Smart monitoring of a microgrid including gas turbines and a dispatched PV-based active generator for energy management and emissions reduction

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***Abstract*-- By taking into account the fluctuations of the renewable energy based power production, this paper describes a 24-hour ahead energy management for a micro grid. Based on the prediction of the energy available from the PV generator, storage availability, the microturbines emissions characteristics and the load prediction, a central energy management system calculates a day-ahead plan of the power references for three gas turbines and a PV-based active generator. A multi objective optimization is implemented in order to minimize the emissions of the three main pollutants coming from the gas turbines: CO_2, CO and NOx.**

***Index Terms*-- Smart grid, micro grid, renewable energy, load forecasting, optimization, emissions minimization, power planning, energy management, multi objective optimization.**

I. Introduction

THIE need to reduce pollutant gas emissions and the liberalization of the electricity market lead to electricity grids with a large ratio of low-carbon electrical production [1], [2]. In the past, electricity was produced mainly in large-scale power stations. In recent years production from small-power dispersed renewable-energy based generators has significantly increased. The power availability of these generators is stochastic and sometimes difficult to predict. This induces difficulties to electrical system operators, which may have to disconnect these generators. In a liberalized electricity market, a cluster of small-scale power generators has to be locally aggregated by its centralized energy management system in order to maximize the use of renewable energy based generators and storage systems connected to them. Communication between the microgrid central energy management system and the distribution system operator can facilitate also large-scale power plants dispatching thus further reducing pollution.

The idea of a "smart-grid" has emerged as the concept for the evolution to a modernized electric grid. The task is to imagine grid architecture to integrate and control synergy interactions of new power components or services and existing distribution system. The architecture is, at least, dependent on innovations in:

_ end-use energy service devices as Renewable Energy Based Generators (REBG), CHP systems, dispatched loads for integrated demand response functions, local energy storage units, Plug-in Hybrid Electric Vehicles,

_ a communication network,

_ an Energy Management System.

The smart grid has to incorporate distributed intelligence at all levels of the electric network, in order to improve efficiency, reliability and security. Currently the distribution system is rather passive and centralized from the supervision point of view, whereas the "smart" distribution system is expected to be active, networked and with decentralized control [3].

As example, the fig. 1 shows a possible architecture, which is organized according to a hierarchical control structure. It relies on Local Controllers (LC) for the various components, a Microgrid Central Energy Management System (MCEMS) for the energy management of a local area. The MCEMS is viewed by the Distribution System Operator (DSO) as a single entity, which is able to locally control a cluster of generators and flexible loads and to permit REBG to provide their full benefits while minimizing the pollution emissions.

LC communicate with the MCEMS, which collects data, performs technico-economical optimization of the microgrid operation and sends power references to dispersed components in the area.

Smart Meters (SM) are used to measure the power flows of producers, consumers or prosumers [4]. Information integration, monitoring, data management and visualization tools for decision making are implemented in the MCEMS, which is used by the grid operators and market participants.

Moreover the MCEMS has to optimize performances in its area by being able to take advantage of the overall infrastructure to optimize energy efficiency, energy use and CO_2 emissions. The optimum management of this energy system through a microgrid central controller is a step towards the smart grid [5] and leads to solutions for small scale power systems. Practical implementations are under development in Europe at Kytnos island (Greece), at Mannheim-Wallstadt (Germany) [6].

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In this context the problem of optimal operation planning consists in reducing pollution emissions of a microgrid in presence of an active generator and three gas turbines. First, the paper recalls the organization the microgrid central energy management. Then the planning and the long term energy management are detailed. After that, a characterization of the gas turbine emissions is made and an implementation of a multi objective optimization to reduce these emissions is presented.

