Subhour Simulation of a Microgrid of All-Electric nZEBs Based on Italian Market Rules

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***Abstract*—In the present work, a microgrid of three active users (nanogrids) with the possibility of connection to the grid has been analysed in the context of the Photo Voltaic Zero Energy Network (PVZEN) project of Politecnico di Torino. The generators of the nanogrids (prosumers) are PhotoVoltaic (PV) strings, while the load is mainly diurnal because the system offers a service for university students and employees. In particular, this work aims to simulate the electrical performance of the system and quantify the economic benefits due to the creation of a microgrid with respect to independent nanogrids. In this framenwork, an ad hoc software in Matlab environment has been developed, implementing the rules of Italian day ahead electric market. Moreover, the software evaluates the optimal configuration of nanogrids (integration of batteries, presence and typology of connection to the grid) that maximizes the economic saving of the system.**

***Keywords*—nZEBs, microgrid, nanogrids, energy community, photovoltaic generators, Italian day ahead electric market, smart grids.**

I. Introduction

In recent years, one of the most important challenges is to limit the climate change. In order to fulfil the increasing energy demand with minimal environmental impact, the European Union has supported the development of Renewable Energy Sources (RES). During 2018 and 2019, the energy policy framework has been updated with the “Clean energy for all Europeans” package. It consists of several legislative acts, which set more ambitious targets in terms of energy efficiency; RES penetration and reduction of greenhouse gases emissions by 2030, including the modernization of the electricity market [1]. Reducing energy consumption and increasing energy production from RES in the building sector is essential to achieve the European Union’s climate and energy goals. Actually, approximately 36% of CO_2 emissions are due to the building sector and consumption due to buildings heating and cooling accounts for almost 40% of the Union’s final energy demand [2]. Directive 2010/31/EU has already established that all the new buildings must be nearly Zero Energy Buildings (nZEBs) starting from the end of 2020. These buildings are energy efficient: in fact, their consumption will be met locally by RES [3]. Within the new package, the Directive 2018/844/EU has established that Member States must support the renovation of their national building stock in order to transform the existing buildings into nZEBs [2]. In this context, a modification of the electrical grid is required. Actually, its actual structure is designed with a top-down approach: the power flows are unidirectional, flowing from high voltage generation to passive users (consumers). With the installation of local generators, consumers can become active users (prosumers), creating a complex electrical structure of local grids [4][5]. If a control system manages the interaction between the generators, the loads and the storage units, the local grid can be defined as a nanogrid. Moreover, each nanogrid could exchange data in real time with the others in order to allow the exchange of electrical energy [6]. The possibility of sharing electrical energy, i.e. the creation of a microgrid (energy community), aims to maximize the self-sufficiency and the self-consumption of the prosumers from local RES, resulting in an economic return for the microgrid [7][8][9]. However, this configuration requires a new structure of the electrical grid, which has to be designed with a bottom-up approach (smart grids) [10] [11].

In the present work, a microgrid of three active users (nanogrids) with the possibility of connection to the grid has been analyzed in the context of the Photo Voltaic Zero Energy Network (PVZEN) project of Politecnico di Torino [12][13]. In particular, the three nanogrids (prosumers) consist of four energy-efficient nZEBs and they will have load profiles similar to tertiary sector buildings. The present paper aims to simulate the electrical performance of the system and quantify the economic benefits deriving from the creation of a microgrid between the nanogrids. This is performed using an ad hoc software developed in Matlab environment, implementing the rules of Italian day ahead electric market. Moreover, in case of microgrid, the software identifies the optimal configuration of the nanogrids in terms of integration of batteries, presence of connection to the electrical grid and type of the grid contract. In case of a microgrid, the connections between the nanogrids are flexible and the energy exchanges are identified by the software. In future works, the software will control, every time step, the connections between the nanogrids by varying the status of suitable contactors and it will predict, step by step (15 min), the energy exchanges by using realistic generation and consumption profiles. In particular, the market rules will be applied in a shorter time step than the Italian electric market and an almost real-time control of the system will be achieved thanks to the immediate data sharing of the nanogrids. The paper is structured as follows: in Section II the case study is presented, while Section III describes the software adopted in this work. The results of the analysis are reported in Section IV, while Section V contains the conclusions.

