the traditional approach whose objective is to match the supply with the demand, but it aims to reverse this idea, matching the demand with the available supply (Warren, 2014). In order to achieve this result, it is possible to use different techniques (Benetti, Caprino, Della Vedova, & Facchinetti, 2016; Gellings, 1985; Warren, 2014), as energy audits, replacement or retrofitting of the end-use devices and load shaping strategies as the load shifting (Gellings, 2009). Finally, DR, that is defined by Albadi and El-Saadany (2008) as the changes of electrical consumption patterns of end-users as response to the energy price changes over the time, is subdivided in two categories: Incentive Based Programs (IBP) and Price Based Programs (PBP).

Another important novelty in grid issues is the Micro-Grid, that is a collective of geographically proximate, electrically connected loads and generators (Sioshansi, 2012). Until some years ago, the Micro-Grid was a concept mainly applied to isolated communities, with particular emphasis in military sites, with the purpose of creating stand-alone settlements which could be built even in places without the availability of a standard power supply line. Nowadays, this concept fits also in urban, rural and industrial areas, where the need for the energy optimization and prediction pushes towards the implementation of Micro-Grids that use also the technologies of a smart grid in order to create smart communities even in places where the energy grid is available as the St. Paul District (Minneapolis, USA), La Sapienza University in Rome and the British Columbia Institute of Technology Minilab.

In industrial settlements, on-site power generation plants that use micro-smart grids are becoming more common (Abdelaziz & Mekhilef 2011; Mekhilef, Saidur, & Safari, 2011). This allows industries to exploit the financial benefits of the incentives associated to the production from renewable sources, and facilitates industries in taking part in energy initiatives at district level (with other industries or with urban centers), thus creating micro-smart grids (Rawlings, Coker, Doak, & Burfoot, 2014). In rural and agro-industrial sites, biomass generators are installed because of the exploitation of various processing waste.

The use of micro-smart grid implicates another important advantage since the deeper knowledge of the energy consumption of industries is among the interests of many actors of the energy supply chain. Being industries one of the most relevant clients of this chain, public utilities usually offer them specific fees and discounts (similar to IBP or BPB) if they implement some tools to become more predictable energy users, for example monitoring plans to define energy use profiles. In that way, the energy trader can limit the risk deriving from a wrong prediction about the quantity of allocated and purchased energy, and thus reducing the consequent penalties for not correct forecasts. Moreover, the database obtainable through a monitoring activity and by using past years' data, can be the kick-off for a continuous monitoring plan, in order to activate a virtuous process of improvement and control.

The present work starts from the assumption that a great contribution to solve the global issues related to the smart grids lies in a "local approach" to the problem. This scenario leads to the definition of the smart-micro grid (also called micro-smart grid) concept, where all the optimizations and good practices are firstly implemented in local sites, building a sort of smart communities where the consumption of locally generated energy is optimized at local level first (Barbero & Pereno, 2013).

Some works can be found in the literature about the implementation of the above described concepts (Asmus, 2010), concentrating not only on the electricity management and optimization (Manbachi, Farhangi, Palizban, & Arzanpour, 2015) but also on the thermal energy management and optimization.

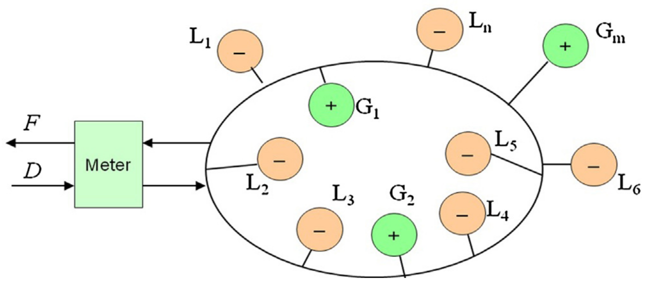

Fig. 1. Scheme of the virtual grid.

1.1. Scope of the work

In this paper, a procedure for the monitoring and the management of a micro-smart grid developed on a small agro-food enterprise is presented. That procedure is based on an ICT architecture able to acquire and report monitored data and to find out the best matching between energy demand and energy supply on a predefined time scale.

The micro-smart grid was developed under a funded project called BEE (Building Energy Ecosystems). Its strategic objective was on one hand the minimization of the energy exchanges between the local grid and the public utility grid and, on the other hand, the optimization of the exploitation of renewable sources. To obtain these objectives, it was necessary to match the energy demand and the energy supply in quite short time periods, going towards a self-sufficient small district. In particular, in this case the shiftable load scheduling was used, because this method was implemented particularly on smart grid (Gelazanskas & Gamage, 2014) and it seemed the most appropriate for the test site.

The industry test site was equipped with: wireless networks of smart meters monitoring the generators and the loads; embedded devices that acts as gateways, data storage and elaboration systems and a user interface to visualize monitored data and suggest the optimization strategies of the smart grid based on the DSM load shifting principle. In this paper, the system architecture, the smart grid modeling, the development of the instant and predictive optimizations and the smart grid monitoring system are presented and some results are discussed.

During all the development stages, there has been a close collaboration with an energy trading company in order to properly design the overall constraints, and to build a valuable solution from both the energy user's side and the utility and energy trader points of view. The energy supply of the site depends on a variety of non-predictable renewable sources and the energy management was obtained through the interaction with people living, working and managing the daily industrial activities on the test site.

Firstly, the methodology that was adopted for the smart grid modeling is presented, then the application to the case study and an example of results are described.

2. Methodology

2.1. Smart grid modeling

In order to simplify the modeling of the smart grid, the scheme reported in Fig. 1 was adopted. Its elements can be grouped into two main categories: the energy consumers (loads) are identified with a minus and with L, while the energy producers (generators) are identified with a plus and with G. The model is generalized as a system composed by n loads and m generators (L_n and G_m). The definition of the system boundaries is of great importance: the elements belonging to the local grid can be seen as an *unicum*: their relationship with the external grid is limited at just one connection point where a meter is usually placed (identified as meter in Fig. 1).

In that way it is possible to quantify:

- the total amount of energy produced by the generators and sent to the external grid (F, feed-in energy);
- the total amount of energy required by the loads and provided by the external grid (D, delivered energy);
- the net exported energy, E, defined as the net energy exported from the system to the external grid (Eq. (1))

$$E(\Delta t) = F(\Delta t) - D(\Delta t) \forall \Delta t \in T \quad (1)$$

The aim of the smart grid management is to find the conditions that limit the energy import from the external grid and maximize the use of on-site generated energy. The net exported energy (E) should tend to zero at each time step (thus arriving as close as possible to a self-sufficient small district) or it should assume positive values (thus resulting in a positive energy system that produces more energy than the one it is consuming within a certain time period).