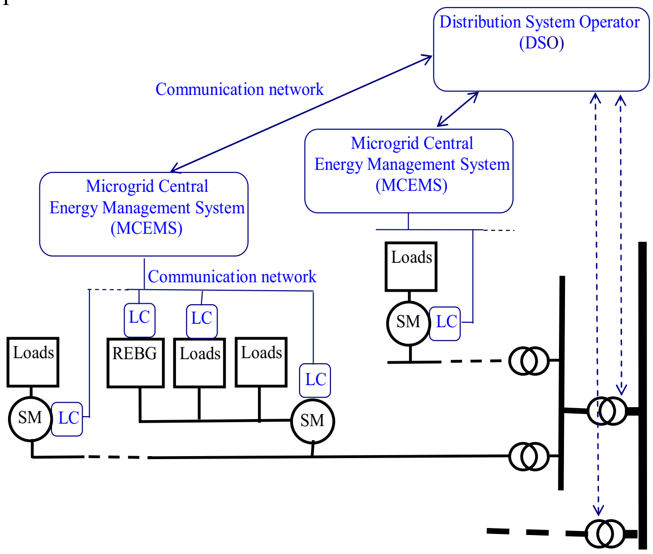

Fig. 1. Microgrid based architecture for smart grid applications

II. STRUCTURE OF THE STUDIED MICROGRID

The studied microgrid integrates residential loads, two 30kW micro gas turbines (CHP), a 60kW gas turbine and twelve 3kW PV based active generators (Fig. 2).

A communication network is set up between the power components and the MCMES allowing it to send power references and exchange data.

An active PV based active generator consists to associate photovoltaic panels with a storage system including a set of batteries as a long-term storage device and a set of ultracapacitors for short term and real time power balancing [9]. They are coupled via a DC bus by choppers and are connected to the microgrid by an inverter. The interest of this hybrid generator is that it is able to deliver a prescribed power (P_{ag_ref}) like a conventional generator [10], [11], [12]. Such a generator is called "active generator" and it can be dispatched (to the MCEMS) if the PV energy availability and the energy stored in the batteries are enough. Hence excess PV energy is locally stored in the batteries for future use when needed. As a power reserve is available, ancillary services can also be provided as for conventional generators.

Here the twelve active generators are, in fact, residential houses with PV panels, storage systems and controllable loads. At home an Energy box (E-box) integrates:

_ the SM to follow energy consumption,

_ the LC of loads to heighten consumer satisfaction with options for an automatic control of some loads and with possibilities of consumption adaptations to time pricing _ _ the LC and energy management of PV panels and storage units.

In this paper we consider advanced E-boxes with onboard intelligence that receives signals from the microgrid central controller and may reduce home demand or may increase power production in a certain margin for matching the total power production with the demand in an optimal way [6], [7], [8].

The active generators are close to each other, have similar characteristics and so they are aggregated as a single 36 kW active generator by the MCEMS.

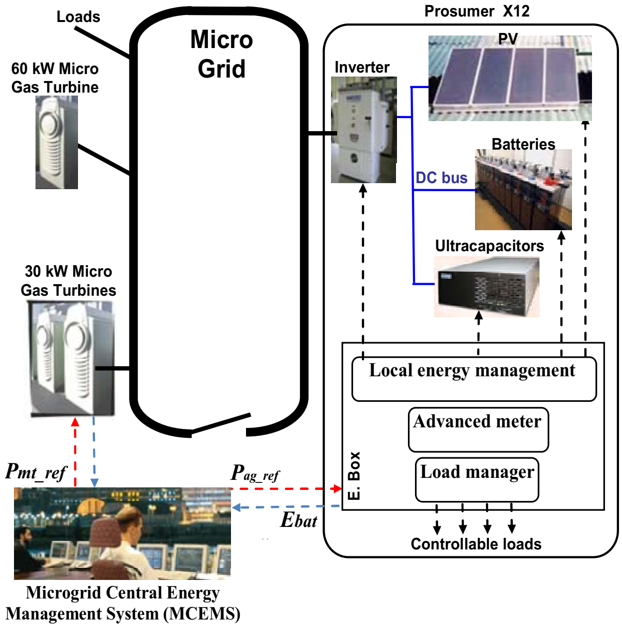

Fig. 2. Microgrid integration of an active generator, gas turbines and central energy management

III. MICROGRID CENTRAL ENERGY MANAGEMENT SYSTEM

From a general point of view the task of the MCEMS is to manage the power and the energy between sources and loads into the microgrid [13]. Then the real and reactive power production must be shared among the DER units (active generators) and the gas microturbines.

So the MCEMS must assign real and reactive power references and also other appropriate control signals to the DER units, conventional production units and controllable loads [13], [14]. The microgrid management is analyzed through various functions that we have classified in a timing scale (Fig. 3).

The long-term energy management includes:

- the hourly "RES production forecast" including the time dependency of the prime source, environmental impacts and cost of generation,
- the management of non-sensitive loads that may be disconnected/shed according to the supervision requirement,
- the provision of an appropriate level of power reserve capacity according to the electricity market and the load demand forecast,
- the maintenance intervals.