II. Description of PVZEN Project

In the context of the PhotoVoltaic Zero Energy Network (PVZEN) project, four buildings will be built in the university campus of Politecnico di Torino, creating three independent electrical users (nanogrids). In particular, they will consist of a control room for the monitoring of the system and a technical room, where energy conversion devices will be located (user #1); two study rooms dedicated to students and university employees (users #2 and #3). In Fig. 1, the layout of the nZEBs is presented for 21st December at 15:30 with the profiles of the shadings by a proper software.

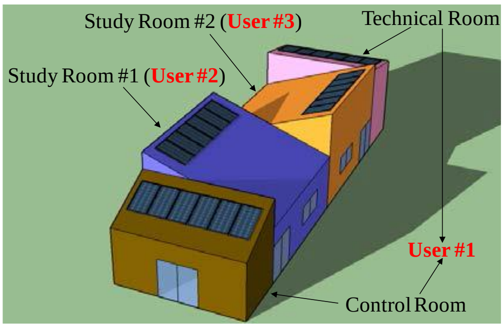

Fig. 1. Layout of the nZEBs on 21st December at 15:30.

The buildings will be nZEBs, built with eco-friendly materials in order to minimize their environmental impact and their specific energy consumption. In particular, the living modules will meet the requirements of the Italian class A buildings [14]. The thermal demand of the buildings will be converted into electrical and supplied by heat pumps. The generation of each user will consist of a PV generator and, eventually, electrochemical storage. The generators will be connected to a device containing a Maximum Power Point Tracker (MPPT) and a Battery Management System (BMS): the first will extract the maximum PV power continuously, while the BMS will control the correct operation of batteries in charge or discharge. These devices will be connected to a unidirectional DC/AC converter, in order to meet the AC demand, and to the grid. In the present work, the system will have a flexible configuration: in fact, the electrical connections between the users will include contactors that can be opened or closed. In particular, their status may be modified locally or using a PC with a dedicated software. Moreover, the inverters belong to the master/slave type and they can be connected in parallel. In this case, the role of master will be continuously updated: its output will be connected to the input of the parallel-connected converters, acting like slaves. These converters will be able to work in stand-alone or grid-connected configurations. The following conversion efficiencies are assumed in the present work: the conversion efficiency taking into account the MPP tracking, the DC/DC and the DC/AC conversion losses in the power conditioning units is η_{PCU} = 97%, while the efficiency of other generation losses (dirt, reflection of the glass in the PV modules, ohmic wiring losses) is assumed η_{array}= 92% and the charging efficiency of batteries is η_{bat}= 96%.

A. *Definition of Generators*

The PV generator of the system has been designed with rated power P_r= 8.64 kW able to exceed far beyond the consumption of the users and consists of four PV strings, with 6 modules (P_r= 360 W) each. In particular, a PV string is installed on the roof of each nZEB. However, user #1 includes two buildings: therefore, the PV strings of technical and control rooms are connected to the same DC/AC converter, behaving like a unique PV generator. The rated power, the azimuth γ and the inclination β of the PV generators are reported in Table 1. The converters have rated power = 5 kW.

