A MULTI-ENERGY MICROGRID INTEGRATING BIO-GAS PRODUCTION FOR LOCAL AND MARKET SERVICES PROVISION

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ABSTRACT

The decarbonisation policy is leading to introduce a huge quantity of renewable generators, mainly supplied by sun irradiation and wind. This policy also assumes the natural gas as one of the fossil fuel still considered for the future energetic development plans. Security of supply and the possibility to maintain a large number of dispatchable and controllable generators, gas supplied, to support the stability of power system should be warranted. Multi-energy systems (MES) integration is the key assumed to ensure a safe energetic future without fossil fuels. MESs are thought as the synergic integration enabling to mobilize several types of services and in particular to the power system. (Multi-Energy) Microgrid play a relevant role in this transformation phase as they encourage the installation of renewable generators and also implement management strategies to strongly integrate the different resources at hand. In this paper a microgrid energy management program is proposed to optimize the production of renewable production (photovoltaic) coupled with thermal and electrical generators to meet electrical and thermal demand. The microgrid considered held a bio-methane generation unit which is able to supply the gas-loads of the microgrid as well as to inject gas inside the (distribution) gas network. The paper highlights the remunerability of the microgrid while it is operated to support the internal demand (electricity, gas and heat) as well to provide ancillary services to power system.

INTRODUCTION

The transformation of energy landscape towards decentralized low-carbon energy systems is leading to redesign the generation devices to supply the demand and revise the management strategies.
Utilities are adapting their business models and new energy services are emerging. In this context, decentralized multi-energy systems support the transition from passive consumers to active prosumers with local generation, demand response and energy efficiency measures. Demand response is a main subject in this transition, it sets programs which provide incentives for consumers to modify their consumption patterns [1]. Distributed multi-energy systems (DMESs), as introduced in [2], emerge as a powerful concept to ensure energy sustainability keeping the prices affordable. DMESs are often meant as neutral and inherently positive solutions, their diffusion faces different barriers favouring centralized energy systems. Bio-gas/bio-methane production plants exploit the anaerobic digestion to treat organic wastes in order to produce bio-gas. These plants are interesting also in the perspective to be fruitfully integrated within microgrid. There is a large number of different sources to supply this type of plant: solid and water urban wastes, agricultural waste etc. These plants represent a well example to close “the circle” of the daily organic wastes produced by human/urban, in the solid and water form, as well as agricultural activities. Indeed, these are transformed into compost (the solid portion) and fuel (the gas portion).
The recent incentive promoted by the Italian government concerning the production of bio-methane is leading medium and small potential producer to evaluate the cost benefit analysis to set a plant. In this paper we address the theme of bio-methane production plant coupled with one microgid which managed different energy carriers to supply electrical, thermal internal demand. The natural gas production can support the supply of CHP device(s) (microgrid equipped with gas engine(s) are able to satisfy both electrical and thermal energy demand at the same time), and can also be injected into the distribution gas network (this is needed to benefit of the incentive due to the bio-methane local production policy).
The paper is organized as follows: in chapter 1 a discussion is proposed about MES, in chapter 2 the model of an energy management system (EMS) is defined as a linear program, in chapter 3 the experimentation results for the EMS model is proposed. Conclusions discuss some remarks on the proposed work and some hints about future activities.

THE MULTI-ENERGY SYSTEMS AND THE SERVICES TO THE ELECTRIC NETWORK

Multi-energy systems are traditionally managed as independent contexts (e.g., electricity, gas and heat). Though, the implementation of decarbonisation policy is strongly requiring the integration at physical and commercial levels of the systems operating across several energy carriers. The physical and commercial coupling enables great synergies among the energy carriers but at the same time introduces a higher level of complexity to be managed.
The integration of optimization and control of multi-energy systems at multiple spatio-temporal scales can bring significant socio-economic, operational efficiency, and environmental benefits [3]. Along with the growing role of distributed energy resources (DERs), the envisioned control architectures are based on a multi-area view. From an operational perspective, the coordinated and seamless control of various energy infrastructures

represents a significant challenge, which favours a local view that renders cities quarters, residential neighbourhoods, and industrial areas the fundamental building blocks of the integrated energy system. Benefits such as the integration of higher levels of renewable energy resources, increases the reliability and improves the efficiency of power systems. The intrinsic *flexibility* that emerges from integrated operation of multiple energy systems at multiple spatio-temporal scales provides relevant resources.