Each load is characterized by a profile of requested energy during time, called $l_n(t)$; similarly, for each generator a profile of energy generated during time can be defined, called $g_m(t)$. The energy requested by a generic user L during the time period Δt is the integral of the function l_n extended to the whole period Δt

$$L_n(\Delta t) = \int_t^{t+\Delta t} l_n(t)dt \text{ [kWh]} \quad (2)$$

In the same way, the energy produced by a generator G in the period Δt, can be expressed as

$$G_m(\Delta t) = \int_t^{t+\Delta t} g_m(t)dt \text{ [kWh]} \quad (3)$$

The total energy requested by all users of the local grid during the time period Δt, is called $L(\Delta t)$ and it is defined as the sum of all the requested energy quantities L_n by all loads L

$$L(\Delta t) = \sum_n L_n(\Delta t) \quad (4)$$

Similarly,

$$G(\Delta t) = \sum_m G_m(\Delta t) \quad (5)$$

If the produced energy is not consumed locally and if no energy storages are present, the net exported energy, according to Eq. (1) can also be expressed as the difference between the total energy produced on site and the total energy demand as

$$E(\Delta t) = G(\Delta t) - L(\Delta t) \quad (6)$$

2.1.1. Load clustering

In order to define an algorithm for the smart grid management, both the loads and the generators were divided into clusters. In particular, the loads were clustered as a function of different priority and importance for the company, following a classification that is also used in the domestic sector (Vázquez, Kastner, Cantos Gaceo & Reinisch, 2011). They were divided into the following sub-groups:

- Permanent Loads (L_{perm}): those uses or devices that work continuously over the time periods;
- Mandatory Loads (L_{mand}): those uses that are not always in activity but that, for their function, must be activated immediately when requested;
- Shiftable Loads (L_{shift}): those uses that are not working continuously and, because their function is not essential, can be temporarily switched off and activated later.

Shiftable loads can be considered as the only free variables of the system and the only elements that can be modified for optimization purposes, since they can be postponed, if it is necessary to balance the smart grid during a certain period of time Δt.

According to this loads classification, the previous total energy demand, $L(\Delta t)$, can be split into 3 terms, as expressed in Eq. (7). The total number of permanent loads, of mandatory loads and of shiftable load is identified as a, b and c respectively, being $n = a + b + c$.

$$L(\Delta t) = \sum_n L_n(\Delta t) = \sum_a L_{perm,a}(\Delta t) + \sum_b L_{mand,b}(\Delta t) + \sum_c L_{shift,c}(\Delta t) \quad (7)$$

2.1.2. Instant and predictive optimization

A first objective of the smart grid management is the minimization of the electricity exchange with the public utility grid. To that purpose, the objective function of the optimization problem can be expressed as

$$f(E(\Delta t)) = 0\forall(\Delta t) \in T \quad (8)$$

and searches for a net exported energy $E(\Delta t)$ close to zero, at each time period Δt. According to the definition of $E(\Delta t)$ given in Eq. (6) and substituting the value of L with the loads classification provided in Eq. (7), the net exported energy from the system to the external grid, can be expressed by

$$E(\Delta t) = G(\Delta t) - L(\Delta t) = \sum_m G_m(\Delta t) - \sum_a L_{perm,a}(\Delta t) - \sum_b L_{mand,b}(\Delta t) - \sum_c L_{shift,c}(\Delta t) \quad (9)$$

The decision variables of the optimization problem are the shiftable loads. A Boolean parameter π is introduced in the model and it is associated to each load to indicate its activation in a given period of time (0 indicates the off mode and 1 indicates the on mode).

$$\pi = [0, 1] \quad (10)$$

By associating a parameter π to each load, the objective function can be written as

$$E(\Delta t) = \sum_m G_m(\Delta t) - \sum_a \pi_{Lp,h} L_{perm,h}(\Delta t) - \sum_b \pi_{Lm,j} L_{mand,j}(\Delta t) - \sum_c \pi_{Ls,k} L_{shift,k}(\Delta t) \quad (11)$$

The solution of the optimization problem (expressed by Eq. (12)) is a set of n parameters π, one for each load: this combination of various switching on and off modes of the loads satisfies the balance, as it is expressed in Eq. (6), and also the constraints expressed in Eqs. (13) and (14). These last equations represent the π parameters of the permanent and mandatory loads.

$$\{\pi, \ldots., \pi\} : (E(\Delta t)) \rightarrow 0\forall \Delta t \in T \quad (12)$$

$$\pi_{p,i} = 1\forall i \quad (13)$$

$$\pi_{m,j} = 1\forall j \quad (14)$$

Each shiftable load with π equal to zero should be switched off during the considered time period, while each shiftable load with π equal to 1 must be activated during the same time period. This approach presents some similarities to the optimization performed for multi-energy systems of previous works (Fabrizio, Filippi, & Virgone, 2009a, 2009b; Fabrizio, 2011).

If the instant optimization is repeated for many consecutive time steps, it is possible to schedule an all day, week or month, thus planning the activities in the best way to match both energy optimization goals and production needs. The considered time period is defined in Eq. (15) as T and it includes all time steps Δt_i.

$$T = \sum_{t=0}^{i} \Delta t_i \quad (15)$$

The objective function reads in this case

$$f\left(\sum_{i=1}^{q} |E(\Delta t_i)|\right) \rightarrow 0\forall \Delta t \in T \quad (16)$$

Eq. (16) is similar to the instant optimization but it is extended to many time periods and the optimization is done on the absolute value of the net exported energy, in order to avoid the possible compensations between positive and negative values of $E(\Delta t)$ in different Δt intervals. The loads classification and the meaning of the parameters π are the same as of the instant optimization case.

The problem solution is the set of parameters π, referred to the shiftable loads, as expressed in Eq. (17). Those values compose a matrix with q rows, corresponding to the included time periods, and k columns, corresponding to all considered shiftable loads, as shown in Fig. 2.

$$\left\{\pi_{Ls,\Delta t1}, \ldots, \ldots, \pi_{Ls,\Delta tq}, \right\} : \left(\sum_{i=1}^{q} |E(\Delta t)|\right)) \rightarrow 0\forall \Delta t \in T \quad (17)$$

In order to meet the daily production needs, that are independent from energy issues, the staff in charge of the production management can define the total number of activation periods that each shiftable load must complete in the time period T. These loads, as identified as shiftable, are considered in the optimization as machineries whose activation can be planned in the most suitable time steps (according to the energy matching goals) with a certain required number of working cycles that must be completed over the considered time period (according to the company orders and needs).

The total number of activation periods, for each shiftable load, is a new constraint for the algorithm as written in Eq. (18), as

$$\sum_{k=0}^{c} \pi_{Ls,k} = x\forall L_{s,k} \quad (18)$$

The result is a plan of activities for the period T, shown by an user interface, where a combination of various switching on and off modes of the shiftable loads is able to take the whole system as close as possible to the balance, satisfying both the energy matching goals and the needs of the company about the use of machineries (labor cost, time to market, etc.. . .).

2.2. Smart grid monitoring

The smart grid monitoring system can be represented by the scheme shown in Fig. 3, in which each layer performs a specific function within the architecture referable to the Internet of Things (IoT) paradigm. The scheme distinguishes three layers, which will be described in detail following a bottom-up approach:

- Smart metering layer.
- Network layer.
- Application layer.