TABLE I. Main Parameters of PV Generators

Type of building	*User*	*P_r (kW)*	β	γ
Control Room	User #1	2.16	30°	26°
Technical Room		2.16	10°	154°
Study Room #1	User #2	2.16	20°	-64°
Study Room #2	User #3	2.16	20°	116°

The online software PhotoVoltaic Geographical Information System (PVGIS) [15] has been adopted to evaluate the yearly PV production $E_{PV,y}$ of the generators. In particular, the PV string of user #1 provides $E_{PV,y}$ = 4451 kWh, while the generators of the other users generate $E_{PV,y}$ equal to 2361 kWh and 1848 kWh, respectively. As well know, this difference is mainly due to the orientation of the PV generators: for this installation site, the optimal orientation that maximizes $E_{PV,y}$ is γ = 0° (South direction). The self-sufficiency is the ratio between the amount of consumption supplied by PV generators (directly or by batteries with a certain delay) and the total electric load. In order to increase this quantity and due to requirements of power compensation in case of stand-alone users or mistaken forecast, the integration of electrochemical storage will be investigated. In particular, lithium batteries will be analyzed with an energy capacity C_{Ebat} = 2.4 kWh per each unit. The operation of batteries can be simulated thanks to the energy model described in [13]. However, their performance can degrade due to several factors (not optimal charging patterns, overcharging, undercharging and abnormal cycling conditions, caused by atypical charging temperature). In order to save the state of health of batteries, a maximum power limit P_{max} is set and a minimum *State Of Charge* SOC_{min} is guaranteed to avoid the complete discharge of the batteries [13]. Moreover, the batteries cannot be charged over a maximum SOC_{max}. In the present work, SOC_{min} and SOC_{max} are 4 % and 96 %, respectively, while P_{max} is equal to 1.3 kW. Finally, batteries can be charged on DC bus by PV generators only, increasing the overall efficiency of the system.

B. *Definition of loads*

The buildings have load profiles that are mainly diurnal and similar to tertiary sector buildings [16]: indeed, they offer a service that is dedicated to students and university employees. The electric load consists of two terms: the first contribution is due to the consumption of electric equipment. In particular, the structure has 23 laptop workstations, with their own plug for laptops and Light Emitting Diode (LED) lamp. Regarding the plugs, their absorption is ≈ 50 W when laptops are at the start, while the steady-state consumption is ≈ 30 W. On the contrary, the consumption of the lamps is 9 W from technical specifications. Moreover, a projector (power ≈ 190 W) is installed in users #2 and #3 and they are supposed working at maximum load 4 h per day. The second term is the thermal demand of the buildings due to heating, ventilation and conditioning. In this work, the thermal load of each user is converted into electrical and supplied by a heat pump with rated power = 2 kW and a seasonal Coefficient Of Performance COP = 3.5 [17]. About yearly thermal demand, the nZEBs require 1509 kWh for cooling and 1562 kWh for heating. Fig. 2 presents the electrical load profiles for user #2 in a typical day in summer (red curve) and winter (black curve). As previously mentioned, the load is mainly diurnal. Moreover, the daily load in summer is ≈ 8.3 kWh (maximum power P_{Lmax} ≈ 1.1 kW), while in winter, the daily load is 6.5 kWh/day, with P_{Lmax} ≈ 0.9 kW.

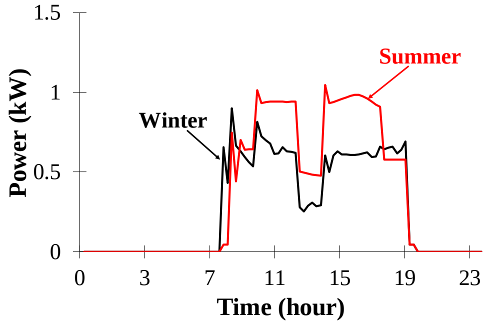

Fig. 2. Load profiles for typical days in winter (January 15th) and summer (July 15th) for user #2.

Fig. 3 shows the aggregate profiles of PV production (green curve) and load (red curve) for a typical day in winter. PV generators cannot supply the electric consumption of the buildings alone: from 8 a.m., batteries (blue curve) are discharged to meet a part of the consumption. At 13 p.m., PV generators have their peak production, fulfilling the load and charging the storage. From 14:30 p.m., batteries and PV generators supply the load: during this day, power is not absorbed from the grid thanks to the integration of the storage.