The distributed dimension of multi-energy generation systems (DMES) well represent the local production of multiple energy vectors (e.g., electricity, heat and cooling), brings substantial economic and environmental benefits with respect to the energy vectors operating with the same multi-energy demand [4]. This is also particularly relevant in the light of development of low carbon communities and microgrid [5], particularly in terms of different modelling aspect and flexibility benefits [6], in which a comprehensive approach to co-optimize energy, reliability and reserves is allowed [7]. DMES can provide advantages to improve energy efficiency, quantified by means of primary energy saving [8] or extended indicators for multi-energy systems [9].

The strong commitment coming from power system concerns the availability of resources for regulation exchanged as ancillary services (AS). The set of ASs consists of different procedures to control the stability and balance the power system. These bring in action active power control resources like primary, secondary and tertiary reserve, power balancing and congestion resolution. DMES/Microgrid are able to offer AS provision in a flexible way combining generators and loads, and in some cases even storage systems. In this view, services are provided by an aggregation strategy which exploits as far as possible the availability of different resources. A bid to buy or sell ancillary services can be commercially sketched as a hurly quantity of active energy to be bought (import energy from the main grid) or sold (export energy to the main grid) at a specific price. An accepted bid is provided at the point of common coupling (PCC). During this time period microgrid exploits all the capability (*flexibilities*) offered by its own equipment, combining extra-availability of generation (or absorption. Flexibility is the technical ability of a system (taken as an unit or as a pool) to modulate electrical power feed-in to the grid and/or power out-feed from the grid over time.

THE EMS MODEL TO EXPLOIT SYNERGIES

The description of the EMS for DMES

The first step to formalize the EMS is to list into a set the energy carriers involved. For the sake of generality, the energy carriers considered this set is specified as:

$$\mathcal{C} = \{\mathcal{C}_1, \mathcal{C}_2, .., \mathcal{C}_n\} \tag{1}$$

The model of electrical load. The demand response (DR) management can be an effective tool to mitigate a number of drawbacks, like the peak load or peak-to-average ratio. DR procedures are typically built upon a comprehensive taxonomy to distinguish different types of loads, as introduced for instance in [10] and [11]. This includes: *Inelastic* (I) (loads which must be supplied), *Elastic* (*E*) loads (loads that can be supplied, in particular after a DR commitment), *Cumulative* (*C*): this type of loads are represented by: a loading time interval (τ), energy to be provided within τ; for instance, these loads can represent vehicle charging stations. The last category *Device* (D) represents the load required by devices to be operated (this last category is mainly centred to the plant manager point of view).

The total load resulting by the contribution of each load category held in the community for each time instant is computed as follows (given a sub-interval τ where cumulative loads have to be supplied within the optimization horizon T, that is: $\tau \subseteq T$):

$$\forall t \notin \tau \tag{2}$$
$$P_{\mathcal{E}}^{L,I}(t) + P_{\mathcal{E}}^{L,D}(t) \le P_{\mathcal{E}}^{L,TOT}(t) \le P_{\mathcal{E}}^{L,I}(t) + P_{\mathcal{E}}^{L,D}(t) + P_{\mathcal{E}}^{L,E}(t)$$

$$\forall t \in \tau \tag{3}$$
$$P_{\mathcal{E}}^{L,I}(t) + P_{\mathcal{E}}^{L,D}(t) + P_{\mathcal{E}}^{L,C}(t) \le P_{\mathcal{E}}^{L,TOT}(t) \le P_{\mathcal{E}}^{L,I}(t) + P_{\mathcal{E}}^{L,D}(t) + P_{\mathcal{E}}^{L,C}(t) + P_{\mathcal{E}}^{L,E}(t)$$

$$\forall t \in T \tag{4}$$
$$\sum_{t\in\tau} P_{\mathcal{E}}^{L,I}(t) + \sum_{t\in\tau} P_{\mathcal{E}}^{L,D}(t) + \sum_{t\in\tau} P_{\mathcal{E}}^{L,C}(t) + \sum_{t\in\tau} P_{\mathcal{E}}^{L,E}(t) = \sum_{t\in\tau} P_{\mathcal{E}}^{L,TOT}(t)$$