The first layer is the smart metering one, which deals with the measurements of the energy consumed by shiftable loads and with the energy produced by using renewable energy sources.

k shiftable loads →

TERMS GENERATED BY THE ALGORITHM (*q* timesteps ↓)	$\pi L_{shift1, \Delta t1}$	$\pi L_{shift2, \Delta t1}$	$\pi L_{shift3, \Delta t1}$	…	$\pi L_{shift\,k, \Delta t1}$
	$\pi L_{shift1, \Delta t2}$	…	…	…	
	$\pi L_{shift1, \Delta t3}$	…	…		
	…	…			
	…				
	…				
	$\pi L_{shift1, \Delta tq}$	$\pi L_{shift2, \Delta tq}$	$\pi L_{shift3, \Delta tq}$	…	$\pi L_{shift\,k, \Delta tq}$
KNOWN TERMS (WORKER INPUTS)	$\sum \pi L_{shift1, T}$	$\sum \pi L_{shift2, T}$	$\sum \pi L_{shift3, T}$		$\sum \pi L_{shiftk, T}$

Fig. 2. Matrix resulting from the predictive optimization algorithm.

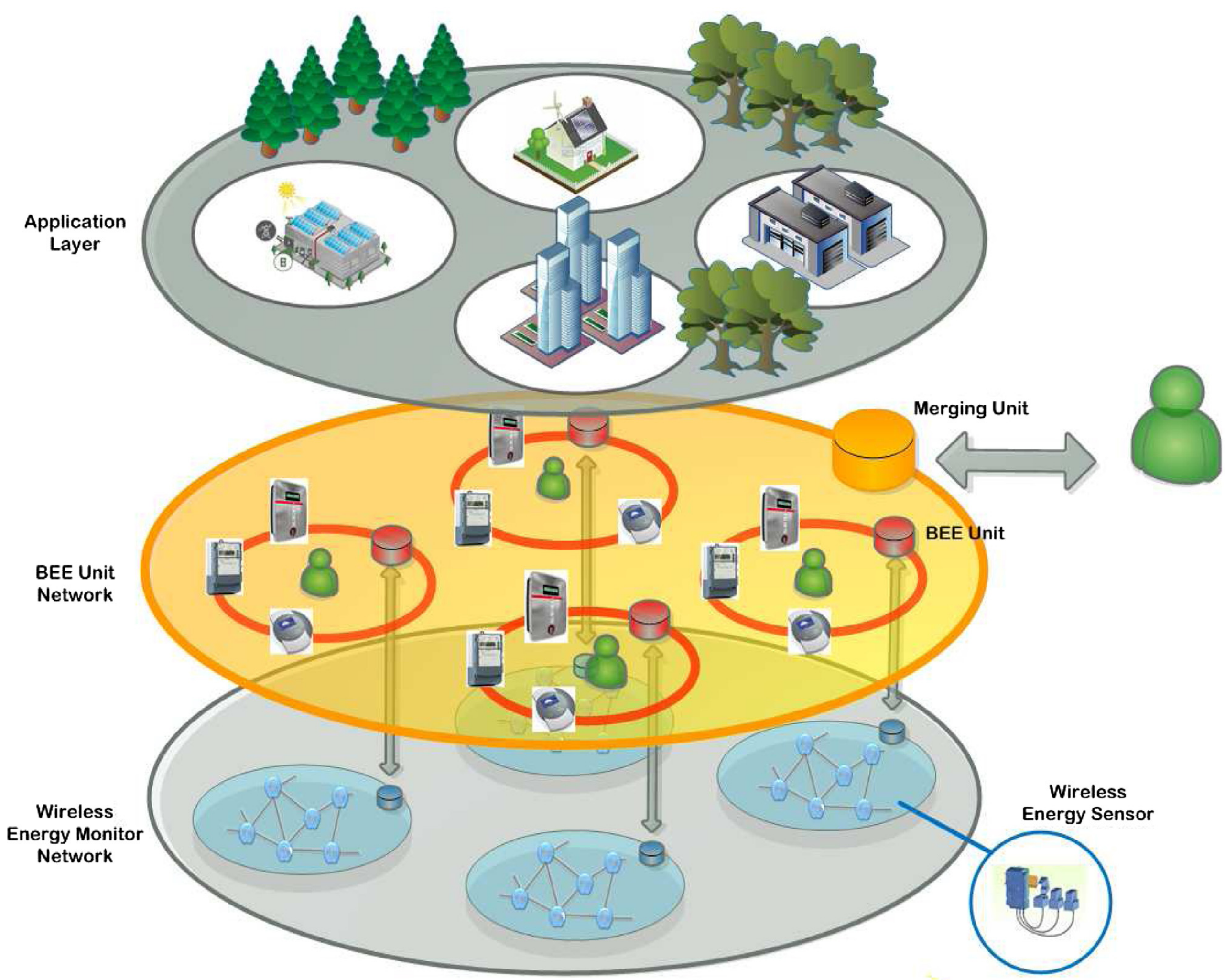

Fig. 3. Architecture of the micro-smart grid monitoring system.

The network layer is the second layer of monitoring system and its main elements are the embedded devices called BEE-Units. Each BEE-Unit is a device that interfaces directly the measurements systems both for the generators and the loads. It has been developed in order to be a flexible solution in a smart grid scenario, including for example the possibility to be interconnected with different type of devices.

Such devices include:

- Voltage and current probes;
- Energy meters already on the market as off-the-shelf components, with which the unit is able to dialogue through typical serial interfaces, like RS-232 or RS-485;
- Data loggers of energy production plants;
- Electricity counters, normally installed in conjunction with electric generators as in the case of photovoltaic units, biomass or wind turbines.

The BEE-Units send the data acquired from different measurement systems to a central control unit, called Merging Unit, through a networking module that could use either Ethernet interface or Wi-Fi interface. The Merging Unit is a data platform in which all the measures are stored in a database (DB).

Finally, there is the application layer that hosts the programs for the elaboration of the data finalized to the micro grid management. In this layer the local energy optimization algorithm described in Section 2.1.2 runs continuously, providing instructions and suggestions to make the system closer to the balance. A user interface input form can activate the predictive optimization algorithm.

The intelligent central unit shows information through an interface (Fig. 4). Beyond the real time energy balance, it also shows energy consumption and production profiles as well as some KPIs related to the load-matching or grid-interaction, that easily communicate how the system is performing about the desired results.

Three indicators were calculated to analyze the performance of the overall system and the fulfillment of the project goals. These are:

2.2.1. Load cover factor over period T ($\gamma(\Delta t)$)

it is the ratio between the smallest between the total generated power and the total requested power, over the total requested power.

$$\gamma(\Delta t) = \frac{\min\left[G(\Delta t), L(\Delta t)\right]}{L(\Delta t)}\ [\%] \tag{19}$$

It expresses in percentage which is the part of the total load that was supplied by on site generated energy. In the most successful case, it will be equal to 100%, thus meaning that the all demand was supplied by on site generation. There is no consensus in literature on the magnitude of the (Δt). For example, Salom et al. (2011), that reports similar indexes, does not clarify the magnitude. In the general description of the management procedure, the magnitude can be variable (e.g. from some minutes to 1 h); in the practical example of application and in the monitoring system that was developed on the test site, the Authors adopted a time step of 1 h for the production optimization.