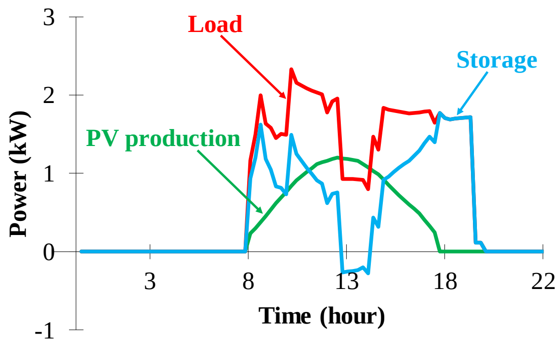

Fig. 3. Aggregate profiles of generation and consumption for a typical winter day.

C. *Configurations of the system*

As mentioned in Section II.A, in the present work, the configuration of the system is flexible, i.e. the connections between the nanogrids may vary during time. In particular, the economic benefits of the following system configurations have been evaluated:

- Case A: Independent Prosumers. The generation consists of the PV generators described in Section II.B. The prosumers are independent, i.e. they cannot exchange energy, and each nanogrid has a 3 kW supply contract with the electrical grid. In this configuration, the storage has not been integrated in the system (Fig. 4).

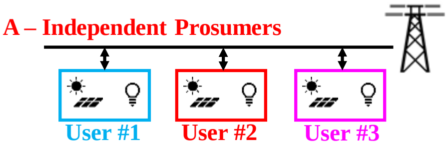

Fig. 4. Scheme of independent prosumers connected to the grid.

- Case B: Prosumers as Energy Community (EC). The prosumers maintain the generators and the supply contracts of case A but, in case of deficit, a prosumer can buy the energy useful to supply its load from other prosumers or the grid (Fig. 5).

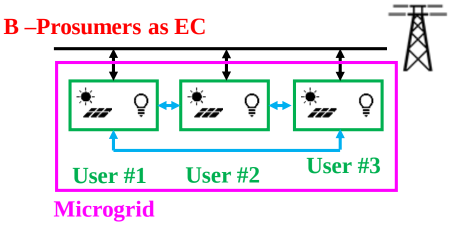

Fig. 5. Scheme of prosumers behaving like an EC.

- Case C: Prosumers with batteries. In this case, nanogrids are independent (case C.1) or acting like an EC (case C.2, Fig. 6) and they can supply their loads using also batteries. The supply contracts are the same of previous cases.

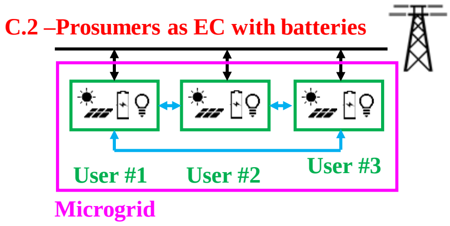

Fig. 6. Scheme of prosumers connected in an EC with batteries.

- Case D: Prosumers as EC with a reduced number of supply contracts. A convenient solution for users could consist of reducing the number of supply contracts. For this reason, two conditions have been analyzed: two 3 kW contracts (case D.1) and one 6 kW contract (case D.2, Fig. 7). However, all the users can buy electricity from the grid and the cost of the contracts are equally partitioned between them. Thus, the identity of the users connected to the grid does not affect the results of the analysis.

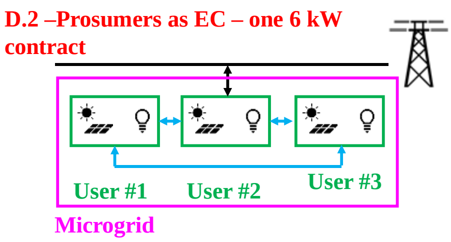

Fig. 7. Scheme of prosumers behaving like an EC with a 6 kW contract.

