Performance Optimization of a Residential Microgrid Balancing Economic and Energy Issues

Marialaura Di Somma
Department of Energy Technologies and Renewable Sources, ENEA - Portici (Naples), Italy
marialaura.disomma@enea.it

Salvatore Favuzza, Francesco Montana, Vincenzo Porgi, Gaetano Zizzo
Department of Engineering, University of Palermo (UNIPA) - Palermo, Italy
salvatore.favuzza@unipa.it, francesco.montana@unipa.it, vincenzo.porgi@community.unipa.it, gaetano.zizzo@unipa.it

***ABSTRACT* — Microgrids are currently seen as the future of power generation and distribution systems. This paper illustrates the optimization of the operation stage of the main components of a microgrid supplying the final demands for electricity, heating and cooling of a residential district. The optimization was performed with reference to four seasonal standard days and optimizing the operating costs or the primary energy use. The electricity production from a photovoltaic system and a combined heat and power (CHP) satisfies the local electricity demand. The heating demand is fulfilled with a gas-fired boiler, a CHP, a solar thermal collector and a reversible heat pump that is employed also for the cooling demand together with an absorbtion chiller. Moreover, a storage system for each demand is also included. The optimization model is formulated through a mixed-integer linear programming approach and implemented in MATLAB. The results show a reduction of costs ranging between about two and four times and a reduction of primary energy use between about two and five times with respect to the traditional scenario (electricity and gas from the grid).**

***KEYWORDS* — Emissions; Energy hub; Microgrid; MILP; Optimization.**

I. Introduction

The recent energy transition from "vertically" to "horizontally" integrated energy grids leads to the research of new cooperative approaches for the different components in the energy system. Moreover, the current trend of research is to analyze small districts or microgrids instead of a single building, in order to investigate further possibilities to attain energy savings, also exploiting synergies coming from the interplay of multiple energy carriers [1].

The scientific interest in the investigation of the energy performance of energy districts arises from many points of view [2]:

- It is possible to predict the demand of many buildings with more accuracy since the load peaks and valleys of a single customer tend to be mitigated in the district;
- Designing zero-energy districts is easier than designing zero-energy buildings since the single building does not have to necessarily meet the zero balance;
- From a practical point of view, it is easier to find adequate spaces to install the renewable energy sources (RES) and heating ventilation and air Conditioning (HVAC) systems.

Another important topic to investigate is the integration of multiple energy carriers such as electricity, natural gas, hydrogen, heating, cooling and mobility, thus encouraging a movement towards multi-energy systems. The availability of many alternatives to meet energy demands also enhances the flexibility to external, unexpected events, as the recent natural gas scarcity in Europe due to the war in Ukraine. Due to the simultaneous interaction of many equipment and energy carriers, microgrids are the perfect test environment to develop new optimal management strategies.

The main issue examined in this paper is the identification of the optimal operation schedule of a residential district modeled as a microgrid with known and fixed energy requirements. An energy hub (EH) model is employed to schematize the components and the energy flows related to the supply of electricity, heating and cooling to the urban district through tranditional and innovative components. In detail, the optimization aims to identify the optimal operation schedule of a gas-fired boiler, a photovoltaic system, a solar thermal collector, a air-to-air reversible heat pump, a micro CHP, an absorbtion chiller, a lithium-ion electrical storage, a hot water storage and a cold water storage system.

A quasi-stationary model is employed to linearize the equations describing the model, ensuring the energy balance of each energy flow and the correct operation of each equipment per each time-step. The model is implemented in a MATLAB script and solved using a mixed-integer linear programming (MILP) method based on a modified version of the Branch and Bound algorithm. Moreover, a multi-objective approach is adopted, considering both cost and environmental issues related to the operation of the microgrid.

II. Methodology and Model

A. Generalities

The microgrid is modelized and optimized using an EH model, a concept introduced in 2007 based on energy balances in steady state condition [3]. An EH can be defined as an energy system using multiple energy carriers and with many components operating in coordination the one with each other, satisfying the final demand of the hub with the objective of improving the energy efficiency. The EH concept was largely employed to optimize multi-energy systems in literature, both in single buildings and in microgrids and applying single-objective or multi-objective optimizations. Usually, the optimizations are performed to attain the minimum cost, maximum energy efficiency or minimum environmental impact [4]–[13].

The original contribution of this paper is to present an optimization model of an EH for the evaluation of the feasibility of the installation of equipments to satisfy local electrical and thermal energy demands along the whole year. Furthermore, both the economic and environmental aspects are considered, comparing the results to identify a compromise solution.