The short-term power balancing includes:

- the real time "Power Balancing" and also power dispatching among internal sources and storage units of a DER according to the storage level capacity and to the specific

requirements/limitations of source, including available power from REBG [15],
- the RMS voltage regulation and the primary frequency control [16].

According to the different management objectives, the proposed energy supervision system is implemented in two locations: the MCEMS for the long term energy management and a short term power balancing in the E-box and the LC of micro turbines.

The communication between these management units should be set up because the data acquisition and information about states of each resource (such as the available energy capacity and the real-time produced power) are very important for the central energy management of the microgrid [17]-[19]. The control orders from the MCEMS should be also sent to the LC, which are integrated in the generators. (Fig. 2). In order to optimize the system operation, the MCEMS has to be upgraded. In this framework several functions in the central energy management have to be modified or created as power prediction from the renewable energy, load forecasting, energy storage reserve, peak shaving, maximized use of renewable energy source and power planning (Fig. 4). So in the next section our proposed long term energy management is detailed.

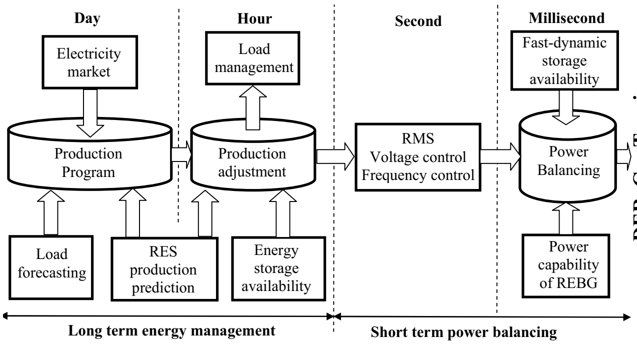

Fig. 3. Timing classification of control functions for EMS.

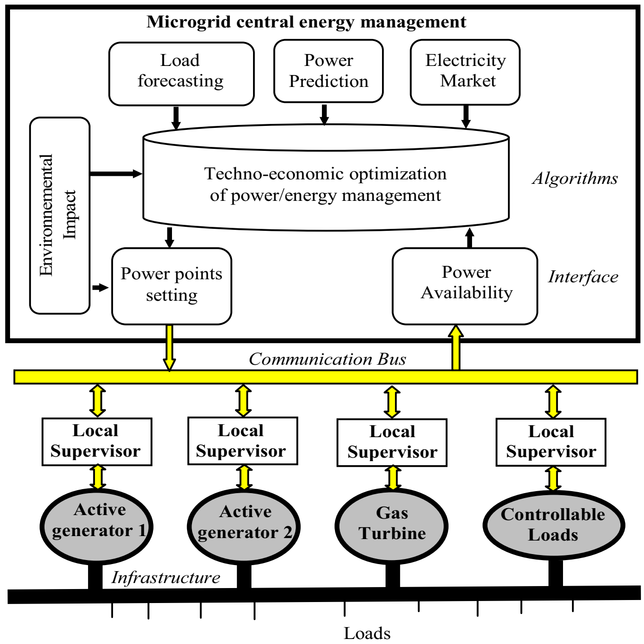

Fig. 4. Framework of the central energy management system.

IV. Long term energy management

A. PV power prediction and load forecasting

The natural bad predictable character of solar energy is a weakness for its use in an electric system.

Photovoltaic panels provide power only during the day and the power supply peak appears around the midday. Meanwhile huge production variations appear.

The power prediction can be adapted more and more accurately to the real situation by means of predictive models [20], [21], [22]. According to the weather forecasting and the historical data base of the PV power, a prediction for the total available PV power for the studied 24 hour period is presented in fig. 5.

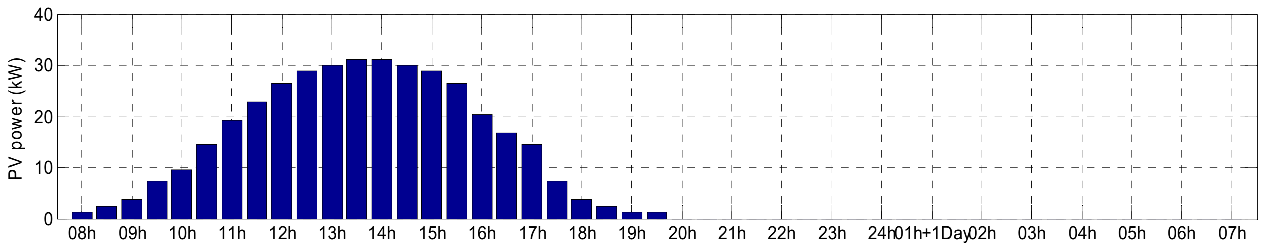

Fig. 5. 24-hour-ahead PV power forecast ($\widetilde{P}_{PV\_24h}$).