2.2.2. Relative grid interaction amplitude (Agr)

it is the difference between the maximum and the minimum values of net exported energy registered over period *T*, both normalized by the total design load of the system

$$A_{gr} = \frac{\max\left[E(\Delta t)\right]}{L(\Delta t)_{des}} - \frac{\min\left[E(\Delta t)\right]}{L(\Delta t)_{des}}\ [-] \tag{20}$$

2.2.3. No grid interaction probability ($PE \approx 0$)

it represents the probability that the system is working in autonomy of the grid, by using on site generation to cover the entire load. It is the number of time steps characterized by a value of net exported energy almost equal to zero, over the period *T*, this ratio being expressed in percentage

$$P_{E\approx 0} = \frac{time_{|E(\Delta t)|<0{,}001}}{T}\ [\%] \tag{21}$$

3. The case study

3.1. The demo site

The demonstrative (demo) site is a small enterprise named *Agrindustria Tecco Srl.*, located in Piedmont region (North-west of Italy); the factory processes natural and vegetal materials by various working phases (cutting, drying, cooling, etc.). The enterprise produces final products as pellets, pre-cooked flours, raw materials for cosmetics, pharmaceutical and feed industry, but also carries out intermediate tasks for other companies, as drying or low temperature micronization.

The industrial area is composed by 4 main detached buildings, where different process phases are carried out, divided by open areas, plus a civil building in which the offices are present. A canopy was recently built in order to shield the gasifier and the co-generation plant.

The buildings features, their use and size are listed in Table 1. The buildings devoted to productive activities consist of about 6620 m^2 of floor area and a corresponding total volume of 67,350 m^3.

3.2. The energy system

Agrindustria Tecco Srl. can be considered a *prosumer*, that is both consumer and producer of energy. Thus the layout of the energy system characterizing the demo-site, from both the energy demand side and the energy production side, contains many loads and generators that need to be considered in their mutual relationships (Branciforti, 2013).

The energy users depend on the activities carried out. These can be grouped into “civil users” for the office building (ICT, printers and kitchen appliances), “industrial users” (productive machineries) and “building services”, aimed at maintaining environmental conditions suitable for the different activities (lighting, environmental heating and cooling, safety systems, automatic gates and transportation systems). Among them, the industrial users represent of course the higher energy demand and are the focus of the present work.

A list of the energy demand side and supply side options is shown in Table 2. The following energy sources are exploited:

- electricity from the public utility grid;
- gasoline from external supplier;
- thermal energy, derived as waste of the syngas combustion process;
- self-produced electricity from PV panels installed on the buildings roofs;
- self-produced electricity, deriving by a co-generation plant with internal combustion engine supplied by syngas.

Part of the energy is obtained by renewable energy sources. These are:

- solar radiation, to produce electricity through PV panels;
- biomass, to produce syngas and consequently thermal energy and electricity;
- wind-energy, through a small wind generator placed on steam chimneys [a prototype].

In Table 2 renewable energy sources (RES) plants can be identified. In particular, the use of PV panels and of the gasifier, while actually the mini-wind generators in chimneys is at the prototype stage due to its very low power (2 kW).

In the demo site there are two PV plants. The first one is placed on the roofs of Building 1 and Building 2, it has a peak power ok

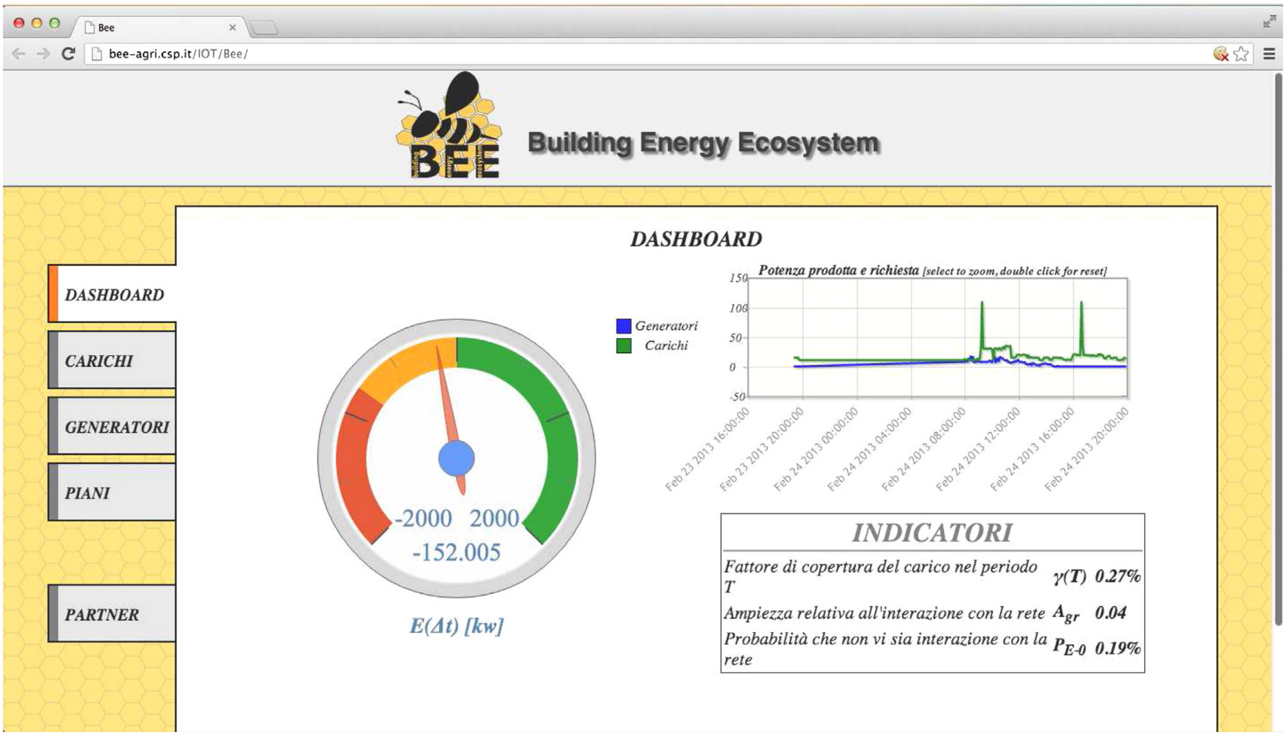

Fig. 4. User interface.

Table 1
Description of the buildings included in the industrial area used as demonstrative site.

Building	Use	Covered area[a] [m^2]	Volume[b] [m^3]
Offices	Offices and kitchen	130	/
Building 1	Raw material processing	600	4500
Building 2	Storage of raw material and packaged product	1500	10000
Building 3	Pellet production	840	11350
Building 4	Corn derived production and storage	3200	41500
Gasifier roof	Protection of co-generation plant	350	/
	Total	6620	67350

[a] (Closed or not by vertical walls on all sides).
[b] (Only completely enclosed spaces).

Table 2
List of the energy demand of the case study and of the different ways they are supplied.

