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Energy Management System for a Smart Green Nanogrid feeding a Research Laboratory with Autonomous Mobile Robots

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Abstract: This paper proposes a mixed-integer linear programming optimization model used to define an energy management system tailored for nanogrids in buildings, integrating renewable energy sources, battery energy storage systems and task-executing autonomous mobile robots. Focused on a nanogrid to be realised at the Savona Campus of the University of Genoa, the energy management system optimizes power flows and robot task scheduling in order to minimize the operating costs, the curtailment of the photovoltaic source and the number of unperformed tasks. Its novelty lies in combining energy and task planning constraints, offering significant potential for sustainable building energy management.

Keywords: Energy management system; Optimal operation; Nanogrids; Prosumer building; Autonomous mobile robots; Renewable energy sources; Battery energy storage system.

1. INTRODUCTION

The building sector is a major consumer of energy, accounting for approximately 40% of final energy consumption in the European Union (EU). Specifically, the electricity consumption constitutes 35% of the energy use in buildings, according to IEA (2022). In order to address this issue, governments have implemented various measures in recent years to reduce energy consumption in buildings and promote the adoption of Renewable Energy Sources (RESs).

In the building sector, the most suitable RES is the Photovoltaic (PV) one: PV modules can be installed on rooftops, exploiting spaces that otherwise would be unused, as observed by Alshahrani et al. (2019). Due to their inherent unpredictability, RESs are usually coupled with Battery Energy Storage Systems (BESSs), able to smooth the fluctuation of RES production, thus providing flexibility to the whole system, as stated by Li et al. (2015).

Freight and logistic sectors are involved in this green transition, too: in fact, the "Fit for 55" package provides that logistic companies will have to gradually electrify their fleet, providing a further boost to the development and penetration of Electric Vehicles (EVs). Delivery EVs will be in charge not only of the long-haul transportation of freight but also of the last-mile delivery (see Osieczko et al. (2021)). Besides, within confined areas like production plants or university campuses, Autonomous Mobile Robots (AMRs) may be used for the final delivery of mail and freight or for performing specific tasks in automated systems, as proposed by Jun et al. (2021).

The system studied in this paper, composed of small-size RESs and BESSs providing power supply to a building equipped with AMRs, can be defined as Nanogrid (NG). NGs require an Energy Management System (EMS), being able to optimize the power flows between its components. Several examples of EMS applied to NGs can be found in literature. Liu et al. (2023) investigate an EMS to be applied to a net-zero energy building equipped with RESs, a BESS and EVs. The EMS aims to provide grid flexibility, being able to support the external utility network during peak demand time periods. In Zhou et al. (2019) and in therein references, several EMSs and advanced control strategies are presented, with a specific emphasis on the seamless integration of buildings and EVs. Bracco and Fresia (2023) and Fresia and Bracco (2023) propose strategies for the optimal operation of an NG made of a prosumer building, owned by the postal service, with PV and wind generation and a fleet of EVs for the delivery of mail. The authors highlight the beneficial effects that RESs and EVs may have on the operation of the NG, both from the technical and the economic point of view. The proposed EMSs take into account both active and reactive power flows. A similar EMS is proposed in Farinis and Kanellos (2021), again accounting both active and reactive power management.

If, on the one hand, literature is well supplied with examples of EMSs for EVs fleets, on the other hand there are

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less examples of EMSs applied to warehouses or production plants, taking into account not only energy constraints but also constraints regarding tasks to be executed by AMRs. An example is provided by Mondal et al. (2020), where an energy efficient warehouse management approach is proposed, with the aim of minimizing the energy costs associated with the transportation of items by mobile units. Nevertheless, the proposed approach totally neglects the energy aspects related to smart charging techniques for the mobile units. Instead, an EMS for the smart charging of a warehouse handling equipment is considered by Carli et al. (2020), taking into account also task planning constraints related to the tasks to be performed. Nevertheless, this study does not consider a facility equipped with RES generation and BESS, therefore not providing a comprehensive formulation of EMS.