III. Development of the Simulation Software

A Graphical User Interface (GUI) has been developed in Matlab environment to simulate the electrical performance of the system and quantify the economic benefits due to the creation of an EC (microgrid) between the nanogrids. In particular, the software permits to show the status of the contactors, therefore the current configuration of the system; the power profiles of PV production and consumption, and the energy exchange between the users, evaluating the economic saving of the system with respect to independent prosumers. In the first part, the GUI acquires the inputs of the simulation: the main parameters of PV generators (P_r, γ, β); the technology of batteries, the *SOC* at the start of the simulation, C_{bat}, P_{max}, SOC_{min} and SOC_{max}; the PV generation and load profiles (estimated by PVGIS); and the prices of electricity that will be defined in next paragraphs. In the second part, the simulation period (1 year) and the time step Δt (15 min) are selected. Finally, the software analyses the system.

A. *Estimation of PV electricity price*

Generally, in case of ideal markets, the price of electricity corresponds to the marginal price: in this case, the price of electricity sold by the users is equal to the investment cost of generators divided by their lifetime and the economic profit is zero regarding the PV generators. In the present work, only marginal prices will be considered.

For each user, the price of its PV energy takes into account the yearly installation cost C_{PV} of PV modules and DC/AC converters. Regarding users #2 and #3, C_{PV} is equal to 158 €/y, while PV generator of user #1 consists of two strings, leading to C_{PV} = 234 €/y. Then, the price of PV electricity p_{PV} is obtained in the following way:

$$p_{PV} = C_{PV} / E_{PV,y} \quad (1)$$

As mentioned in Section II.A, in the present work, PV generators have different installation conditions, resulting in different energy production and prices of electricity. In particular, the orientation maximizing the PV production corresponds to user #1, resulting in the lowest PV price (p_{PV} = 5.2 c€/kWh). Regarding users #2 and #3, p_{PV} is equal to 6.7 c€/kWh and 8.5 c€/kWh, respectively.

Batteries can behave like generators (in discharge) or loads (during charge). For this reason, two prices of electricity are defined: the price of electricity charging the storage $p_{bat,c}$ and the price of electricity sold by the batteries in discharge $p_{bat,d}$. In this case, the batteries are integrated with the PV system, being charged by the PV generators only. Thus, the price of electricity charging the storage is assumed equal to p_{PV} of PV generator selling energy to batteries. On the contrary, during discharge, $p_{bat,d}$ is the sum of p_{PV} and a term taking into account the investment cost of batteries Δp_{bat} [18]:

$$\Delta p_{bat} = C_b / (C_{Ebat} \cdot n_c \cdot \eta_{bat} \cdot DOD) \quad (2)$$

where C_b is the investment cost of storage, n_c is the number of cycles guaranteed by the manufacturer and DOD is the Depth Of Discharge [19]. Here, C_b is 990 €, n_c is 10000 and DOD is 92 %, resulting in Δp_{bat} = 8.2 c€/kWh. Thus, the price of electricity sold by batteries $p_{bat,d}$ is 13.4 c€/kWh (user #1), 14.8 c€/kWh (user #2) and 16.7 c€/kWh (user #3).

B. Estimation of the price of electricity for loads and electrical grid

As presented in Section II.B, the PVZEN project aims to provide a continuous service to university students and employees. For this reason, the supply of the load is required (rigid load), independently from the price of electricity of the generators. Therefore, the user is willing to pay electricity at any price and the price of loads p_{load} (80 c€/kWh) is assumed far higher than the price of all the generators.