Energy demand	Energy supply and on site production
Electricity	Electricity from the public grid (external supplier)
	Electricity from PV panels (solar radiation on site)
	Electricity from syngas engine (biomass in the gasifier on site)
	Electricity from mini-wind generators (wind generators in chimneys) [prototype]
Thermal Energy	Thermal energy from gasoline (external supplier)
	Thermal energy from syngas combustion (gasifier on site)
Thermal Energy for cooling purposes	Electricity from the public grid (external supplier)

197 kW_p and can produce about 180 MWh per year (from monitored data of 2013). The second one is placed on the roofs of Building 3 and Building 4, it has a peak power ok 523 kW_p and it is estimated to produce about 560 MWh per year. The PV plants are provided with a 22 kWh storage system.

The other RES used in *Agrindustria Tecco Srl.* is biomass, in particular wood chips that is converted into *syngas* by a partial oxidation process that is carried out in the gasifier. The obtained *syngas* is used in a cogeneration system in order to both produce thermal and electrical energy. The nominal power of the gasification and cogeneration system is 200 kW_e and it is fuelled by 200 kg of wood per hour.

A schematic representation of the internal electricity distribution network is reported in Fig. 5, where all elements listed above are displayed together with their connections and locations. Different fossil energy sources and renewable ones (biomass, solar energy, etc.) are used because of already existing power plants.

On the left side, the 3 main energy sources used within the factory are listed (electricity from the public grid, solar energy and biomass). On the right side, all final users are listed and named according to the names used by the internal staff, to facilitate the cooperation and understanding of the project development. The users are clustered in some groups (grey areas in Fig. 5), depending on the building they are located in. In the central part of the schematics, some energy converters are represented, as the PV pan-

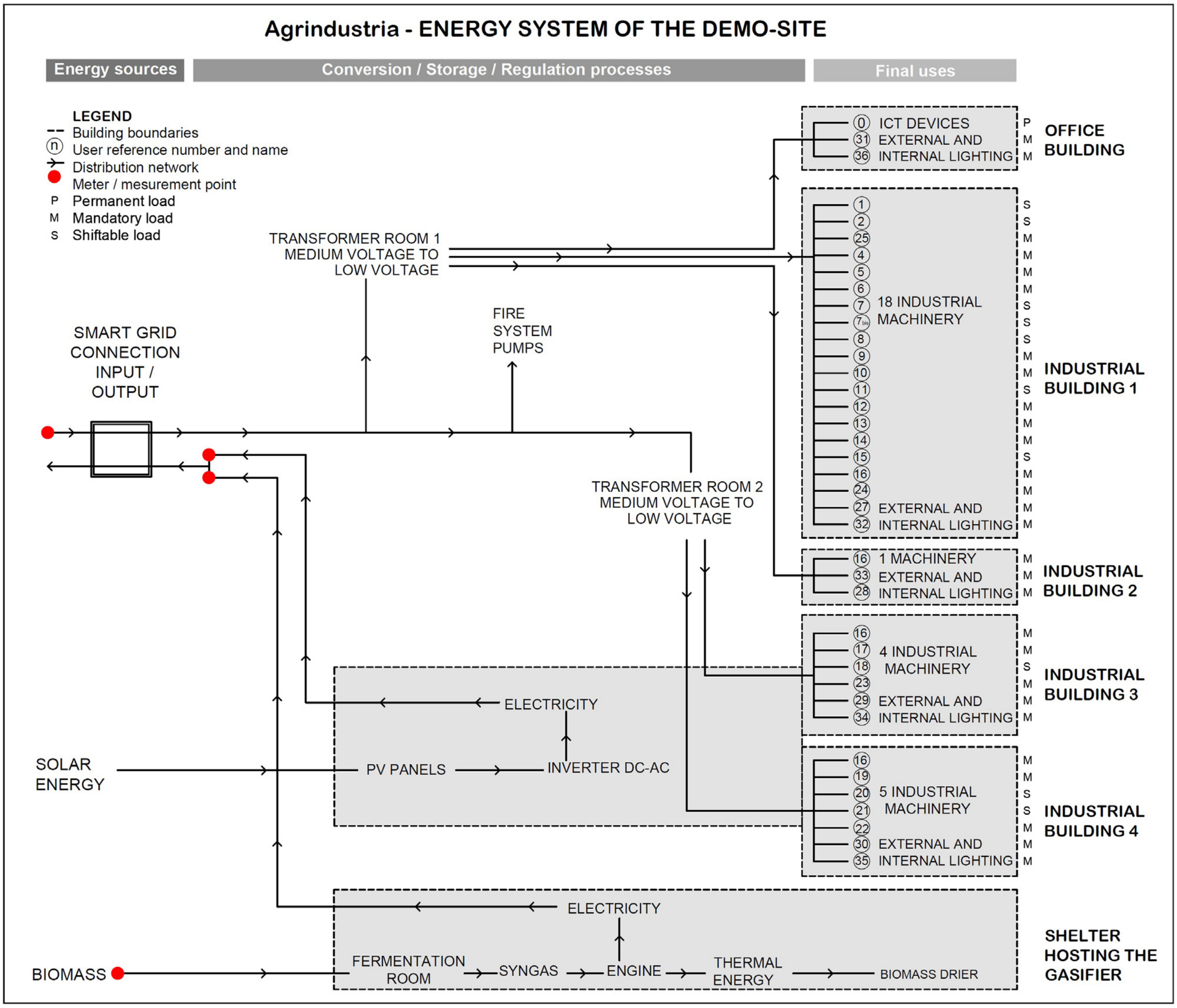

Fig. 5. Schematics of the energy system of demo-site.

els and the gasifier. The lines connecting these elements and the arrows show the way electricity is distributed from the delivering point to all buildings, and from the arrival point of each building to the machineries and building services (HVAC, lighting, communication, alarms, etc.). All users are identified by their own name and a numeric code, useful to recognize them in all following elaborations. In Fig. 5 the distinction between mandatory, permanent and shiftable loads (indicated as M, P or S respectively next to each number/name of the machinery) can be found for each final use.

In order to characterize the energy demand (requested power and its time profile), an inventory of the energy users was organized, using data deriving from the owner experience and needs (Asian Productivity Organization, 2008). Each productive line composed by more than one machinery was considered as a single unit with total power request equal to the sum of all the engines composing a production line.

For each productive line, the following information were also collected:

- the use pattern, in particular the power profile, the average daily and weekly working hours and the activation days per each week, according to the owner experience during last years. As an example of the loads monitoring, the power profile of the corncob crasher machinery for a typical week is reported in Fig. 6.
- the time that is necessary to complete a working cycle and after which it is possible to stop the machinery;
- the possibility to stop the activity of each machinery for a certain period of time – in order to apply the load shifting principle – according to the clients requests and the orders to be dispatched;
- the location of each machinery in the building, in order to prepare possible monitoring activities that need the machineries to be connected to an electricity sub-station.