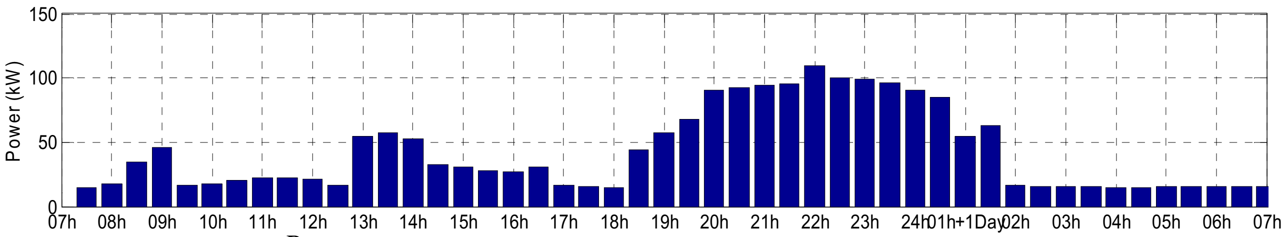

Fig. 6. 24-hour-ahead load forecast (P_{Load_24h}).

This PV-based active generator consists of twelve PV installations, located on the same site, each having 3kW maximum power output and identical characteristics. In the context of this study they are considered as a single active generator. The load forecasting is also very important for the energy management. Based on historic electrical power production requirements, the behavior of the loads can be forecasted and estimated. A 24-hour ahead load forecast is given in fig. 6 with meteorological data and historical consumption data each half an hour [23].

B. *Energy estimation*

The scheduled daily energy of PV production and load can be calculated with data from the PV power prediction and load forecasting.

$$\widetilde{E}_{PV\_24h} = \int_0^{24h} \widetilde{P}_{PV}(t)dt = \sum_{n=1}^{48} \widetilde{P}_{pv}(n \cdot Te) \qquad (1)$$

The sample time of the power prediction is Te=30min=1800sec.

For this study, the operation of the PV based active generator is cut in two time zones (day and night), as shown on fig. 7. The time point of sunset, the initial time point of the day (t_0) and the length of the day (Δt) depend on the season and the weather conditions.

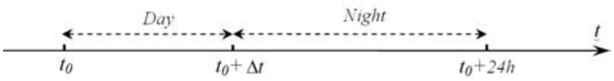

Fig. 7. Time axis for the PV power application

In order to plan the power production program, the energy (demanded by the load) is also divided into two parts (day and night):

$$\widetilde{E}_{Load\_day} = \int_0^{0+\Delta t} \widetilde{P}_{load}(t)dt \ , \quad \widetilde{E}_{Load\_night} = \int_{0+\Delta t}^{0+24h} \widetilde{P}_{load}(t)dt \qquad (2)$$

In this studied case four types of power sources are considered: PV based active generators and three micro gas turbines (fig. 2). Because of the renewable energy benefits (less gas emission and low operating cost), PV based active generators are considered as the prior source and the micro gas turbines as back-up sources for the missing energy.

V. Setting of Power References During the Day.

According to daily predictions of the available PV power at maximum power point ($\widetilde{P}_{PV\_MPPT} = \widetilde{P}_{PV\_24h}$), the total energy from the PV ($\widetilde{E}_{PV\_24h}$) and the required power and energy of the loads ($\widetilde{P}_{Load\_night}, \widetilde{P}_{Load\_day}, \widetilde{E}_{Load\_night}, \widetilde{E}_{Load\_day}$), a power production planning for the active generator (P_{AG_ref}) and for the three micro turbines ($P_{MGT\_ref\_1}, P_{MGT\_ref\_2}, P_{MGT\_ref\_3}$) must be determined for each Te period.

The capacity of the energy storage is finite and has to be considered: $E_{bat\_\max}$.

Another constraint is the loading level of the gas turbines. Manufacturers prescribe the use of the turbines at a load level above 50% of their maximum power. Otherwise the electrical efficiency decreases, fuel consumption per unit of produced power increases drastically as well as the emissions, as shown on fig.8 [24]. This means that each gas turbine will be switched on only if the load demand is at least equal to 50% of its maximum power. If the power demand is lower, only one or two of the turbines will remain on. This constraint is also taken in account when sizing the studied system.