B. Methodology

The EH developed for the present study aims to meet the energy requirement of a final user. This might be a single family-house, a multi-storey building or a microgrid. The electrical and thermal (both heating and cooling) demands are considered in the optimization. In order to meet these requirements, the installation of a set of converters (Natural Gas Boiler (NGB), Heat Pump (HP), Combined Heat and Power (CHP) and Absorbtion Chiller (AC)), renewable generators (Photovoltaic (PV) and Solar Thermal Collectors (STC)) and storages (electrical (STO_e) and thermal (STO_t and STO_c)) is considered. In the optimization of microgrids, each of these components might be considered as the equivalent of many smaller omologous component distributed along the EH.

The aim of the optimization study is to identify the optimal schedule of these components during the analyzed period, tipically one year [14]. The mathematical model is based on the following simplifying assumptions:

- The energy balances are evaluated in a steady state condition;
- The efficiency or coefficient of performance (COP) of each component is constant and independent on the load partialization;
- The energy losses in the hub are considered only in components, while lines and networks losses are neglected.

The assumptions listed above allow this optimization model to be composed by linear equations and relations, simplifying the identification of an absolute optimal solution. Since there are three storage systems, some integer variables have to be included in the model. Thus, the solution is identified choosing a MILP optimization algorithm, based on a modified version of the Branch and Bound algorithm.

C. Mathematical Model

The variables of this EH model (values to be optimized) are the energy flows in input and output to each component and from the main power grid and gas pipeline.

The parameters of the model are constant input values, *i.e.* the energy requirement of the microgrid and values describing the component's behavior (efficiencies, COP, costs and primary energy impact).

The objective functions to be minimized are the daily cost and the daily primary energy use to supply electricity and natural gas from the main networks to the microgrid to fulfill the final requirements.

$$\min C_{TOT} = \min C_{GAS} + C_{GRID} = \min \Sigma_{t=1}^{T} [C_{NG}NG_{in}(t) + C_{E}E_{in}(t)] \quad (1)$$

$$\min PE_{TOT} = \min PE_{GAS} + PE_{GRID} = \min \Sigma_{t=1}^{T} [PE_{NG}NG_{in}(t) + PE_{E}E_{in}(t)] \quad (2)$$

where C is the cost, PE is the primary energy, subscript $_{TOT}$ means total, subscript $_{NG}$ means natural gas, subscript $_{E}$ means electricity, NG_{in} is the gas supply from the pipeline and E_{in} is the power supply from the grid.

The objective funcitons are subject to equality and inequality constraints, representing the mass balance and energy balance in steady state for each time-step and each energy carrier or describing the physical behavior of the components. Balance equations were imposed for electrical energy (E), for thermal energy (H) and for cooling energy (F), while a mass balance was imposed for the supply of natural gas (NG), with reference to the schematic reported in Fig. 1. These constraints are illustrated in Eqn. (3)–(6).

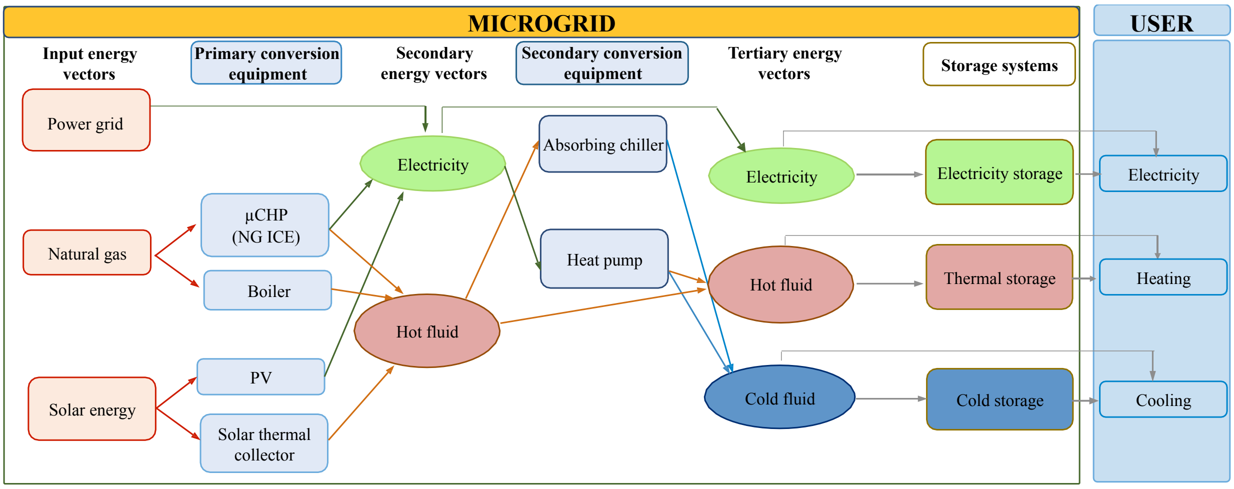

Fig. 1. Schematic for the energy hub model employed in this study

$$E_{grid}(t) + E_{CHP}(t) - E_{HP}(t) + E_{PV}(t) - E_{STO,in}(t) + E_{STO,out}(t) = E_{user}(t) \quad (3)$$