In the present work, the electrical grid is considered an auxiliary generator in order to improve the reliability of the system if PV-storage systems of the nanogrids cannot supply the entire load of the users or during their maintenance [20]. Regarding the price of electricity absorbed from the grid p_g, it consists of a variable ($p_{g,v}$) and a fixed ($p_{g,f}$) term: the first is related to the amount of energy absorbed from the grid during a year, while the second quantity is a constant price paid by the user at the end of the year. In this framework, the actual tariffs in Italy have been taken into account [21] and two types of supply contracts for residential users in Italy have been analyzed, with a maximum instantaneous power of 3 kW and 6 kW, respectively [22]. Generally, in the analyzed system, the nanogrids are connected to the grid with a 3 kW contract. However, in case of one grid connection, the system has to supply the peak load, which is higher than 3 kW. Thus, in this case, the 6 kW contract is considered. Regarding the 3 kW contract, the variable term $p_{g,v}$ is equal to 15 c€/kWh, while $p_{g,f}$ = 132 €/year. The 6 kW contract has the same variable term but $p_{g,f}$ is higher (196 €/year). If the PV production of the system exceeds the consumption, the surplus is injected into the grid and the price of electricity p_{sur} is the minimum price guaranteed by Italian authority, Gestore dei Servizi Energetici (GSE), and it is = 4 c€/kWh [22].

C. Simulation of the system

The simulation of the system starts from the average power balance of each nanogrid. In particular, the surplus/deficit at time step Δt_i P_{grid} (deficit if P_{grid} >0 and surplus if P_{grid} <0) is evaluated in the following way:

$$P_{grid}(\Delta t_i) = P_{load}(\Delta t_i) - P_{PV}(\Delta t_i) - P_{bat}(\Delta t_i) \quad (3)$$

where P_{load} is the consumption, P_{PV} is the PV production and P_{bat} is the power provided by the batteries. P_{bat} is >0 when the storage is in discharge, while P_{bat} <0 with charging batteries. Then, the internal market of each nanogrid is solved (step #1). In particular, each prosumer supplies its load using its PV-storage system. Therefore, the possibility for each prosumer to be self-sufficient is investigated: the generators of the other prosumers and the electrical grid do not participate to the market and step #1 is organized in the following sub steps:

- Supply of load by PV generators. The amount of consumption supplied by PV generators is a part of the self-consumed load L_{RES}, i.e. the quota locally met by RES.
- Supply of load by batteries ($SOC > SOC_{min}$). If the SOC of the storage is > SOC_{min}, batteries can provide energy to fulfil the user consumption. In such condition, each prosumer will exploit its storage to increase L_{RES}.
- Quantification of deficit (L_{share}) and surplus (P_{share}) of each nanogrid. If the self-consumed load of a nanogrid is not equal to its total electrical load L_{TOT}, a part of the demand is not fulfilled by the corresponding PV-storage system (L_{share}). On the contrary, if the PV-storage production of a prosumer is larger than its demand, i.e. the prosumer is totally self-sufficient, a part of generation P_{share} is available.

In case of independent prosumers, if the users are in deficit, L_{share} is met by the electrical grid ($p_{g,v}$). On the contrary, if the users have a surplus, E_{share} is injected into the grid (p_{sur}). This is performed in step #2A. On the contrary, if prosumers are allowed to exchange energy, the software evaluates, at each time step, the connections maximizing the economic benefits (step #2B) using defined market rules. In particular, in this step, the market of the microgrid is solved and it is organized in the following sub steps:

- Definition of the role of storage units of each prosumer. After step #1, batteries can be completely charged (SOC = SOC_{max}, i.e. the PV generator alone supplies L_{TOT} of the corresponding nanogrid), partially charged ($SOC_{min} < SOC < SOC_{max}$, i.e after the supply of the consumption, the storage is able to provide an additional amount of energy in order to fulfil the loads of the other prosumers) or completely discharged ($SOC = SOC_{min}$, i.e. the batteries cannot provide energy to supply the load of other prosumers). Therefore, the storage is assumed as a generator in the first two cases, while discharged batteries are loads.