A day-ahead planning is needed because using the active generators (with storage) combined with the gas turbines offers more flexibility in supplying electricity to the system. In every period, several possibilities can exist, whether the gas turbines will be switched on to supply the loads, or batteries will be used. Also the above constraints have to be satisfied in order to ensure optimal operation of the system.

As no power is available from PV panels during the night, power references are calculated separately for the night ($P_{AG\_night\_ref}, P_{MGT\_night\_ref}$) and for the day ($P_{AG\_day\_ref}, P_{MGT\_day\_ref}$).

In the day three cases are distinguished:

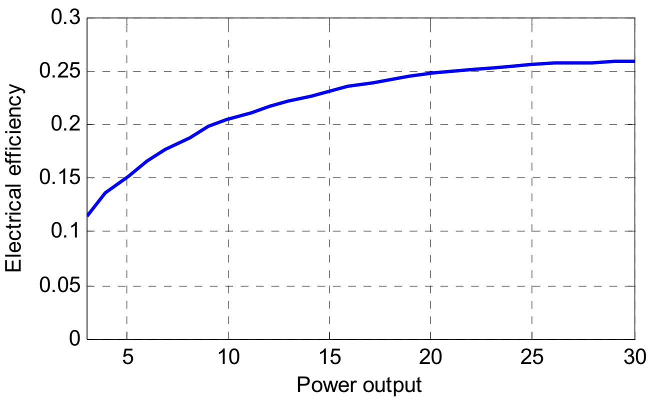

Fig. 8. Electrical efficiency as a function of power output for Capstone C30 micro turbine.

<u>First case:</u>

If the maximum PV energy for the period p ($p \in [0, \frac{\Delta t}{Te}]$)added with the minimum gas turbine energy is less than the demanded load energy $\widetilde{E}_{PV\_p} + \sum_{m=1}^{3} \widetilde{E}_{MGT\_\min\_m} < \widetilde{E}_{load\_p}$, the maximum power can be extracted from the PV panels (MPPT mode) and all PV power is injected in the grid.

The micro gas turbines have to generate the missing power:

$$P_{AG\_ref} = \widetilde{P}_{PV\_MPPT} \qquad (3)$$

$$\sum_{m=1}^{3} P_{MGT\_ref\_m} = \widetilde{P}_{Load\_p} - P_{AG\_ref} \qquad (4)$$

In this case a multi objective optimization algorithm is used to determine the power references of the micro gas turbines so that the quantities of the three main pollutants (CO_2, CO and NOx) are minimum. In the next section the methods for emission assessment, the optimization objectives and the constraints will be discussed. Depending on the demanded power to supply the loads one or two of the micro turbines can also be stopped, but one micro gas turbine at least has to be used for supply security reasons.

Second case:

If the maximum PV energy for the period p added with the minimum gas turbine energy is more than the demanded load energy ($\widetilde{E}_{PV\_p} + \sum_{m=1}^{3} \widetilde{E}_{MGT\_\min\_m} > \widetilde{E}_{load\_p}$), and the surplus energy is also more than the capacity of batteries $\widetilde{E}_{PV\_p} + \sum_{m=1}^{3} \widetilde{E}_{MGT\_\min\_m} - \widetilde{E}_{load\_p} > E_{bat\_\max} - \widetilde{E}_{bat\_ini}$ then PV panels must work in a limitation mode. $\widetilde{E}_{bat\_ini}$ is the initial capacity of batteries. The micro gas turbines work with a minimum power, depending on the demanded power one or two of them can be switched off:

$$P_{AG\_ref} = \widetilde{P}_{Load\_p} - \sum_{m=1}^{3} P_{MGT\_\min\_m} \tag{5}$$

$$\sum_{m=1}^{3} P_{MGT\_ref\_m} = P_{MGT\_\min\_1} + P_{MGT\_\min\_2} + P_{MGT\_\min\_3} \tag{6}$$

Third case:

If the maximum PV energy for the period p added with the minimum gas turbines energy is more than the demanded energy from loads ($\widetilde{E}_{PV\_p} + \sum_{m=1}^{3} \widetilde{E}_{MGT\_day\_\min\_m} > \widetilde{E}_{load\_p}$), and the surplus energy is less than the capacity of batteries $\widetilde{E}_{PV\_p} + \sum_{m=1}^{3} \widetilde{E}_{MGT\_\min\_m} - \widetilde{E}_{load\_p} < E_{bat\_\max} - \widetilde{E}_{bat\_ini}$ then PV panels work in MPPT. The surplus of energy is stored in the batteries. The micro gas turbines work with a minimum power and one or two of them can be switched off.