The energy consumption data of the last 4 years were also analyzed in order to know how the system was performing before the proposed management strategy was put in place. The average electricity consumption of the period 2008–2011 was about 3 GWh per year. More information on the monitoring activity of some of the machineries of the test site are reported in the Data in brief related to this article (Fabrizio et al., 2016).

3.3. Monitoring system

The smart metering layer deals with the measurements of the energy consumed by shiftable loads and of the energy produced by

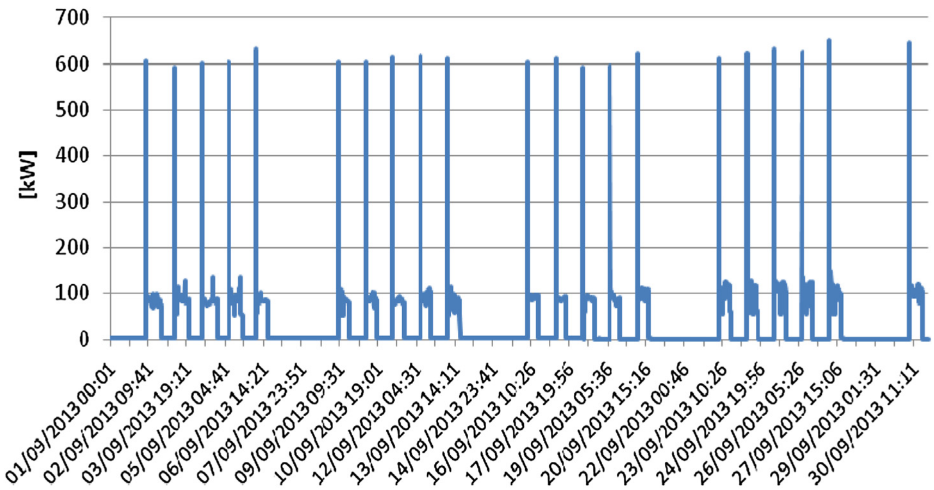

Fig. 6. Power profile of a corncob crasher (corresponding to L_{shift9}).

renewable energy sources. In the case study, the chosen solution for loads monitoring was the Wi-LEM (Wireless Local Energy Meters) system, supplied by LEM, a worldwide leader in current transducers production. LEM current transducer are very useful in an industrial context where 3-phase high currents have to be measured, and they allow acquiring measurements without modifying the already existent plant wiring.

The system allows to measure continuously and in real-time the energy consumption of shiftable loads through a network of wireless sensors that communicate using the IEEE 802.15.4 standard. That system is very resilient and suitable to be used in a harsh environment, such as an industrial one, which is characterized by many obstacles from the radio propagation perspective.

Wireless sensor networks deployed in the demo site use a mesh topology, that is deeply fault-tolerant, and use three type of devices:

- Mesh Gate*(MG):* the device which acts as coordinator of the network;
- Mesh Node (MN): this device acts as an intermediate router, ensuring a reliable wireless communication in extended areas even in case of presence of obstacles.
- Energy Meter Node (EMN): this device measures different energy physical quantities such as, active, reactive and apparent power as well as the current and the maximum voltage.

BEE-Units are used in the network layer, interfaced at this level with the following components:

- Wi-LEM wireless sensor networks, that measure the energy consumed by shiftable loads; the communication between the MG and the BEE-Unit is based on the Modbus protocol
- Data-Loggers produced by Solar-LOG that measure the energy produced by photovoltaic plants.

BEE-Units send data acquired from different measurement systems to a Merging Unit, in which all the measured data are stored in a NOSQL (Not Only Structured Query Language) DB, a not relational DataBase which is very suitable to manage a big amount of data. In addition to real time data from measurement tools on the field, other data converge to the Merging Unit platform, like weather forecast, estimation based on previous days and constraints decided by the user for the considered period (urgent orders, priority of some activities, need to work with some machineries, etc.).

4. Example of results

In the following paragraph an example of the optimization strategy that was realized into the micor-smart grid of the demo site is presented. The micro-grid was defined to be programmed along a period T composed by 8 time intervals Δt of one hour and having the following features:

- 3 generators of the following design power:

$$G_1 = 523\,\text{kW(PVpanelsonbuildings3and4)}$$

$$G_2 = 196\,\text{kW(PVpanelsonbuildings1and2)}$$

$$G_3 = 200\,\text{kW(gasifier)}$$

with a total maximum produced power is 919 kW, as shown in Fig. 7;

- permanent loads (e.g. servers) and mandatory loads (e.g. emergency lighting system) with the following features:

$$\Sigma L_{perm} = 953\,\text{kW}$$

$$\Sigma L_{mand} = 1040\,\text{kW}$$

The previous values may be lower, depending on the considered interval (for example because of daily hours of offices activity or evening and night time with light activation). The power requested by these loads is represented in Fig. 8;

- 7 shiftable loads, with the following features:

$$L_{shift1+2} = 31\,\text{kW}$$

$$L_{shift3+4+5} = 75\,\text{kW}$$

$$L_{shift6} = 34\,\text{kW}$$

$$L_{shift7} = 127\,\text{kW}$$

$$L_{shift8} = 144\,\text{kW}$$

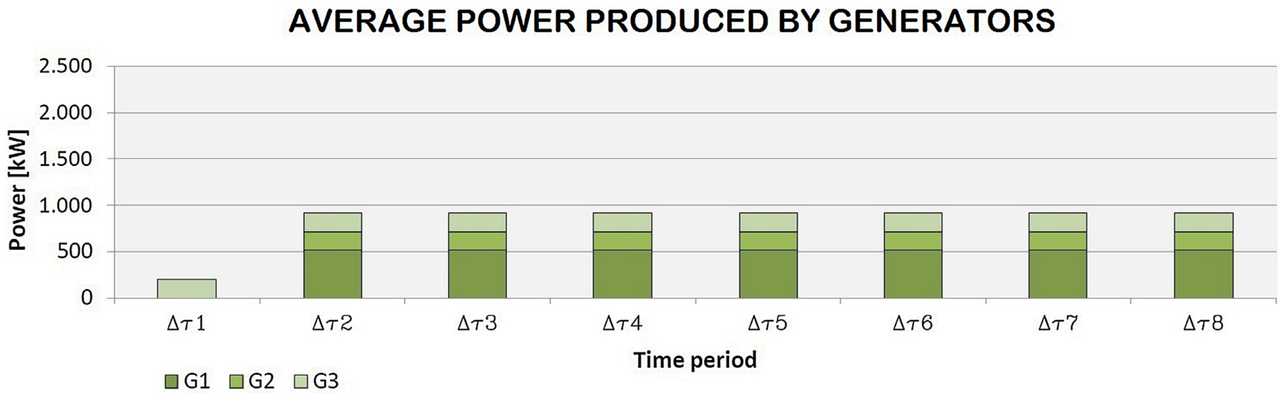

Fig. 7. Average power produced by generators in the 8 time intervals period T.