The goal of the present paper is to define an EMS for the optimal operation of an NG owned by the University of Genoa, to be located in the Savona Campus. The NG has been completely designed and will be implemented in the upcoming months within the framework of the Italian National Center for Sustainable Mobility (CN MOST): it will consist of a Research Laboratory (RL), equipped with a PV plant, a BESS, electric loads and three AMRs used to execute different tasks. The EMS will define the optimal operation of the PV and of the BESS systems, while optimizing the charging process of the AMRs, considering the tasks that they will have to perform. Therefore, the novelty of the proposed EMS is the integration of both energy and task planning constraints within the same tool, allowing the extension of such approach also to other facilities like large warehouses.

The paper is structured as follows: Section 2 provides a detailed description of the laboratory, Section 3 fully details the optimization model, Section 4 presents and discusses the results and Section 5 provides some conclusive remarks and future developments of the model.

2. LABORATORY DESCRIPTION

This section provides a detailed description of the RL that is object of the study. It is important to specify that the RL is not existing yet: the design phase has been completed, whilst its implementation is pending. The RL will be located in the so-called Smart Energy Building (SEB) of the University of Genoa, located in the Savona Campus. The SEB is a Zero-Emission Building and is part of the so-called Smart Polygeneration Microgrid (SPM), the microgrid that provides electric and thermal energy to the Savona Campus: these facilities are respectively described in Bianco et al. (2020) and Bracco et al. (2013). SEB is a prosumer building because it is equipped with a PV plant and geothermal heat pumps in order to satisfy its own electric and thermal loads: if needed, the SEB is able to recall energy from the SPM. The RL will be equipped with PV modules, to be located on the rooftop of the SEB, a BESS, three AMRs with dedicated charging points and electric loads, related to the research activity therein carried out. Therefore, the RL can be considered as an NG within a prosumer building, located in a polygenerative microgrid. The RL will be connected to the SEB, in order to be able to withdraw energy from the building. The RL electric loads will be located in the AC portion of the NG, while PV and BESS will be interfaced to the AC NG by means of a single inverter. Besides of lighting, electric loads will be associated with the research activity carried out within the RL: desktop computers, monitors, laptops, a server and a printer. The three AMRs that will be available at the facility will be considered as time-shiftable electric loads, since their charging scheduling will be an output of the EMS. Loads will be fed both by energy provided by the inverter (and therefore coming from PV and/or BESS) and by energy coming from the SEB. Power injection from the RL-NG to the SEB will be forbidden due to regulatory reasons. BESS will not be able to be charged simultaneously with energy coming from the PV and from the SEB, due to the inverter control structure. A scheme of the facility is presented in Fig. 1.

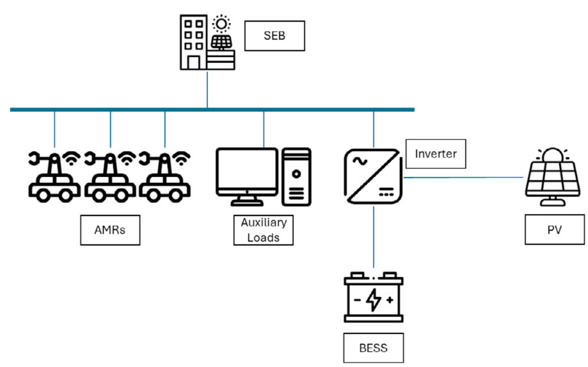

Fig. 1. Scheme of the NG

3. MATHEMATICAL MODEL

This section provides a detailed mathematical description of the EMS. The optimisation problem has been modelled as a MILP problem, that considers both continuous and binary decision variables, with linear constraints and linear objective function. The optimisation horizon is one day, subdivided in T time intervals of duration Δ.