$$P_{AG\_day\_ref} = \widetilde{P}_{PV\_MPPT} \tag{7}$$

$$P_{MGT\_ref\_m} = P_{MGT\_day\_\min\_m} \tag{8}$$

VI. Setting of power references during the night.

The energy management during the night depends on the available energy from batteries. This energy ($\widetilde{E}_{bat}$) can be estimated or communicated by the local controller to the central energy management system. In the night two cases are distinguished but for both cases batteries have to be discharged and be ready for charging next day.

First case:

If the stored battery energy added with the minimum gas turbines energy is more than the demanded energy from loads for the period p ($p \in [\frac{\Delta t}{Te}, 47]$), ($\widetilde{E}_{bat} + \widetilde{E}_{MGT\_\min} > \widetilde{E}_{load\_night}$), the gas turbines work with the minimum power (one or two of them can also be switched off):

$$P_{AG\_ref} = \widetilde{P}_{Load\_p} - \sum_{m=1}^{3} P_{MGT\_\min\_m} \tag{9}$$

Second case:

If the stored battery energy added with the minimum gas turbine energy is less than the demanded energy from loads ($\widetilde{E}_{bat} + \widetilde{E}_{MGT\_\min} < \widetilde{E}_{load\_p}$), the gas turbines must generate the missing power:

$$P_{AG\_night\_ref} = P_{bat\_\max}. \tag{10}$$

$$\sum_{m=1}^{3} P_{MGT\_ref\_m} = \widetilde{P}_{Load\_night} - P_{bat\_\max} \tag{11}$$

In this case the optimization algorithm has to calculate the micro gas turbines power references, so that the emissions are at their minimum.

VII. Optimization for reducing the pollutant emissions

The MCEMS calculates a day-ahead plan with the power references for the active generator and the three gas turbines. A multi objective optimization algorithm is implemented, in order to calculate power references for the gas turbines so that the pollutant emissions are at their minimum.

The fuel consumption represents the energy efficiency goal. In economic terms, it also corresponds to the minimization of the system's operating costs [25]. In addition, as the three gas turbines in the studied system use the same fuel (natural gas), the fuel consumption minimization approximately corresponds to CO_2 emissions minimization, according to [25], [26]. The relevant aspect here is that costs and CO_2 are not conflicting objectives under the considered hypotheses in this study. The energetic efficiency of a MGT is expressed as:

$$\eta = \frac{E_{MGT}}{F} \tag{12}$$

, F (kWht) is the fuel thermal energy and E_{MGT} is the useful electric energy output, the fuel consumption of one micro gas turbine can be estimated with the following equation:

$$F_{MGT\_m} = \frac{\alpha_m . P_{MGT\_m\_MAX} . Te}{\eta_m} \tag{13}$$

$P_{MGT\_m\_MAX}$ is the rated power of microturbine m. α_m (%) is the loading level of the micro turbine:

$$\alpha_m = \frac{P_{MGT\_m}}{P_{MGT\_m\_MAX}} .100\% \tag{14}$$

P_{MGT_m} is the micro turbine's electric power output. For emissions assessment, the emission factor model is used [26]. According to this model, any pollutant emission (CO_2, CO, NOx etc.) from combustion devices can be evaluated through a model such as:

$$m_x = \mu_x . E \tag{15}$$

μ_x is the emission factor (specific emissions) for the pollutant x to produce the generic useful energy output E. m_x [mg/kWh] is the mass of pollutant x, emitted to produce the useful energy output E (kWh).

The CO_2 emission characterization can be derived from (12). The usual approach is, to consider the emission factor μ_{CO2} to be equal to 202.10^3 mg/kWh$_t$, referred to the fuel thermal power F(kWht) generated by burning the fuel as input to the gas turbine.

With equation (12), the efficiency of the three micro turbines can be expressed in function of their load using their partial-load characteristics [27], [28].