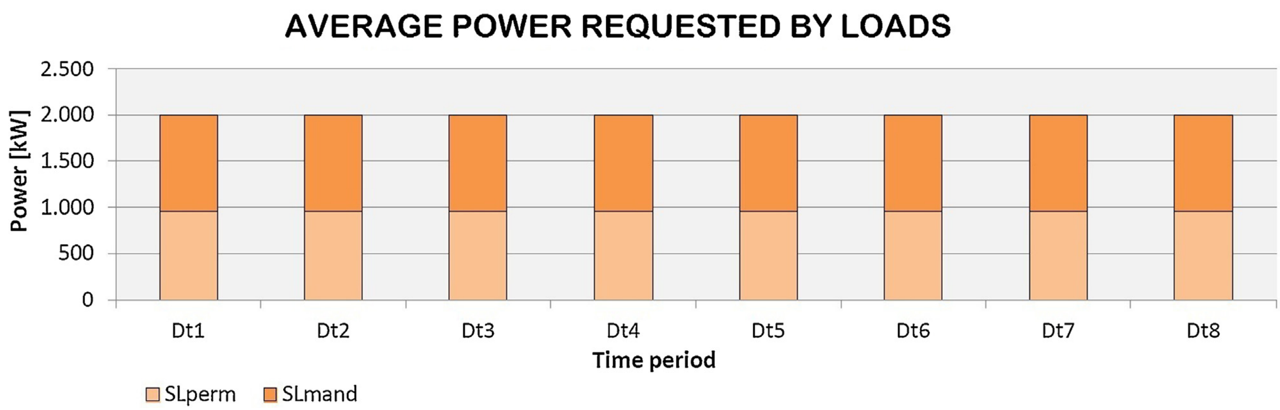

Fig. 8. Average power requested by permanent and mandatory loads over period T.

$L_{shift9} = 10\,\text{kW}$

$L_{shift10} = 18\,\text{kW}.$

More information about shiftable loads are provided in Table 3. In this table, for each shiftable load considered in this analysis, more data are showed. These are the task carried out by the machinery, the duration of a single production cycle, the estimated working time and the nominal power of the machinery. In the last row the total nominal power of the shiftable loads is given. In this way it is possible to compare that value (439 kW) with the total permanent loads value (953 kW), the total mandatory loads value (1040 kW), the total power from PV plants (197 and 560 kW_p) and the power from the gasifier (220 kW_e);

- for each shiftable load a number of necessary activations time steps during the time period *T* is defined. The information is provided as total amount of activations time steps for the 7 shiftable loads:

$$\Sigma\pi L_{shift1+2} = 2$$

$$\Sigma\pi L_{shift3+4+5} = 1$$

$$\Sigma\pi_{Lshift6} = 3$$

$$\Sigma\pi_{Lshift7} = 1$$

$$\Sigma\pi L_{shift8} = 1$$

$$\Sigma\pi_{Lshift9} = 2$$

$$\Sigma\pi L_{shift10} = 1$$

This means that the first group of machineries must be activated twice during the period *T*, the second only once, the third 3 times and so on. These data are defined as a function of the production requirements by the site manager and change daily.

The constraints can be expressed as follows:

$$\pi L_n = [0, 1]\pi L_{perm} = 1\pi L_{mand} = 1\text{or}0$$

$$\Sigma\pi L_{shift\,1+2} = 2;\ \Sigma\pi L_{shift3+4+5} = 1;\ \Sigma\pi L_{shift6} = 3;$$

$$\Sigma\pi L_{shift7} = 1;\ \Sigma\pi L_{shift8} = 1\,\Sigma\pi L_{shift9} = 2;$$

$$\Sigma\pi L_{shift10} = 1$$

The group of values that, for the given constraints, satisfies Eq. (17), are represented in a matrix in Fig. 9. Each column represents one of the 7 shiftable loads and each row represents one of the 8 time steps Δt. The energy produced by generators is not enough to supply not even permanent and mandatory loads. The situation changes after the time step Δt_1, when two more generators start working. It is in that phase, since the 2nd time step, that the problem solution indicates how to locate the shiftable loads, distributing them in order to arrive close to the system balance and at the same time to satisfy the requested number of working processes, that are part of the constraint.

Because the problem is more complex than the one of “instant optimization”, it is not always possible to arrive to an exact grid

Table 3
List of the shiftable loads of the test site.

Code	Machinery	Time for a production cycle [min]	Estimated working time [h/year]	Nominal power [kW]
L_{shift1}	Clay micronization	10	2000	25
L_{shift2}	Clay bagger	3	1500	6
L_{shift3}	Steam autoclave (to prepare product for further tasks)	15	2400	17
L_{shift4}	Sanitizer for thermal treatment	15	3000	19
L_{shift5}	Belt dryer	30	400	39
L_{shift6}	Seeds micronization at low temperature	10	1600	34
L_{shift7}	Knife mills (preparing the product starting from scraps)	10	2500	127
L_{shift8}	Corncob crasher (preparing product for further tasks	15	2500	144
L_{shift9}	Corncob crasher (preparing product for further tasks	15	2000	10
$L_{shift10}$	Batteries recharger for forklifts	60	250	18
			Total	439

k shiftable loads →

q timesteps ↓

		$L_{shift\ 1+2}$	$L_{shift3+4+5}$	$L_{shift\ 6}$	$L_{shift\ 7}$	$L_{shift\ 8}$	$L_{shift\ 9}$	$L_{shift\ 10}$
TERMS GENERATED BY THE ALGORITHM	Δt_1	0	0	0	0	0	0	0
	Δt_2	0	0	0	0	0	1	0
	Δt_3	0	0	0	0	1	1	0
	Δt_4	0	0	0	1	0	0	0
	Δt_5	1	0	1	0	0	0	1
	Δt_6	0	0	1	0	0	1	0
	Δt_7	0	0	1	0	0	0	0
	Δt_8	1	1	0	0	0	0	0
KNOWN TERMS (WORKER INPUTS)		**2**	**1**	**3**	**1**	**1**	**2**	**1**

Fig. 9. The matrix resulting from "predictive optimization".

balance at each time step: nevertheless, the solution is the closest to the energy balance. Fig. 10(A) shows the time steps in which the electricity demand is higher than the electricity supply. Fig. 10(B) represents the value of $E(\Delta t)$, net exported energy from the local grid to the external one, calculated as difference between produced and consumed energy. Negative values highlight a scarcity of self-produced energy in comparison to the energy demand present at the same moment, thus imposing to rely on the electricity from the external grid to satisfy that request. This chart is also useful to quantify the distance of the value assumed by $E(\Delta t)$ from the ideal situation of a perfect supply-demand matching (x-axis).

In relation to this example, the values of the indicators described in paragraph 2.2 were also calculated. The load cover factor over T, $\gamma(\Delta t)$, corresponds to 40% which means that less than a half of the total requests was supplied by the on-site generators. The interaction with the external grid was continuous, because at no time step the electricity generated on-site was sufficient to completely supply the electricity demand: for this reason, the no grid interaction probability ($P_{E\approx 0}$) indicator is equal to zero. Nevertheless, this interaction was characterized by a quite flat profile, and the electricity requested to the external grid was quite constant during the period of analysis, except for the first time step, as shown in the last chart of Fig. 10: the relative grid interaction amplitude (A_{gr}) was equal to 0.3.