- Solution of the microgrid market. The surplus/deficit of each nanogrid (step #1) participates to the microgrid market. The identification of the energy exchanges between users is performed using the rules of Italian day-ahead electric market, in order to maximize the economic saving of the system [23]. In particular, the aggregate demand curve and the aggregate supply curve of the microgrid are built [24]. The supply curve is traced starting from the PV surplus of each nanogrid P_{share} and its price p_{PV}; the energy available in charged batteries, if present, and its price $p_{bat,d}$. The last term is related to the energy that can be absorbed from the grid paying the variable term $p_{g,v}$. On the contrary, the demand curve is obtained from the deficit of each nanogrid L_{share} and its price p_{load}, and the energy necessary to completely charge the batteries ($p_{bat,c}$). The optimal solution of the market is identified by the intersection of demand/supply curves, thus determining the subjects exchanging energy, the exchanged Market Clearing Quantity (MCQ) and the Market Clearing Price (MCP) [24]. Fig. 8 shows an example for case B (microgrid of grid-connected nanogrids without batteries): user #3 is in deficit (L_{share}, red line), while users #1 and #2 have a PV surplus P_{share} (blue line). The grid has a higher electricity price than PV generators of users #1 and #2, while the consumption of user #3 has the highest price because it is a rigid load. For this reason, according to the intersection between demand and supply curves, user #3 buys PV energy from user #1 at its p_{PV}. The remaining PV surplus of user #1 P_{rem} and the generation of user #2 will be injected into to the grid according to step #3B.

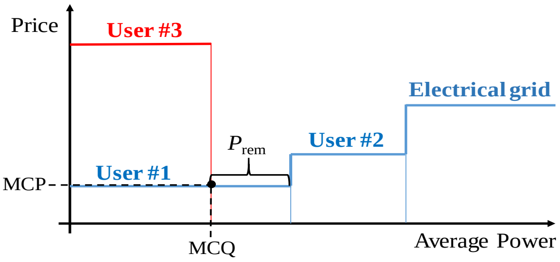

Fig. 8. Example of aggregate demand and supply curves for case B.

In the present work, Δt_i = 15 min but, in future, this interval will be reduced to 1 min, which is lower than Italian electric market, to control the system with fast response. As mentioned in Section I, at each time step, the software will control the connections between the nanogrids and it will predict their energy exchanges for the next time step using real production and load profiles. During high PV production or low consumption, a residual amount of PV generation can be available after the energy exchange in the microgrid. Therefore, in step #3B, the remaining PV surplus P_{sur} is injected into the grid and the price is the minimum guaranteed (4 c€/kWh). The flowchart of the entire procedure for each time step Δt_i is reported in Fig. 9.

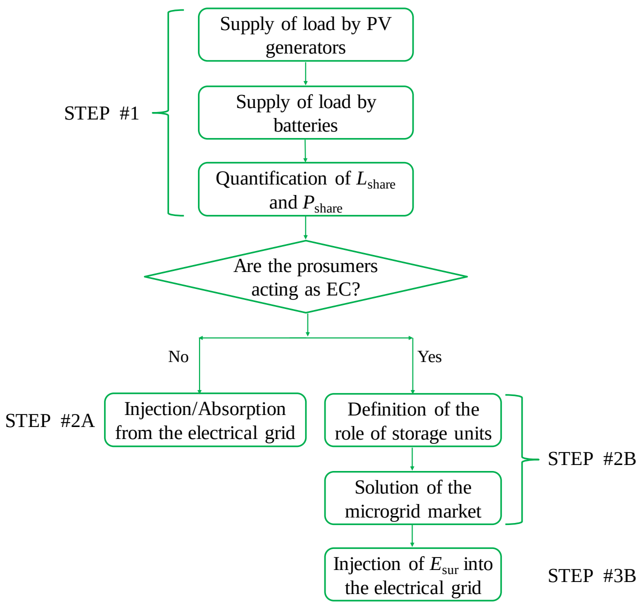

Fig. 9. Flowchart of the procedure performed at each Δt_i.

IV. Results of the Simulations

In case of passive users, the yearly economic expenditure C_y of the system is 985 €: in this condition, users supply their load absorbing electricity from the grid. On the contrary, prosumers (case A) fulfil their load, or a part of it, by PV production generated locally, resulting in C_y = 856 €. In the present work, case A is assumed as the reference: the results of the other system configurations are provided in terms of relative cost C_{rel}, which is the C_y of the case under study, normalized with respect to case A.