NOx are the most hazardous pollutant gazes from equipment fed by natural gas [25], [26], especially in urban areas often subject to strict regulatory air quality constraints. For the three gas turbines, the NOx emission factor is expressed in function of their loading levels:

$$\mu_{NOx\_m} = F(\alpha_m) \quad (16)$$

The CO emissions are typically very low at full load operation, but are drastically increasing under partial loads, due to incomplete combustion and due to aging of the components or poor maintenance of the equipment. Like NOx, the CO emissions are expressed by their emission factor in function of the gas turbine's loading level:

$$\mu_{COx\_m} = F(\alpha_m) \quad (17)$$

In this study NOx emissions, CO emissions and fuel consumption are conflicting objectives, because NOx and CO emissions are higher under low load operation of the gas turbines [27]. Moreover, these characteristics are unique for each of the micro gas turbines in the system.

The calculation of the power references for the micro gas turbines implies the use of multi-objective optimization, as there are three conflicting objective functions:

- The total amount of fuel consumed during the operation of the gas turbines:

$$F_{MGT\_TOTAL} = \sum_{m=1}^{3} \frac{\alpha_m . P_{MGT\_m\_MAX} . Te}{\eta_m} \quad (18)$$

- The total mass of NOx emissions :

$$m_{NOx\_TOTAL} = \sum_{m=1}^{3} \mu_{NOx\_m} . \alpha_m . P_{MGT\_m\_MAX} . Te \quad (19)$$

- The total mass of CO emissions:

$$m_{COx\_m} = \sum_{m=1}^{3} \mu_{COx\_m} . \alpha_m . P_{MGT\_m\_MAX} . Te \quad (20)$$

The first constraint is the balance between the produced power and the demanded power demanded:

$$\sum_{1}^{i} P_{LOAD\_i} = P_{ref\_AG} + \sum_{m=1}^{3} P_{MGT\_m\_ref} \quad (21)$$

The second constraint is the gas turbine loading level. As stated above, each gas turbine should be switched off if there is not enough power demand for it to operate at above 50% of the rated maximum power output:

$$P_{MGT\_m} \in [0.5 P_{MGT\_m\_max}, P_{MGT\_m\_max}] \quad (22)$$

The third group of constraints refers to the microgrid operation mode. The constraints differ from one mode of operation to another one (i.e. day/night, PV power available or not). They are expressed with equations (3)-(11).

VIII. Simulation Results.

Inputs of the model are the 24-hour the load forecast (fig. 5) and the power from the photovoltaic installations (fig. 6).

For this study, multi objective optimization has been calculated with the MATLAB function "fgoalattain". Optimization constraints are expressed by the power balance in the system, the micro gas turbine operating modes and the system's long-management strategies. Priority is given to the PV-based active generator, as it emits no pollution during its operation.

On fig. 8 the obtained power references for the active generator are presented. By using the batteries it can store energy when demand is low (11:30-13:00 fig. 8) and deliver this energy to the system when there is no PV power available (after 16:30 on fig. 8). On fig. 9, 10 and 11 are presented the 30-minute power references for the three gas turbines. Turbines 1 and 2 (fig. 9 and fig. 10) have 30kW maximum power output and gas turbine 3 (fig. 11) has 60kW maximum power output. Gas turbine 1 (fig. 9) is always running, except of when power demand is in the range between 30kW and 60 kW (7:30-9:30, 18:30-19:30 and 1:30-2:00 on fig. 8). In this case the gas turbine 3, which has a 60kW maximum power output, supplies energy to the system. If power demand is in the range between 90kW and 120kW all three gas turbines are working to supply the loads (between 20:00 and 24:00).

In order to calculate the quantities of equivalent CO_2, 1 gram of NOx has been considered equivalent to 298 grams of CO_2 [28] and 1 gram of CO equivalent to 3 grams of CO_2 [29]. The total amount of equivalent CO_2 gazes emitted by the system without using the active generator and the optimization is 646 kg of equivalent CO_2. Using the active generator and the optimization proposed in this study, the total amount is 587 kg of equivalent CO_2, which means an economy of 9.17% of equivalent CO_2.

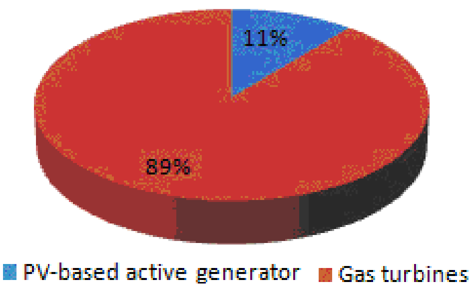

Fig. 12. Energy from the microturbines and energy from the active generator

IX. Conclusions.

A long-term energy management model of a micro grid with an active generator and three micro gas turbines is presented. The microgrid central controller integrates a multi-objective optimization algorithm that reduces pollutant emissions, minimizes fuel consumption and gives priority to the non-polluting PV-based active generator. Simulation results show that the active generator delivers 11% of the total energy to the system, as shown on fig. 12. By using the active generator and the optimization algorithm a 9.17% reduction of equivalent CO_2 is achieved.