3.1 PV model

Regarding the PV plant, the main decision variables are the power production P_t^{PV} and the curtailment power $P_t^{PV,curt}$, $t = 1, \ldots, T$. The input data is the available power $P_t^{PV,av}$, $t = 1, \ldots, T$. For each time interval, the sum of the power generation and of the curtailed power must be equal to the PV available power. In formulas:

$$P_t^{PV} + P_t^{PV,curt} = P_t^{PV,av} \quad \forall t = 1, \ldots, T \tag{1}$$

Besides, the curtailed power has to be limited between 0 and the available power:

$$0 \leq P_t^{PV,curt} \leq P_t^{PV,av} \quad \forall t = 1, \ldots, T \tag{2}$$

The power production can be split in two contributions: a contribution used to feed the load, $P_t^{PV,L}$, and a contribution used to charge the BESS, $P_t^{PV,ST}$, $t = 1, \ldots, T$:

$$P_t^{PV} = P_t^{PV,ST} + P_t^{PV,L} \quad \forall t = 1, \ldots, T \tag{3}$$

A further constraint is needed to limit the power that can be exchanged between the PV and the BESS, due to the control scheme of the inverter:

$$0 \leq P_t^{PV,ST} \leq P_t^{PV,av} \cdot x_t^{PV} \quad \forall t = 1, \ldots, T \tag{4}$$

where x_t^{PV}, $t = 1, \ldots, T$, is a further binary decision variable that is equal to 1 when the PV unit provides power to the BESS and 0 otherwise.

3.2 BESS model

As for the BESS, the decision variables are the charging and discharging power, $P_t^{ch,ST}$ and $P_t^{dch,ST}$, the charging and discharging state binary variables, $x_t^{ch,ST}$ and $x_t^{dch,ST}$, respectively equal to 1 when the BESS is in charging or in discharging mode, the power that the inverter provides to the BESS, $P_t^{INV,ST}$, and the BESS energy content, E_t^{ST}, $t = 1, \ldots, T$. Input data are the maximum charging and discharging power, $P^{ch,ST,max}$ and $P^{dch,ST,max}$, the capacity of the BESS, C^{ST}, the minimum energy content, $E^{ST,min}$, the initial energy content, $E^{ST,ini}$, the self-discharge rate, ϕ^{ST}, and the charging and discharging efficiencies, $\eta^{ch,ST}$ and $\eta^{dch,ST}$. The relevant constraints are presented below.
The charging power is given by the sum of the power coming from the PV and the power provided by the SEB, converted into DC, $P_t^{INV,ST}$, $t = 1, \ldots, T$, representing the DC output power of the inverter during AC/DC operations:

$$P_t^{ch,ST} = P_t^{PV,ST} + P_t^{INV,ST} \quad \forall t = 1, \ldots, T \tag{5}$$

By definition, $P_t^{INV,ST}$, $t = 1, \ldots, T$, has to be greater than 0:

$$P_t^{INV,ST} \geq 0 \quad \forall t = 1, \ldots, T \tag{6}$$

Limits on charging and discharging power have to be imposed:

$$0 \leq P_t^{ch,ST} \leq P^{ch,ST,max} \cdot x_t^{ch,ST} \quad \forall t = 1, \ldots, T \tag{7}$$

$$0 \leq P_t^{dch,ST} \leq P^{dch,ST,max} \cdot x_t^{dch,ST} \quad \forall t = 1, \ldots, T \tag{8}$$

The simultaneous charging and discharging of the BESS is forbidden:

$$x_t^{ch,ST} + x_t^{dch,ST} \leq 1 \quad \forall t = 1, \ldots, T \tag{9}$$

The energy balance of the BESS is formalised as follows:

$$E_{t+1}^{ST} = (1 - \phi^{ST}) \cdot E_{t+1}^{ST} + \Delta \cdot P_t^{ch,ST} \cdot \eta^{ch,ST} - \Delta \cdot P_t^{dch,ST} \cdot 1/\eta^{dch,ST} \quad \forall t = 1, \ldots, T-1 \tag{10}$$