Generators: it is assumed a general representation for a generator where each input energy carrier contributes to produce one (or more) output energy carrier, with a specified efficiency, limited within explicit boundaries, as follows:

$$P_{\mathcal{C}j}^{Gin,\mathcal{C}1}(t) \cdot \eta_{\mathcal{C}j}^{\mathcal{C}1} \cdot \ldots \cdot P_{\mathcal{C}n}^{Gin,\mathcal{C}1}(t) \cdot \eta_{\mathcal{C}j}^{\mathcal{C}n} = P_{\mathcal{C}j}^{Gout}(t) \tag{5}$$

and boundaries

$$P_{\mathcal{C}j}^{Gmin} \le P_{\mathcal{C}j}^{Gout}(t) \le P_{\mathcal{C}j}^{Gmax} \tag{6}$$

Storages: the next state of energy of the storage system is defined as the current state of energy plus the charge contribution, minus the discharge withdrawal and the leaks.

$$SE_{\mathcal{C}i}(t+1) = SE_{\mathcal{C}i}(t) + P_{\mathcal{C}i}^{dch}(t) \cdot \eta_{\mathcal{C}i,dch}^{-1} + P_{\mathcal{C}i}^{ch}(t) \cdot \eta_{\mathcal{C}i,ch} - \nu_{\mathcal{C}i}(t) \tag{7}$$

where $P_{\mathcal{C}i}^{ch}$ and $P_{\mathcal{C}i}^{dch}$ are the charge and discharge powers, respectively, and $\nu_{\mathcal{C}i}$represents the leaks of the storage system. The state of energy is then limited by physical or optimal technology limits:

$$SE_{\mathcal{C}i}^{min} \le SE_{\mathcal{C}i}(t) \le SE_{\mathcal{C}i}^{max} \tag{8}$$

The *electrical grid*: the model of the electrical grid embodies not only the access to the electrical network but the participation to the different electricity markets. This is organized in two stages. The first step consists to access the *day-ahead market* (DAM) to supply the loads not supplied internally. The second step represents the DMES access to the electricity (ancillary) services market (ASM). In this case, coherently to the electricity exchanges previously set, energy is increased to export (*up*-versus) or import (*dw*-versus), for up and down services, respectively. Formally, the grid model designed for market participation is as follows:

$$P_{grid}^{\mathcal{E}max} \geq P_{\mathcal{E},DAM}^{imp}(t) + P_{\mathcal{E},ASM}^{imp} \geq P_{grid}^{\mathcal{E}min} \quad (9)$$

and

$$P_{grid}^{\mathcal{E}max} \geq P_{\mathcal{E},DAM}^{exp}(t) + P_{\mathcal{E},ASM}^{exp} \geq P_{grid}^{\mathcal{E}min} \quad (10)$$

The *energy management problem* to optimally planning the operation of a pool of technologies differently aggregated including generators, loads and storages interconnected through suitable energy carrier networks is completed by the balance equations set for each carrier $\mathcal{C}_i$ with respect to a time horizon T (typically 24-hours) with a specified time grain (for instance 1 hour):

$$\forall t \in T \quad (11)$$
$$\sum_{G,S,L \in Pool} [P_{\mathcal{C}i}^{Gout}(t) + P_{\mathcal{C}i}^{Sdch}(t) = P_{\mathcal{C}i}^{L}(t) + P_{\mathcal{C}i}^{Sch}(t)]$$

For the electrical carrier the balance equation is further complicated as it has to represent the DMES electricity market participation. In this case the balance equation is partitioned into two components to represent the two stages. The first stage DMES market participation:

$$\forall t \in T \quad (12)$$
$$\sum_{G,S,L \in Pool} [P_{\mathcal{E}}^{Gout}(t) + P_{\mathcal{E}}^{Sdch}(t) + P_{\mathcal{E},DAM}^{imp}(t) = P_{\mathcal{E}}^{L}(t) + P_{\mathcal{E}}^{Sch}(t) + P_{\mathcal{E},DAM}^{exp}(t)]$$

During this first stage the electrical-grid ensures to supplies the loads when internal generation is not suitable and to absorb the extra-generation provided by the generators of the DMES pool. Loads are supplied in the rigid components (inelastic-*I*, device-*D*, and cumulative-*C*), while the elastic component (*E*) is supplied as far it is economically convenient. The second stage takes as constraint the grid exchanges set during the first stage, and verifies whether the existing flexibility can be proposed to the ancillary service market as services. The second stage:

$$\forall t \in T \quad \sum_{G,S,L \in Pool} \quad (13)$$
$$[P_{\mathcal{E}}^{Gout}(t) + P_{\mathcal{E}}^{Sdch}(t) + \bar{P}_{\mathcal{E},DAM}^{imp}(t) + P_{\mathcal{E},ASM}^{imp}(t) = P_{\mathcal{E}}^{L}(t) + P_{\mathcal{E}}^{Sch}(t) + \bar{P}_{\mathcal{E},DAM}^{exp}(t) + P_{\mathcal{E},ASM}^{exp}(t)]$$