$$H_{CHP,TH}(t) + H_{NGB,TH}(t) + H_{STC,TH}(t) + H_{HP}(t) - H_{STO,in}(t) + H_{STO,out}(t) = H_{user}(t) \quad (4)$$

$$F_{AC}(t) + F_{HP}(t) - F_{STO,in}(t) + F_{STO,out}(t) = F_{user}(t) \quad (5)$$

$$NG_{grid}(t) = NG_{CHP}(t) + NG_{NGB}(t) \quad (6)$$

In the equations above, the subscripts refer to the abbreviations introduced for the components in section *B*. Further constraints are set in the model to describe each component of the hub:

1) Combined Heat and Power (CHP)

The CHP system is fed by the main natural gas network and is used to produce electricity and heating energy simultaneously with higher efficiency than with traditional generation systems:

$$E_{CHP}(t) = NG_{CHP}(t) \cdot LHV_{NG} \cdot \eta_{CHP\_ele} \quad (7)$$

$$H_{CHP}(t) = E_{CHP}(t) \cdot \eta_{CHP\_th} / \eta_{CHP\_ele} \quad (8)$$

$$H_{CHP}(t) = H_{CHP,TH}(t) + H_{CHP,AC}(t) \quad (9)$$

$$E_{CHP,min} \cdot x_{CHP}(t) \leq E_{CHP}(t) \leq E_{CHP,max} \cdot x_{CHP}(t) \quad (10)$$

where LHV is the lower heating value of the natural gas, η_{CHP_th} and η_{CHP_ele} are the thermal and electrical efficiencies of the cogenerator, respectively, $H_{CHP,TH}$ and $H_{CHP,AC}$ are the fractions of H_{CHP} used for the heating demand of to feed the absorbtion chiller, respectively, x_{CHP} is a boolean status variable indicating if the component is on or off and $E_{CHP,min}$ and $E_{CHP,max}$ are the minimum and maximum load partialization allowed, respectively.

2) Natural Gas Boiler (NGB)

The natural gas boiler integrates the heating system to fulfill the heating demand of the hub:

$$H_{NGB}(t) = NG_{NGB}(t) \cdot LHV_{NG} \cdot \eta_{NGB} \tag{11}$$

$$H_{NGB}(t) = H_{NGB,TH}(t) + H_{NGB,AC}(t) \tag{12}$$

where η_{NGB} is the thermal efficiency of the boiler, and $H_{NGB,TH}$ and $H_{NGB,AC}$ are the fractions of H_{NGB} used for the heating demand of to feed the absorbtion chiller, respectively.

3) Heat Pump (HP)

The heat pump fulfills part of the space heating or cooling demand of the single customers:

$$H_{HP}(t) = E_{HP}(t) \cdot COP_{TH} \tag{13}$$

$$F_{HP}(t) = E_{HP}(t) \cdot COP_{COOL} \tag{14}$$

$$x_{HP,H}(t) + x_{HP,F}(t) \leq 1 \tag{15}$$

$$H_{HP,min} \cdot x_{HP,H}(t) \leq H_{HP}(t) \leq H_{HP,max} \cdot x_{HP,H}(t) \tag{16}$$

$$F_{HP,min} \cdot x_{HP,F}(t) \leq F_{HP}(t) \leq F_{HP,max} \cdot x_{HP,F}(t) \tag{17}$$

where COP_{TH} and COP_{COOL} are the coefficients of performance in heating and cooling mode, respectively, $x_{HP,H}$ and $x_{HP,F}$ are boolean status variables indicating if the component is in heating or in cooling mode, $H_{HP,min}$ and $F_{HP,min}$ are the minimum load partialization allowed in heating and cooling mode, respectively, and $H_{HP,max}$ and $F_{HP,max}$ are the maximum load partialization allowed in heating and cooling mode, respectively.

4) Solar Thermal Collector (STC)

The STC system is used to produce heating energy exploiting the solar radiation. The total energy production is determined before the optimization, based on the available surface, on the tilt angle and on the local solar radiation:

$$H_{STC}(t) = H_{STC,TH}(t) + H_{STC,AC}(t) \tag{18}$$

where $H_{STC,TH}$ and $H_{STC,AC}$ are the fractions of H_{STC} used for the heating demand of to feed the absorbtion chiller, respectively.

5) Photovoltaic (PV)

The PV system is used to produce electricity exploiting the solar radiation. The total energy production is determined before the optimization, based on the available surface, on the tilt angle and on the local solar radiation. No further constraint was set in the model.