Given the formulation of (10), the initial value of the BESS energy content has to be set:

$$E_1^{ST} = E^{ST,ini} \tag{11}$$

The energy content of the BESS has to be limited between the minimum value and the capacity of the BESS:

$$E^{ST,min} \leq E_t^{ST} \leq C^{ST} \quad \forall t = 1, \ldots, T \tag{12}$$

3.3 Inverter

The main decision variables related to the inverter are the input DC power and the output AC power during DC/AC operations, respectively $P_t^{DC,INV}$ and $P_t^{INV,L}$, and the input AC power and output DC power during AC/DC operations, respectively $P_t^{SEB,INV}$ and $P_t^{INV,ST}$, $t = 1, \ldots, T$. Besides, two binary variables describe the operation mode of the component: $x_t^{DC,INV}$, $t = 1, \ldots, T$, equal to 1 when the device works as a proper inverter and 0 otherwise, and $x_t^{SEB,INV}$, $t = 1, \ldots, T$, equal to 1 when the device works as a rectifier and 0 otherwise. The inverter is characterised by its size A^{INV} by its efficiency, η^{INV}. The input power on the DC side during DC/AC operations is given by:

$$P_t^{DC,INV} = P_t^{PV,L} + P_t^{dch,ST} \quad \forall t = 1, \ldots, T \tag{13}$$

The input power on the DC side is limited by the size of the inverter and has to be equal to 0 when the inverter works in AC/DC mode:

$$0 \leq P_t^{DC,INV} \leq A^{INV} \cdot x_t^{DC,INV} \quad \forall t = 1, \ldots, T \tag{14}$$

The same stands for the input power on the AC side, $P_t^{SEB,INV}$, $t = 1, \ldots, T$:

$$0 \leq P_t^{SEB,INV} \leq A^{INV} \cdot x_t^{SEB,INV} \quad \forall t = 1, \ldots, T \tag{15}$$

When the inverter works in DC/AC mode, the link between the DC input power and the AC output power is:

$$P_t^{INV,L} = P_t^{DC,INV} \cdot \eta^{INV} \quad \forall t = 1, \ldots, T \tag{16}$$

The same is valid during AC/DC operations:

$$P_t^{INV,ST} = P_t^{SEB,INV} \cdot \eta^{INV} \quad \forall t = 1, \ldots, T \tag{17}$$

The inverter cannot work simultaneously in AC/DC and DC/AC modes. Therefore:

$$x_t^{DC,INV} + x_t^{SEB,INV} \leq 1 \quad \forall t = 1, \ldots, T \tag{18}$$

Besides, given the structure of the inverter control, the BESS can be charged only using either power from the PV or power from the inverter (and therefore from the AC side of the NG). In formulas:

$$x_t^{PV} + x_t^{SEB,INV} \leq 1 \quad \forall t = 1, \ldots, T \tag{19}$$

3.4 Auxiliary loads

If in the RL some auxiliary loads are present, there could be the possibility of not-satisfying their demand. Therefore, the main decision variables are the power provided to the auxiliary loads, P_t^{AUX}, and the auxiliary demand that is not satisfied, $P_t^{AUX,uns}$, $t = 1, \ldots, T$. The input data is the desired auxiliary load demand $P_t^{AUX,des}$, $t = 1, \ldots, T$. The relevant constraints are:

$$P_t^{AUX} = P_t^{AUX,des} - P^{AUX,uns} \quad \forall t = 1, \ldots, T \tag{20}$$

$$0 \leq P_t^{AUX,uns} \leq (1-\alpha) \cdot P_t^{AUX,des} \quad \forall t = 1, \ldots, T \tag{21}$$

where α is the share of auxiliary loads to be always satisfied.

3.5 Autonomous Mobile Robots

This section presents both the energy and task planning constraints related to the AMRs. The number of AMRs present at the RL is N^R.