The degree of participation to the ancillary service market is bounded by the economic advantages to exchange extra electricity-generation or to supply extra electricity-load. This is set by a suitable objective function as follows:

$$\mathcal{J} = \min_P \big[[P_{\mathcal{E}}^{Gout}(t) \cdot cost_G(t) - P_{\mathcal{E}}^{L}(t) \cdot rem_L(t) + \bar{P}_{\mathcal{E},DAM}^{imp}(t) \cdot cost_{DAM}^{imp}(t) + P_{\mathcal{E},ASM}^{imp}(t) \cdot val_{ASM}^{DW} - \bar{P}_{\mathcal{E},DAM}^{exp}(t) \cdot rem_{DAM}^{exp}(t) - P_{\mathcal{E},ASM}^{exp}(t) \cdot val_{ASM}^{UP}\big] \quad (14)$$

This objective function assumes the first stage has fixed the main electrical grid exchange ($\bar{P}_{\mathcal{E},DAM}^{imp}(t)$ and $\bar{P}_{\mathcal{E},DAM}^{exp}(t)$ $\forall t \in T$, are fixed vectors) and verifies according to the extra availability of generation and load whether the remaining flexibility margins available is economically advantageous be exchanged in the ancillary service market. The participation to the ancillary service is remunerated differently according to the specific service, thus the equation generically refers to "*val*" the *service (economic) value* associated to.

To give an overview of this second step, a more detailed discussion is provided concerning the notion of flexibility.

Flexibility provided by DMES technologies

The flexibility ($\mathcal{F}$) provided by a DMES is the result of the flexibility provided by (electrical) generator, load and storage systems computed with respect to the (planned) operating status. Flexibility is then distinct into upward capacity and downward capacity. The flexibility margin in the former consists to the power available to increase the current power operating point, while the latter consists in the ability to lower the current power operating point.

Generators: flexibility of a generator refers to the availability of the device. The unit commitment gives meaning to the flexibility terms.

$$\mathcal{F}_{UP}^{G}(t) = uc_G(t) \cdot (P_{\mathcal{E}}^{Gmax} - P_{\mathcal{E}}^{Gout}(t)) \quad (15)$$
$$\mathcal{F}_{DW}^{G}(t) = uc_G(t) \cdot (P_{\mathcal{E}}^{Gout}(t) - P_{\mathcal{E}}^{Gmin}) \quad (16)$$

Loads: flexibility of a load refers to the availability of the device to modulate the supplied power. As stated by the equations defining the loads, the availability to modulate a load is essentially concentrated to elastic loads. Thus flexible margins for an elastic load are as follows:

$$\mathcal{F}_{UP}^{L}(t) = P_{\mathcal{E}}^{L,E}(t) \quad (17)$$
$$\mathcal{F}_{DW}^{L}(t) = P_{\mathcal{E}}^{L,E}(t) - P_{\mathcal{E}}^{L,Emax}(t) \quad (18)$$

where $P_{\mathcal{E}}^{L,Emax}(t)$ is the total amount of elastic adjustable load at time *t*.

Storage: flexibility provided by storage systems is a precious resource as, in most cases, it can be provided with, de facto, no time constraints (in the general case it can be provided instantaneously). Storage systems are encouraged to give their contribution to the flexibility provision. Though, the computation of flexibility quantity cannot be limited to the identification of power limits. In this case, indeed, it is necessary to meet these limits with the energy actually stored. In this case the computation of the two flexibility terms becomes:

$$\mathcal{F}_{UP}^{S}(t) = min\left\{\left(P_{\mathcal{E},dch}^{Smax} - P_{\mathcal{E}}^{Sdch}(t)\right) \cdot uc_{Sdch}(t); SE_S(t) \cdot \eta_{S,dch}^{-1} \cdot \tau^{-1}\right\}; \quad (19)$$

$$\mathcal{F}_{DW}^{S}(t) = min\left\{\left(P_{\mathcal{E},ch}^{Smax} - P_{\mathcal{E}}^{ch}(t)\right) \cdot uc_{S,ch}(t);\ SE_S(t) \cdot \eta_{S,ch} \cdot \tau^{-1}\right\}; \quad (20)$$