6) Absorbtion Chiller (AC)

The AC system is used to exploit the excess heating production to provide space cooling during summer:

$$F_{AC}(t) = [\, H_{CHP,AC}(t) + H_{NGB,AC}(t) + H_{STC,AC}(t) \,] \cdot COP_{AC} \tag{19}$$

where COP_{AC} is the coefficient of performance of the absorbtion chiller.

7) Electricity storage (STO_e)

The STO_e is used to store the excess electricity production that may occour during the day to provide the demand of the night:

$$SOC_{STOe}(t+1) = SOC_{STOe}(t) \cdot (1 - E_{sto,loss}) + E_{STO,in}(t) \cdot \eta_{STOe,in} - E_{STO,out}(t) \cdot 1/\eta_{STOe,out} \tag{20}$$

$$SOC_{STOe}(1) = SOC_{STOe}(end) \tag{21}$$

$$x_{STOe,in}(t) + x_{STOe,out}(t) \leq 1 \tag{22}$$

$$E_{STO,in}(t) \leq x_{STOe,in}(t) \cdot SOC_{STOe,max} \tag{23}$$

$$E_{STO,out}(t) \leq x_{STOe,out}(t) \cdot SOC_{STOe,max} \quad (24)$$

$$SOC_{STOe,max} \cdot DoD \leq SOC_{STOe}(t) \leq SOC_{STOe,max} \quad (25)$$

where SOC_{STOe} is the state of charge of the electrical energy storage, $\eta_{STOe,in}$ and $\eta_{STOe,out}$ are the charge and discharge efficiencies of the electrical storage, respectively, $E_{sto,in}$ and $E_{sto,out}$ are the electricity flows in input and output of the storage, respectively, $E_{sto,loss}$ is the self-discharge coefficient, assumed as a fraction of the state of charge, $x_{STOe,in}$ and $x_{STOe,out}$ are boolean variables that indicate whether the electrical storage is charging or discharging at time t, respectively, $SOC_{STOe,max}$ is the upper limit to SOC_{STOe} and DoD is the depth of discharge of the electrical storage.

8) Thermal storage (STO_t and STO_c)

The thermal storages are used to store the excess thermal energy production when the heating and cooling demands are limited. The equations describing the STO_t are illustrated below, while the constraints related to the STO_c are omitted, since they are analogous:

$$SOC_{STOt}(t+1) = SOC_{STOt}(t) \cdot (1 - \phi_{STOt}) + H_{STO,in}(t) \cdot \eta_{STOt,in} - H_{STO,out}(t) \cdot 1/\eta_{STOt,out} \quad (26)$$

$$SOC_{STOt}(1) = SOC_{STOt}(end) \quad (27)$$

where SOC_{STOt} is the state of charge of the thermal energy storage, and $\eta_{STOt,in}$ and $\eta_{STOt,out}$ are the charge and discharge efficiencies of the thermal energy storage, respectively, $H_{STO,in}$ and $H_{STO,out}$ are the thermal flows in input and output of the storage, respectively, and ϕ_{STOt} is the heat loss of the storage, assumed as a fraction of the state of charge.

III. Case Study

A. System description and main hypotheses

Fig. 1 shows the diagram of the distributed energy network superstructure to be used in the optimization model, consisting of a range of electric and thermal generation, conversion, and storage technologies capable of meeting the electric, thermal, and cooling demands of a residential user. In detail, the generation technologies considered include a CHP based on an internal combustion engine, a NGB, a STC, and a roof-integrated PV system; conversion technologies include a reversible HP and a single-stage AC; and finally, storage technologies include a battery, and a thermal storage system used for heating or cooling. The user's electrical demand can be met by CHP, PV system, battery, and the national power grid. The user's thermal demand (space heating and domestic hot water) can be met by the CHP, STC, NGB, HP, and thermal storage. Finally, the user's cooling demand can be met by the HP, AC powered by CHP, STC and NGB, and thermal storage.

The model developed for this study has the advantage of being able to be applied not only to various types of users (*e.g.* single-family house, multi-family house, small district), but also to users of various kinds within the same typology (*e.g.* different climate, different urban context).

In order to demonstrate the possible application of the model, a case study is developed based on a multi-family building located in Turin (Italy). The building has a base surface of about 5,000 m^2 and a shape factor $S/V = 0.5$ m^{-1}. Although hourly values of energy requirement should be adopted to obtain accurate results in energy simulation studies, this level of accuracy may be useless for an optimization problem, where relations are usually simplified in order to identify the optimal solution. The annual demand is thus modeled using four seasonal standard days, unified as follows:

- 90 days in the cold season, from December to February;
- 92 days in the mid cold season, from October 15th to November 30th and from March 1st to April 15th;
- 91 days in the mid warm season, from April 15th to May 31th and from September 1st to October 15th;
- 92 days in the hot season, from June to August.