Energy model The energy decision variables are the actual charging power of each robot r at the time interval t, $P_{r,t}^{ch}$ and the energy content of the battery of each AMR, $E_{r,t}$, $r = 1, \ldots, N^R$ and $t = 1, \ldots, T$, and the total actual charging power for the three AMRs, P_t^R, $t = 1, \ldots, T$. Three binary variables describe the state of operation of the AMRs: $y_{r,t}^{ch}$, $r = 1, \ldots, N^R$ and $t = 1, \ldots, T$, equal to 1 when the robot r is in charging mode at the time interval t and 0 otherwise; $y_{r,t}^{W}$, $r = 1, \ldots, N^R$ and $t = 1, \ldots, T$, equal to 1 when the robot r is doing a task at the time interval t and 0 otherwise; $y_{r,t}^{I}$, $r = 1, \ldots, N^R$ and

$t = 1, \dots, T$, equal to 1 when the robot r is in idle mode at the time interval t and 0 otherwise. The main input data are the constant charging power of the AMRs provided by the manufacturer, P^{ch}, the capacity of the batteries and the minimum energy content, respectively C^R and $E^{R,min}$, the initial energy content E_r^{ini}, $r = 1, \dots, N^R$, the charging efficiency $\eta^{ch,R}$ and the energy consumption related to working and idle modes, $\psi^{R,W}$ and $\psi^{R,I}$.

The actual charging power of the robot r at the time interval t is given by:

$$P_{r,t}^{ch} = P^{ch} \cdot y_{r,t}^{ch} \quad \forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T \tag{22}$$

The total actual charging power of the AMRs at the time interval t is:

$$P_t^R = \sum_{r=1}^{N^R} P_{r,t}^{ch} \quad \forall t = 1, \dots, T \tag{23}$$

The energy balance of each AMR can be formalised as follows:

$$E_{r,t+1} = E_{r,t} + \Delta \cdot P_{r,t}^{ch} \cdot \eta^{ch,R} - \psi^{R,W} \cdot y_{r,t}^{W} - \psi^{R,I} \cdot y_{r,t}^{I}$$
$$\forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T-1 \tag{24}$$

Given the structure of (24), the initial energy content of AMR batteries has to be defined:

$$E_{r,1} = E_r^{ini} \quad \forall r = 1, \dots, N^R \tag{25}$$

The energy content of each AMR battery has to be limited between a minimum and a maximum value:

$$E^{R,min} \le E_{r,t} \le C^R \quad \forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T \tag{26}$$

The three operational states of the AMRs (charging, working, idling) cannot be simultaneous. Therefore:

$$y_{r,t}^{ch} + y_{r,t}^{W} + y_{r,t}^{I} = 1 \quad \forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T \tag{27}$$

Besides, AMRs are enabled to work only when personnel is present at the RL, so from 9 AM to 8 PM. In the other time intervals $y_{r,t}^W = 0$.

Task planning Three sets of task planning decision variables are defined. The first one, $z_{j,r,t}$, is equal to 1 when the robot r is doing the task j at time interval t and 0 otherwise, $j = 1, \dots, N^J$, $r = 1, \dots, N^R$ and $t = 1, \dots, T$, being N^J the total number of daily tasks to be possibly done at the RL. The second one, $w_{j,r,t}$, $j = 1, \dots, N^J$, $r = 1, \dots, N^R$ and $t = 1, \dots, T$, is equal to 1 if the robot r starts the task j at time t and 0 otherwise. The last decision variable, u_j, $j = 1, \dots, N^J$, refers to tasks: it is equal to 1 if the task j is completed within the optimization horizon and 0 otherwise.