X. Acknowledgment

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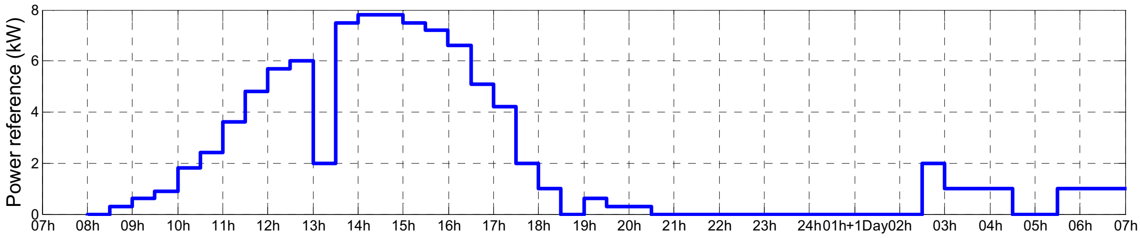

Fig. 8. 30min power references for the active generator

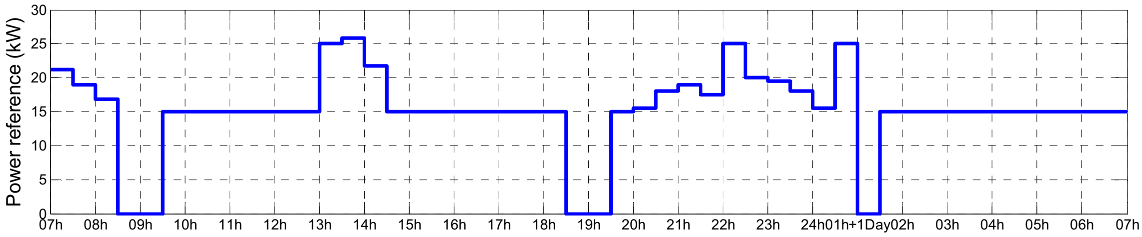

Fig. 9. 30 min power references for gas turbine 1

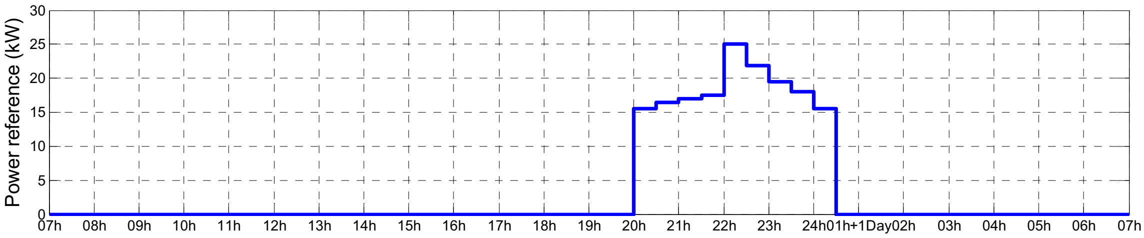

Fig. 10. 30 min power references for gas turbine 2

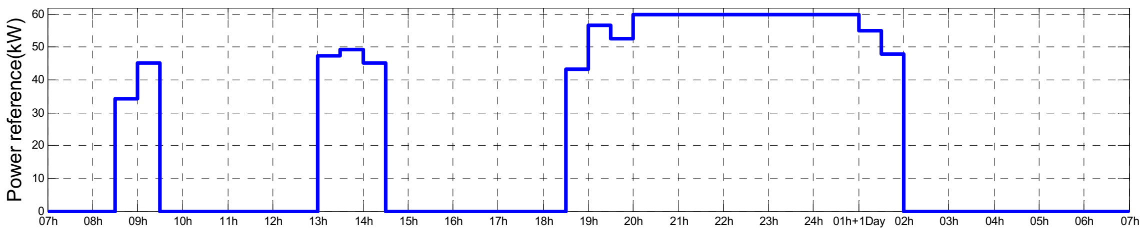

Fig. 11. 30 min power references for gas turbine 3

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