Figs 2-5 show an example of the energy demands with hourly detail in the cold and hot seasons, while the main parameters are recapped in Table I. The costs adopted for electricity and gas supply are set by the Italian Energy Authority for the second trimester of 2022 [15]; the primary energy conversion factor for the electricity and gas from the grid are also set by the Italian Energy Authority [16-17]. Data on the local irradiance is gathered from [18]. The other values are set according to the average values of components available on the market [19]-[21].

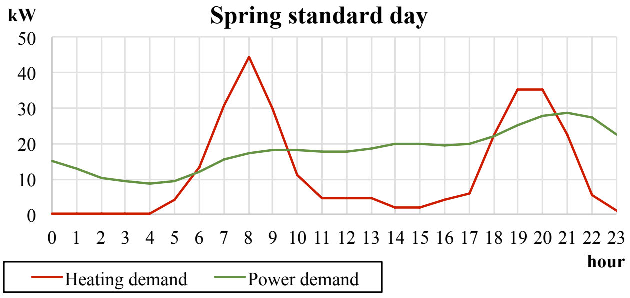

Fig. 2. Energy demands in the standard day for Spring

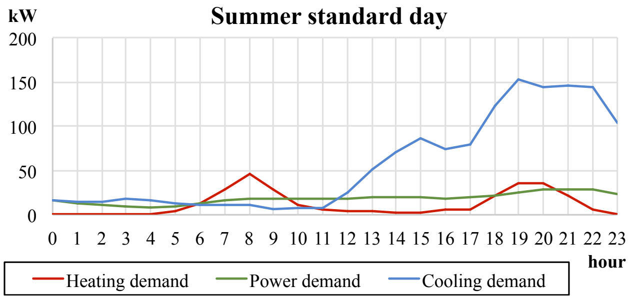

Fig. 3. Energy demands in the standard day for Summer

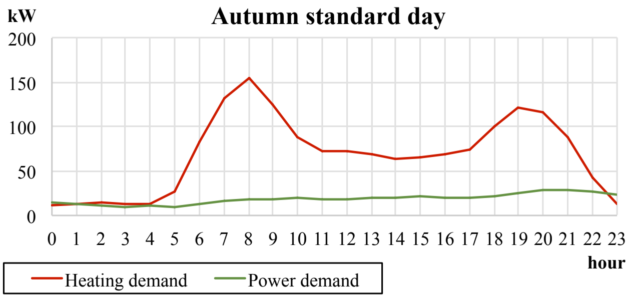

Fig. 4. Energy demands in the standard day for Autumn

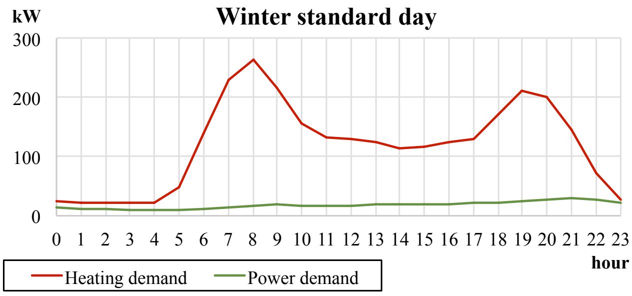

Fig. 5. Energy demands in the standard day for Winter

IV. Results

The optimization model allows to obtain a set of optimal solutions minimizing cost or primary energy use in each seasonal standard day.

The main results of the simulation, *i.e.* the values assumed by the objective functions in the eight optimizations that were performed for this study, are recapped in Table II and Table III. In these tables, the results are compared with the traditional scenario, where the power demand is totally fulfilled using power from the grid, the thermal requirement is satisfied using a gas-fired boiler with efficiency equal to 0.85 and a non-reversible air conditioner with COP equal to 3 is used to meet the cooling demand.

TABLE I. Main Parameters Used for the Case Study

Parameter	Value
C_{NG}	0.9018 €/Sm^3
C_E	0.3102 €/kWh
PE_{NG}	0.82 TOE/kNm^3
PE_E	0.187 TOE/MWh
LHV_{NG}	9.96 kWh/Sm^3
η_{CHP_ele}	0.34
η_{CHP_th}	0.48
η_{NGB}	0.9
COP_{TH}	3.5
COP_{COOL}	3
COP_{AC}	0.8
$\eta_{STOe,in}$	97%
$\eta_{STOe,out}$	97%

Parameter	Value
DoD	20%
$E_{sto,loss}$	1%
$\eta_{STOt,in}$	100%
$\eta_{STOt,out}$	100%
ϕ_{STOt}	5%
ϕ_{STOc}	5%