The first constraint states that an AMR may be doing a task only if it is not charging or idling. In formulas:

$$\sum_{j=1}^{N^J} z_{j,r,t} = y_{r,t}^W \quad \forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T \tag{28}$$

Besides, at each time interval, each AMR can do only one task and a task can be done only by one AMR at most, i.e.

$$\sum_{j=1}^{N^J} z_{j,r,t} \le 1 \quad \forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T \tag{29}$$

$$\sum_{r=1}^{N^R} z_{j,r,t} \le 1 \quad \forall j = 1, \dots, N^J; \quad \forall t = 1, \dots, T \tag{30}$$

In addition, at each time interval, an AMR can start only one task. In formulas:

$$\sum_{j=1}^{N^J} w_{j,r,t} \le 1 \quad \forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T \tag{31}$$

A big-M constraint is needed in order to state that if an AMR starts a task at time t, that robot cannot be able to start any other task for the following D_j time intervals, $j = 1, \dots, N^J$, where D_j is the duration of task j:

$$\sum_{l=1}^{N^J} \sum_{h=t+1}^{t+D_j-1} w_{l,r,h} \le M \cdot (1 - w_{j,r,t}) \quad \forall j = 1, \dots, N^J;$$
$$\forall r = 1, \dots, N^R; \quad \forall t = 1, \dots, T \tag{32}$$

where M is the big-M constant.

Besides, if a task j is started at time t by robot r, that robot has to perform that task for D_j time intervals, $j = 1, \dots, N^J$:

$$w_{j,r,t} \le z_{j,r,h} \quad \forall j = 1, \dots, N^J, \ \forall r = 1, \dots N^R,$$
$$\forall t = 1, \dots T - D_j + 1, \ \forall h = t, \dots t + D_j - 1 \tag{33}$$

If the task j is performed within the optimization horizon by the robot r, the duration of the task has to be equal to D_j, $j = 1, \dots, N^J$. In other words, if task j is started, it has to be finished:

$$\sum_{r=1}^{N^R} \sum_{t=1}^{T} z_{j,r,t} + D_j \cdot u_j = D_j \quad \forall j = 1, \dots, N^J \tag{34}$$

Finally, since the tasks are not mandatory, they can be either performed or not performed within the time horizon:

$$\sum_{r=1}^{N^R} \sum_{t=1}^{T} w_{j,r,t} + u_j = 1 \quad \forall j = 1, \dots, N^J \tag{35}$$

3.6 Electric power balance

The electric power balance has to be satisfied at each time interval:

$$P_t^{SEB} + P_t^{INV,L} = P_t^{AUX} + P_t^R + P_t^{SEB,INV} \quad \forall t = 1, \dots T \tag{36}$$

where $P_t^{SEB} \ge 0$, $t = 1, \dots, T$ is the power withdrawn from the SEB.

3.7 Objective function

The objective function to be minimized is both economic and related to task planning. The optimization problem is set to minimize the costs associated with the number of tasks not performed by the AMRs, the curtailment of the PV source, the withdrawal of energy from the SEB and the unsatisfied demand of auxiliary loads. In formulas:

$$Obj = \sum_{j=1}^{N^J} p_j^R \cdot u_j + \Delta \cdot c^{PV,curt} \cdot \sum_{t=1}^{T} P_t^{PV,curt}$$
$$+ \Delta \cdot \sum_{t=1}^{T} p_t^{SEB} \cdot P_t^{SEB} + \Delta \cdot p^{AUX} \cdot \sum_{t=1}^{T} P_t^{AUX,uns} \tag{37}$$

where p_j^R, $j = 1, \dots, N^J$, is the penalty associated with the non-performance of task j, expressed in $[€/task]$, $c^{PV,curt}$ is the curtailment cost of the PV source, in $[€/kWh]$, considered equal to the Levelized Cost of Electricity for the PV source, p_t^{SEB}, $t = 1, \ldots, T$ is the penalty related to the withdrawal of energy from the SEB, expressed in [€/kWh], and p^{AUX} is the penalty for not meeting a part of the auxiliary loads, in [€/kWh].

4. RESULTS

This section shows the results of the optimisation over a whole sunny summer day, assuming Δ equal to 5 minutes. Before providing them, some numerical input data are reported to enhance the comprehension of the reader. The EMS has been implemented in Matlab/Yalmip environment and it has been solved with Gurobi solver.