MECS represent a precious resource to be involved in the electric system during excess/deficit of generation. In these systems the aggregation of different resources in a pool represent a powerful mean to increase the service provided in term of quantity (energy provided) but and in terms of quality. As far as it concerns the quality of service provision it refers to the fact that the pool stresses the abilities of the different technologies held. This is a logical consequence of the fact that the flexibility of the pool is essentially the summation of the summation of the single technologies held. Actually, the flexibility of the DMES is defined as follows,

$$\mathcal{F}_{UP}^{DMES}(t) = \mathcal{F}_{UP}^{G}(t) + \mathcal{F}_{UP}^{S}(t) + \mathcal{F}_{UP}^{L}(t) \quad (21)$$

$$\mathcal{F}_{UP}^{DMES}(t) = \mathcal{F}_{DW}^{G}(t) + \mathcal{F}_{DW}^{S}(t) + \mathcal{F}_{DW}^{L}(t) \quad (22)$$

THE EXPERIMENTATION

The model of energy management for the DMES defined in the previous section has been coded with the Cplex code (IBM-ILOG©) and tested across one year. The plant designed is composed as follows:

generators: *CHP* (1500 kWwl, 1000 kWth and η_{el}=0.4, ηth=0.38), Heat-Pump (*HP*) (1000 kWth, COP 2.5), photovoltaic (*PV*) field (1000 kWp), Gas-Boiler (*GB*) (1000 kWth), bio-methane production plant (2834 kW);

storage systems: electric storage (*BATT*) (*dch=ch*=200 kW, energy=500 kWh) thermal storage (*THS*) (dch=ch=2500 kW_{th}, energy=7000 kWh_{th}),

loads: electric loads (inelastic, cumulative, elastic and devices: CHP, HP, bio-methane plant), thermal loads (internal demand and bio-methane thermal consumption), gas loads (CHP, gas boiler).

The microgrid is connected to the electrical grid through the Point of Common Coupling (PCC), and to the distribution gas grid. The value of the incentive for the bio-methane injected into the gas grid is paid with the Italian regulation according to the *net calorific value*, it results about 60 c€/kWh plus the daily cost of gas.

The energy management for the plant has been tested against 4 working days taken in 4 different year seasons described by specific electricity and gas market prices (downloaded from the web site of GME the Italian manager of the electricity and gas markets, [12], and loads (inelastic, elastic and cumulative).

The profiles of electric and thermal loads during the days taken into account:

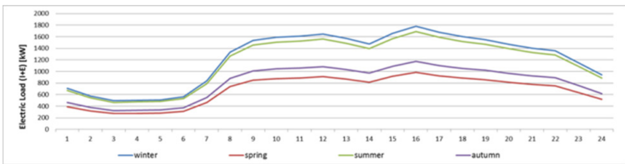

Figure 1 – Trends of the electric and thermal loads

The prices to buy energy on the DAM in the selected days is,

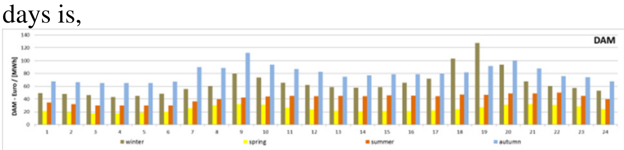

Figure 2 – Trends of the DAM prices

The prices for the ancillary service market in the four days are as follows,

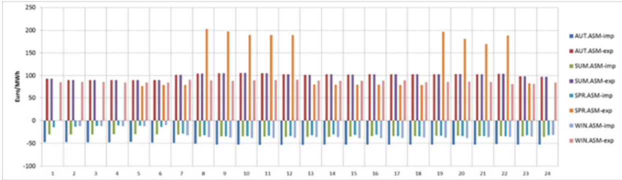

Figure 3 – Trends of the ASM prices

These results of the simulations shown how the plant is able to exploit all the flexibility proposed in the design. The figures in the following are built through the cumulative values of the variables computed along the 24 hours of each daily program result of the EMS evaluation for DAM and ASM for the days taken into account. The value for a variable *q* reported in the different graphs expresses a percentage variation between the DAM measure and ASM measure. In detail, it is computed according to this rule:

$$\hat{q} = {(q_{ASM} - q_{DAM})}/{q_{DAM}} \cdot 100$$

The next figure shows the percentage of increment/decrement of the exploitation (power output) of the main technologies compared between the DAM and ASM program. In this respect, the technology most exploited, especially during the spring and summer is the HP. HP in fact can be employed in many ways: to supply the thermal load and provide services to the ancillary service market. During the winter season there is no much difference between DAM and ASM program, the greater variation between these two stages is the BAT program which in autumn has a huge increment between DAM and ASM.