TABLE II. COMPARISON OF OPERATING COSTS

Season	Operating Cost [€/day]		
	Traditional scenario	*Min. Cost scenario*	*Min. Energy scenario*
Spring	164,82	87,92	87,92
Summer	306,66	89,93	89,93
Fall	313,80	92,30	92,30
Winter	438,56	109,51	110,67

TABLE III. COMPARISON OF OPERATING PRIMARY ENERGY

Season	Operating Primary Energy [TOE/day]		
	Traditional scenario	*Min. Cost scenario*	*Min. Energy scenario*
Spring	0,1086	0,0632	0,0632
Summer	0,1942	0,0645	0,0645
Fall	0,2428	0,0620	0,0620
Winter	0,3577	0,0678	0,0667

The first, most evident outcome of the present study is that the two objective functions selected for this study have the same values in three out of four standard days. This feature can be explained taking into account that the objective functions are based only on the supply of electricity and gas from the main grids, while the purchase of the components was neglected. Nevertheless, the energy flows in each optimization study exhibit different trends. The main differences are:

- HP, STO_t and STO_c are mostly employed in the energy minimization studies;
- STC and CHP are managed differently during the day, although the total energy in the day is the same.

Another main feature is that the optimization allows a cost reduction spreading between 2 and 4 times and a reduction of primary energy use spreading between 1.5 and 5 times, with respect to the traditional scenario.

In order to verify that the energy and mass balances shown in Eqn. (3)-(6) were satisfied, a graph for each balance equation and for each optimization study was prepared. An example of these graphs for the electrical and thermal energy balance is shown in Fig.s 6-7.

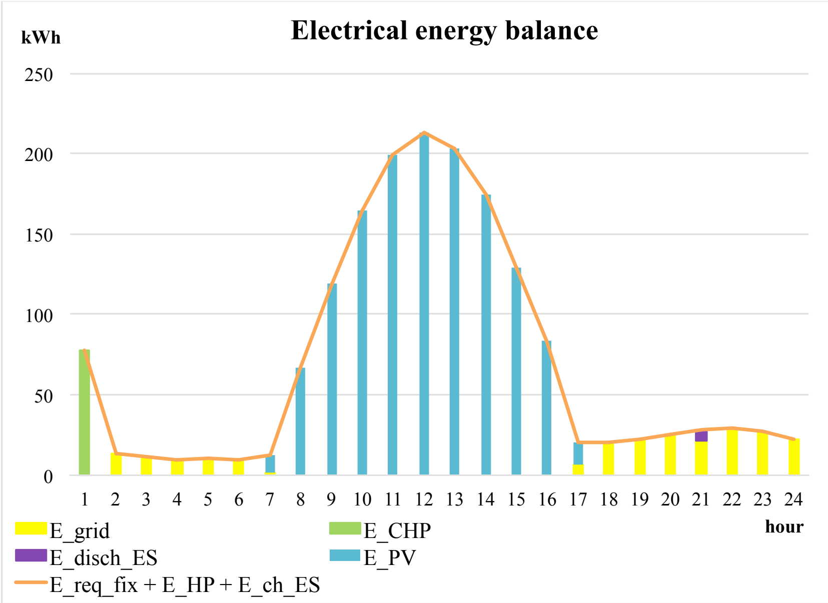

Fig. 6. Daily trend of the electrical power flows in the Autumn standard day with minimum cost

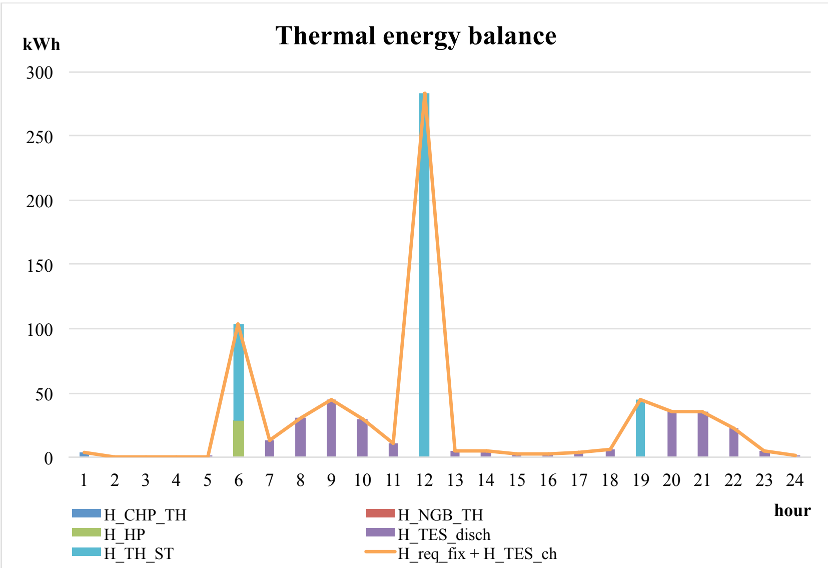

Fig. 7. Daily trend of the thermal power flows in the Spring standard day with minimum cost