4.1 Input data

The PV plant to be installed on the rooftop of the SEB has a rated peak power of 3 [kW]. The BESS has a rated capacity of 9.6 [kWh], with maximum charging and discharging power equal to 5 [kW] and charging and discharging efficiencies equal to 97.5 [%]. The BESS can be completely discharged and is supposed to have an initial energy content of 5 [kWh]. Self-discharge rate is put equal to 0 [%] since its impact over a single day is negligible. The inverter rating is 10 [kVA], with an efficiency of 95 [%]. Peak load is equal to 2.17 [kW] and α has been set equal to 1, meaning that the auxiliary loads demand has to be always satisfied. Three AMRs are supposed to be present at the RL. Each AMR has a battery capacity of 0.537 [kWh], with a charging power of 0.512 [kW] and a charging efficiency of 95 [%]. AMRs batteries can be totally discharged. The energy consumption during working and idling modes, $\psi^{R,W}$ and $\psi^{R,I}$, are equal to 5.7 [Wh] and 5.6 [Wh] for each time interval. The initial energy content of each AMR has been considered equal to half of the battery capacity. The number of tasks to be possibly performed by the AMRs has been set equal to 45, each one with a duration of either 5, 10 or 15 minutes. Regarding the weight coefficients in the objective function, p_t^{SEB}, $t = 1, \ldots, T$ is set equal to 0.11919 [€/kWh] for off-peak hours (from 12 AM to 8 AM and from 7 PM to 12 AM) and 0.12762 [€/kWh] for peak hours (from 8 AM to 7 PM), $c^{PV,curt}$ is set equal to 0.128 [€/kWh], as stated in de Simón-Martín et al. (2022), p_j^R, $j = 1, \ldots, N^J$, takes integer values between 1 and 10 [€/$task$], randomized by Matlab in order to give priority to the different tasks to be performed and p^{AUX} is set equal to 10 [€/kWh], since the satisfaction of all the auxiliary loads is a key point of the EMS. The profile of PV active power generation has been obtained from PVGIS Online Tool, while the profile of $P_t^{AUX,des}$, $t = 1, \ldots, T$, has been obtained with a bottom-up approach, starting from assumptions about the occupancy level and timetable and about the available devices (laptops, desktops, server, printer and lighting).

4.2 Optimal results

The optimal results of the EMS are presented and discussed in the present section. The active power balance of the NG is presented in Fig. 2. It is evident that during night the demand related to the base load and to the charging of the AMRs is met withdrawing energy from the SEB. During the early morning, before 8 AM, the PV output is used to charge the BESS, while the load and the AMRs charging demand continues to be satisfied with energy from the SEB: when the BESS is charged by the PV unit, the AC and DC portion of the NG are independently working, due to the fact that the simultaneous charging of BESS with energy from the PV and from the AC portion of the NG is forbidden. Then, during peak hours when the penalty associated with the withdrawal of energy from the SEB is higher, the PV unit and the BESS are able to satisfy the whole demand by their own: due to shape of the load curve, the BESS needs to be discharged during the afternoon, when the PV contribution decreases while the load demand remains almost constant at peak level. Starting from 7 PM, when the penalty related to the withdrawal of energy from the SEB becomes lower and the PV contribution is zero, the SEB is in charge of satisfying the load and AMRs charging demand.