Fig. 10 presents the results of cases A, B and C: the costs of the single users are reported and the cost of the system corresponds to the sum of the costs of single nanogrids. If the nanogrids are allowed to exchange energy (case B) creating an energy community, it is more convenient for users to buy electricity from the other nanogrids because the price of PV energy p_{PV} and batteries ($p_{bat,d}$) is lower than the price of the grid $p_{g,v}$. In fact, this case results in C_{rel} = 98% and user #1 has the highest saving, because its PV production is usually higher than its load, i.e. a surplus for other users is generally available. If batteries are integrated in the system, the results are worse. Actually, if each prosumer has a storage installed (C_{bat} = 2.4 kWh), the economic saving due to a lower grid absorption cannot compensate for the investment cost of batteries, both in case of independent prosumers (case C.1) and energy community (case C.2). Hence, the storage is not an economically convenient solution for independent nanogrids or prosumers connected in a microgrid. Then, a reduced number of supply contracts has been analyzed: in particular, two 3 kW contracts (case D.1) or a single 6 kW contract (case D.2) have been investigated. Fig. 11 shows the relative cost of case D.1, resulting in an overall C_y = 83%, with a corresponding saving of ≈ 17%. In case of a single contract (case D.2), results are even better, resulting in a total cost that is 75% of case A and an economic saving of about 25%.

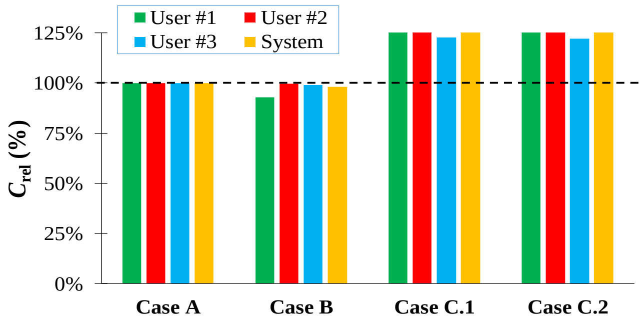

Fig. 10. Yearly relative costs in case of independent prosumers or microgrid, with and without batteries

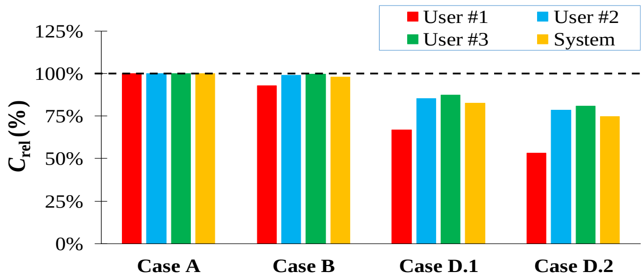

Fig. 11. Yearly relative costs for microgrid with modified number and typology of connections to the grid

As a consequence, the configuration of prosumers behaving like a microgrid with a 6 kW supply contract maximizes the economic saving for the system, meeting the energy requirements of [3] in terms of self-sufficiency.

V. Conclusions

The present work aims to simulate the electric performance of a microgrid of nZEBs and quantify the corresponding economic benefits with respect to independent prosumers. The analysis is performed using an ad hoc software developed in Matlab environment using the rules of Italian day-ahead electrical market in order to maximize the economic saving of the system. The results show that the connection of prosumers (energy community) leads to a economic saving. Moreover, the integration of batteries is not a convenient solution, both in case of independent prosumers and energy community. This is due to the current investment costs of the storage, which cannot be compensated by the economic saving due to a lower grid absorption. A reduction in the number of supply contracts can be an effective solution to reduce the costs of the system, guaranteeing a saving of ≈ 17% (two 3 kW contracts) and ≈ 25% (one 6 kW contract). In the future, for every time step, the software will control the connections between the nanogrids by varying the status of contactors and it will predict the energy exchanges for the next time step using real generation and consumption profiles.

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