Among other interesting results, the electrical storage charge-discharge daily cycle was analyzed. In the eight optimizations performed in this study, the following trends were observed:

a) A steep discharge phase in one hour and a low charge phase occourred in the cost optimization in each season;
b) A low discharge phase by night and a low charge phase occourred in the energy optimization in spring, summer and winter;
c) Two steep discharge phases and two low charge phases occourred in the energy optimization in autumn.

An example of these trends is shown in Fig. 8.

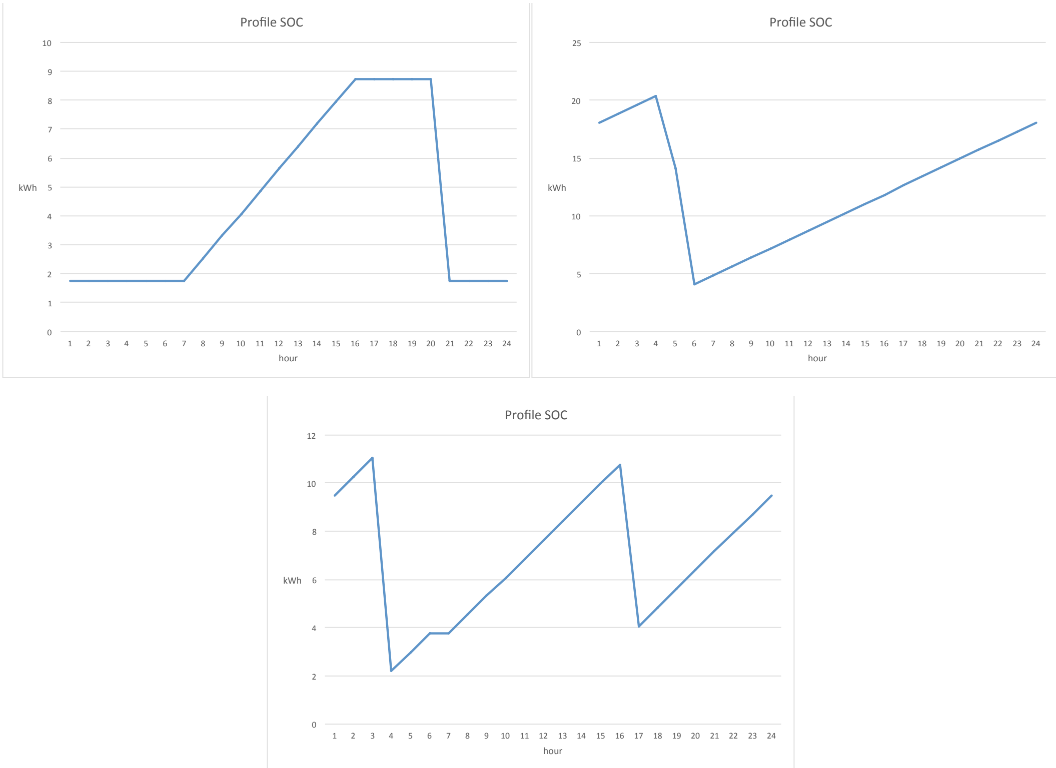

Fig. 8. Examples of charge-discharge daily cycles of the electrical storage: a) steep discharge; b) low discharge; c) two discharges.

V. Conclusions and Future Developments

This study shows a methodology to evaluate, optimize and compare costs and environmental impacts related to the energy demand of an urban district, using an EH optimization model. A linear mathematical model composed by real and integer variables is solved using a MILP algorithm.

The proposed optimization model is able to coordinate the components included in the EH model in order to meet the final energy demand of the user minimizing the operating cost or the operating primary energy use.

The analysis shown in this study will be deepened coupling the optimization model with a more reliable simulation model considering for all the non-linearities of each component. Major attention might be given to the life-cycle of the electrical storage system reduction due to the different daily trend in the different seasons. Further analyses might also include the adoption of a multi-objective optimization approach, in order to identify the compromise solutions between the two objective functions.

Acknowledgment

The results presented in this paper have been obtained within the framework of the project "SOLARGRID"—cod. ARS01_00532, jointly funded by the European Union and Italian Research and University Ministry (MUR) under the Programma Operativo Nazionale "Ricerca e Innovazione" 2014–2020 (PON "R&I" 2014–2020).