The management procedure of a micro-smart grid that was presented showed the following three main benefits for the industrial site:

1 A better use of the machineries: the monitoring and managing system helps to define an appropriate use of production lines and also to early detect when rupture or maintenance needs emerged. The presence of peaks in the loads can also highlight irregularities in the functioning of the equipment and the need for replacement of some components before the device breaking, thus avoiding long inactivity periods and consequent delays and financial losses;

2 Remote control of the machineries: the production manager can remotely monitor the energy consumption of the machineries, the proper use by workers, as well as any unforeseen problem or delay. This facilitates the monitoring phase, guaranteeing fast interventions in cases of malfunctioning, without constant, or at least extended, physical presence and supervision;

3 Management of peak power: each machinery has a peak power consumption during the power-up, while later the power use becomes stable and equal to the average value of electricity consumption. The identification of these peaks allows a better organization of the switch-on phase of production lines to be done – if possible – in different identified moments. An effective distribution of the peak loads also provides financial advantages.

5. Conclusions

In this paper a monitoring and managing system that was realized on a micro-smart grid in an agro-industrial site is presented. This work can be seen not only as a case study, but also as a contribution to the literature as regards the managing procedure and the general system architecture. For the example of application that was presented, the load cover factor over period T ($\gamma(\Delta t)$) is equal to 40%, therefore less than a half of the total energy requirement was supplied by the on-site generators. Despite that result, the

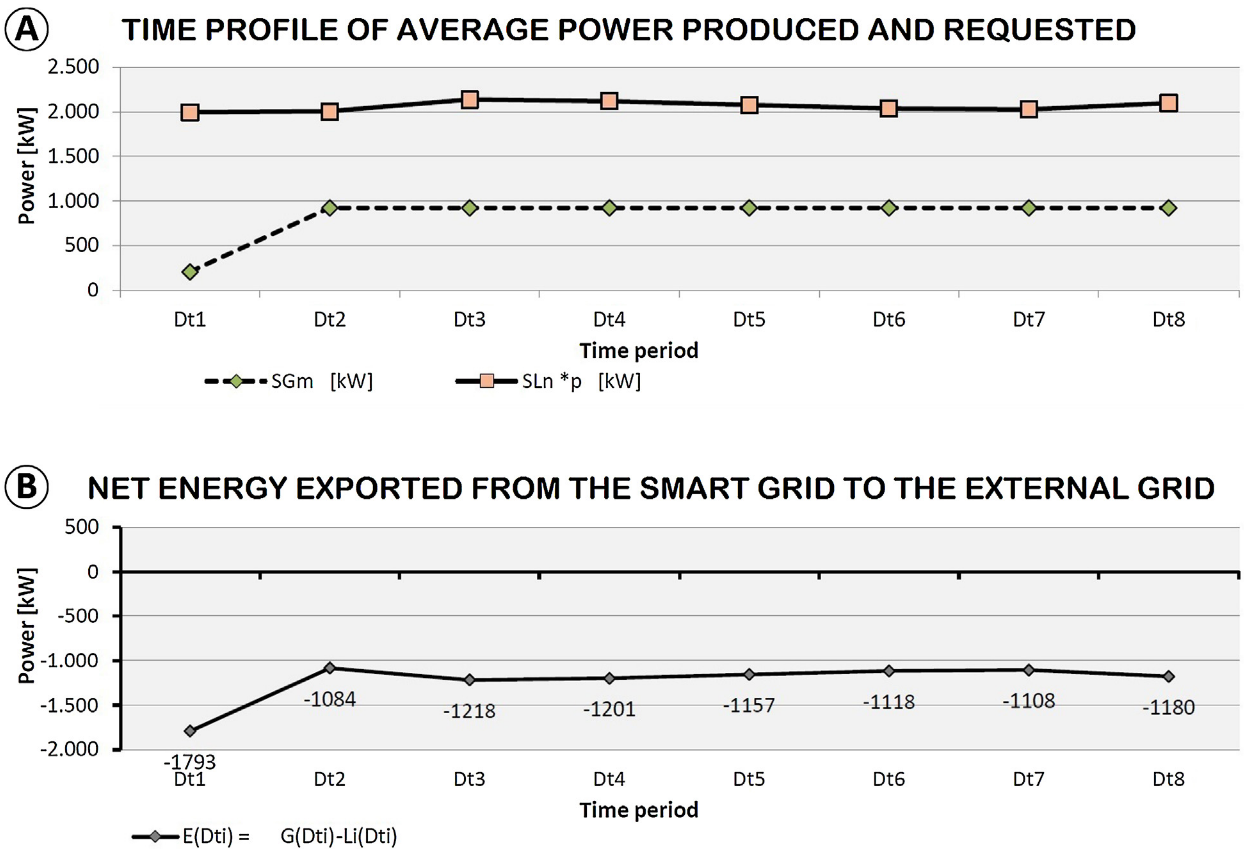

Fig. 10. Electricity supply and demand (A) and Net Exported Energy over the time period T (B).

investigation showed that the monitoring and managing system gives interesting benefits. First of all, the use of machineries can be improved, because the system helps to optimize the production lines use. Second, the presence of the monitoring system allows a remote control of machineries data (as energy consumption or unforeseen troubles), facilitating faster interventions. Finally, the proposed managing procedure allows to identify machineries peak power in order to generate a peak clipping of the total power demand profile of the agro-food industry.

The application developed in this work showed also that it is important to pursue the matching between energy demand and energy supply not only for the obtainable financial advantages (place some loads in the hours of energy surplus, thus profiting of hourly fees) but also because, through a reduced interaction with the external grid, the quantity of transmitted electricity, and the related distribution losses, decrease.

Furthermore, a deep knowledge of factories consumptions is among the interests of many actors of the energy supply chain. Since industries are the final clients of this chain, public utilities usually offer specific fees and discounts for those clients who implement tools to have a more predictable energy profile (monitoring schemes for example): in that way the energy trader limits the risk that derives from wrong predictions about the quantity of booked and purchased electrcity and the consequent penalties for not correct predictions. Moreover, the database obtained with the monitoring activity on the test site, with past years' data, can be a starting point for a continuous monitoring plan, in order to activate a virtuous process of improvement and control.

About the ICT tool used in the project, the paradigms of IoT communications and systems can be successfully applied to the micro-smart grid scenario, thus increasing the system knowledge through the capillary monitoring of energy sources and loads.

Finally, concerning the energy management, it can also be sated that every proposal aimed at obtaining energy or financial savings, should be flexible enough and should always include some free and random interventions by workers. In this way energy related goals will be easily achieved without compromising the company activities. This work may be useful as a starting point for the development of micro-smart grids at a larger scale, as the one of districts and cities. Developing a micro-smart grid in an agro-industrial site has the advantage that all the decisions regarding DSM strategies (as load shifting) can be taken in agreement with few persons, as the energy managers and/or the factory's owners. In this way, it is possible to investigate and test in field the various aspect related to micro-smart grids without the complications of larger systems that involve different users and increase the knowledge and accelerate diffusion of micro-smart grids.

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