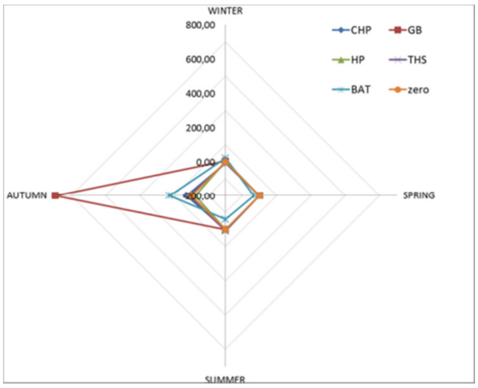

Figure 4 – The increment/decrement of the percentage of usage of the technologies between DAM and ASM

About the comparison among cost/remuneration, quantity of imported gas quantity and percentage of elastic load supplied the next figure shows that the participation to the DAM and ASM markets produces many advantages: the remuneration increases (around 10% in each season), the percentage of elastic load supplied increases significantly (around 20% in all season), and the importation of gas is stable between the first and the second stage (it is around zero unless in the case of autumn where it grows up around 30%).

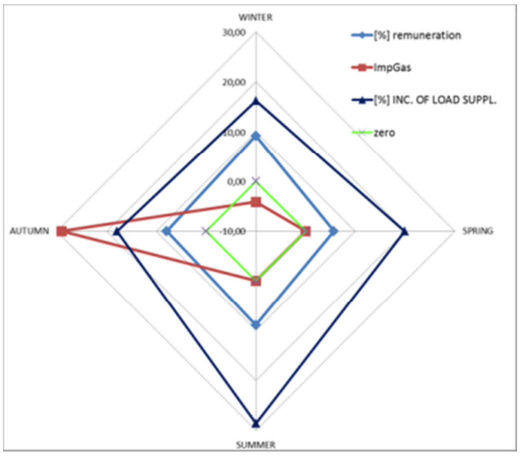

Figure 5 – The increment/decrement of the percentage of remuneration, gas import and load supplied between DAM and ASM

The last result reported concerns the trends of import and export of electricity between DAM and ASM phases. In this case, in particular during autumn and winter there is a great exploitation of the ancillary service provision. The network programs are coherent between DAM and ASM, thus what can be computed is: how ASM increases or decreases its contribution with respect to DAM. This is implemented through the index:

$$\widehat{net} = {(n_{ASM})}/{q_{DAM}} \cdot 100$$

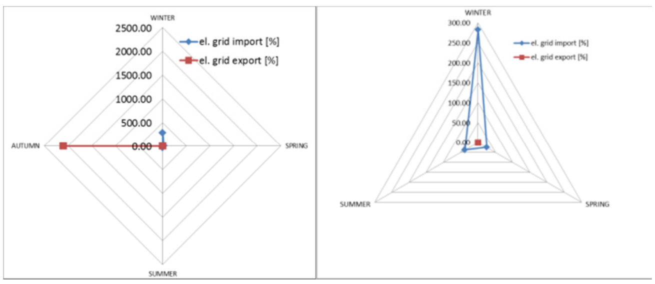

Figure 6 – Network import-export percentage variations through DAM and ASM.

The huge reduction of electricity import between DAM and ASM steps for autumn gives rise to the huge import of gas in order to support the supply of the thermal load by the gas-boiler. From the results shown, it appears that a microgrid with several types of generators is able to easily face different alternatives. In particular, it can switch between thermal and electric production according to demand and ancillary service requests.

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CONCLUSIONS

The paper proposes the description of an energy management system enabling a microgrid to participate to different electricity markets in order to exploit the opportunities. The microgrid embodies three of the main energy carriers: electricity, heat, and gas. Advantages include: the increment of the plant remuneration, the increment of the quote of flexible loads (those not necessarily supplied). As shown, the EMS is able to exploit the opportunities in each of the carrier. The flexibility model proposed has not been included into in the definition of the EMS. In order to enhance the energy devoted to support ancillary services, this model will be included. It will be also interesting to test how specific market services can be effectively supported by a pool of technologies.

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