References

[1] Di Somma, M., Yan, B., Bianco, N., Graditi, G., Luh, P. B., Mongibello, L., & Naso, V. (2017). Design optimization of a distributed energy system through cost and exergy assessments. *Energy Procedia*, *105*, 2451-2459.

[2] IEA EBC Annex 67. Literature review on energy flexibility definitions and indicators for building clusters. 2018.

[3] M. Geidl, "Integrated Modeling and Optimization of Multi-Carrier Energy Systems," Swiss Federal Institute of Technology (ETH), Zurich, 2007.

[4] G. Attardo, S. Longo, F. Montana, E. Riva Sanseverino, Q. T. T. Tran, and G. Zizzo, "Urban Energy Hubs Economic Optimization and Environmental Comparison in Italy and Vietnam," in 2018 IEEE 4th International Forum on Research and Technology for Society and Industry (RTSI), 2018, pp. 1–6.

[5] N. Cannata, M. Cellura, S. Longo, F. Montana, E. Riva Sanseverino, Q. L. Luu, and N. Q. Nguyen, “Multi-Objective Optimization of Urban Microgrid Energy Supply According to Economic and Environmental Criteria,” in 2019 IEEE Milan PowerTech, 2019, pp. 1–6.

[6] D. Curto, V. Franzitta, S. Longo, F. Montana, E. Riva Sanseverino, and E. Telaretti, “Flexibility Services in a Mediterranean Small Island to Minimize Costs and Emissions Related to Electricity Production from Fossil Fuels,” in 2020 IEEE 20th Mediterranean Electrotechnical Conference (MELECON), 453-458, 2020.

[7] Di Somma, M., Buonanno, A., Caliano, M., Graditi, G., Piazza, G., Bracco, S., & Delfino, F. (2022). Stochastic Operation Optimization of the Smart Savona Campus as an Integrated Local Energy Community Considering Energy Costs and Carbon Emissions. Energies, 15(22), 8418.

[8] Foiadelli, F., Nocerino, S., Di Somma, M., & Graditi, G. (2018, June). Optimal design of DER for economic/environmental sustainability of local energy communities. In 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-7). IEEE.

[9] E. Fabrizio, V. Corrado, and M. Filippi, “A model to design and optimize multi-energy systems in buildings at the design concept stage,” Renew. Energy, vol. 35, no. 3, pp. 644–655, 2010.

[10] M. Salimi, H. Ghasemi, M. Adelpour, and S. Vaez-Zadeh, “Optimal Planning of energy hubs in interconnected energy systems: a case study for natural gas and electricity,” IET Gener. Transm. Distrib., vol. 9, no. 8, pp. 695–707, 2015.

[11] B. Li, R. Roche, D. Paire, and A. Miraoui, “A price decision approach for multiple multi-energy-supply microgrids considering demand response,” in 2018 IEEE International Energy Conference (ENERGYCON), 2018, pp. 1–6.

[12] D. Arnone, M. Bertoncini, G. Paternò, A. Rossi, M. G. Ippolito, and E. Riva Sanseverino, “Smart Multi-carrier Energy System: Optimised Energy Management and Investment Analysis,” in 2016 IEEE International Energy Conference (ENERGYCON), 2016, pp. 1–6.

[13] D. Zhang, S. Evangelisti, P. Lettieri, and L. G. Papageorgiou, “Optimal design of CHP-based microgrids: Multiobjective optimisation and life cycle assessment,” Energy, vol. 85, pp. 181–193, 2015.

[14] A. Piacentino, C. Barbaro, F. Cardona, R. Gallea, and E. Cardona, “A comprehensive tool for efficient design and operation of polygeneration-based energy grids serving a cluster of buildings. Part I: Description of the method,” Appl. Energy, vol. 111, pp. 1204–1221, 2013.

[15] ARERA – Autorità di Regolazione per Energia Reti e Ambiente, “ARERA website”, link: https://www.arera.it/it/prezzi.htm (*in Italian*).

[16] AEEG – Autorità per l'energia elettrica e il gas, “Delibera EEN 3/08 del 20-03-2008” (*in Italian*).

[17] MISE – Ministero dello Sviluppo Economico, “Circolare del 18 dicembre 2014” (*in Italian*).

[18] ASHRAE International Weather files for Energy Calculations (IWEC weather files). Users manual and CD-ROM, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, USA; 2001.

[19] Makbul A.M., Ramlia H.R., E.H. Bouchekarab Abdulsalam, S.Alghamdia. Optimal sizing of PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm, Renewable Energy 2018, 121,400-411.

[20] Darrow, K., Tidball, R., Wang, J., Hampson, A. Catalog of CHP technologies; 2015. Available: https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf.

[21] Technology Data for Energy Plants. Energinet.dk; 2012. Available: https://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning/Technology_data_for_energy_plants.pdf.