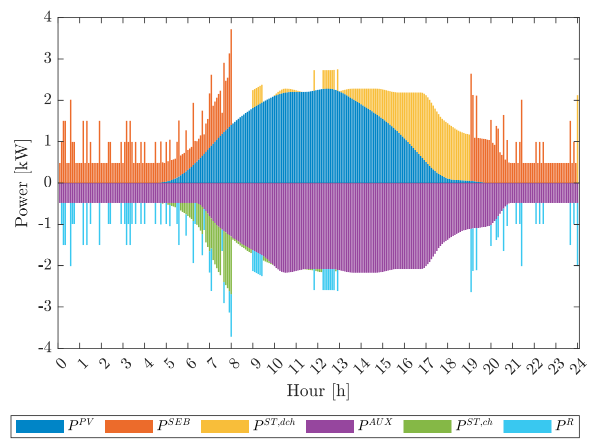

Fig. 2. NG active power balance

The main energy quantities are reported in Table 1. The curtailed energy of the PV unit $E^{PV,curt}$ is 0, meaning that the energy yield E^{PV} is the maximum one. The auxiliary demand E^{AUX} is totally satisfied (i.e. the unsatisfied auxiliary demand $E^{AUX,uns}$ is 0). In order to do this, some energy (E^{SEB}) has to be withdrawn from the SEB, when the PV unit and/or the BESS are not able to meet the demand by their own. The fact that the energy discharged from the BESS, $E^{dch,ST}$, is more than the charged one, $E^{ch,ST}$, is due to the fact that the final energy content of the BESS is not constrained by the EMS. The energy globally charged into the AMRs, $E^{ch,R}$, is the one needed to perform the tasks.

Table 1. Main energy results

E^{PV}	18.39 [kWh]	$E^{PV,curt}$	0 [kWh]
E^{AUX}	28.69 [kWh]	$E^{AUX,uns}$	0 [kWh]
E^{SEB}	10.65 [kWh]	$E^{ch,R}$	3.97 [kWh]
$E^{ch,ST}$	1.81 [kWh]	$E^{dch,ST}$	6.58 [kWh]

The activity states of the three AMRs are presented in Fig. 3. During the hours in which personnel is not present at the RL, the AMRs can only be either idling or charging.

All the 45 tasks are completed during the time window 9 AM - 8 PM. Despite not having defined an activity balancing constraint to share equally the number of tasks among the AMRs, the number of time intervals of working activity is more or less the same for all the AMRs.

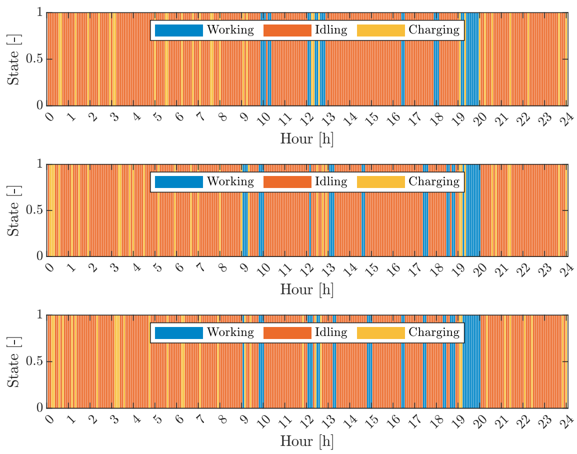

Fig. 3. AMRs activity states

5. CONCLUSIONS

This paper aimed at developing an EMS for the optimal operation of an NG representing an RL, equipped with a PV unit, a BESS and three AMRs for the performance of some tasks. The RL is located in a prosumer building, in turn located in a polygenerative MG. The goal of the EMS was to maximize the number of performed tasks, while trying to minimize the curtailment of the PV source and the withdrawal of energy from the SEB. The EMS was run over a whole day, with a time resolution of five minutes, in order to be compliant with the typical task planning time granularity. The EMS has been run over a sunny summer day. The results showed that the PV system is never curtailed, while the BESS is charged during the early morning, to be then discharged in the afternoon in order to satisfy the demand when the PV production is reduced. The AMRs are able to perform all the assigned tasks.

Different aspects could be investigated in the near future to extend the proposed EMS: increase of the number of tasks in order to evaluate its impact on the operations of the facility, consideration of reactive power constraints and modelling of the building electric network to compute losses. Moreover, it could be interesting to apply a model predictive control formulation to the EMS, in order to compare the results with the ones obtained with a day-ahead formulation.

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