Multi-Objective Optimization of Urban Microgrid Energy Supply According to Economic and Environmental Criteria

N. Cannata, M. Cellura, S. Longo, F. Montana, E. Riva Sanseverino
Department of Energy, Information Engineering and Mathematical Models (DEIM),
University of Palermo (UNIPA),
Palermo, Italy

Q. L. Luu, N. Q. Nguyen
Institute of Energy Science (IES),
Vietnamese Academy of Science and Technology (VAST),
Hanoi, Viet Nam

Abstract—**This study is focused on the optimization of the annual cost and environmental impact related to the supply of natural gas and electricity of an urban microgrid through the installation of components as renewable energy sources, energy storage units and converters. As input parameters of the optimization model, the energy demand of a medium density urban district was estimated, while average costs and emissions of equipments were collected in market reports and literature. The outputs of the model are the optimal size and the schedule of each component. Moreover, optimization analysis was carried out for two different scenarios, comparing Italian and Vietnamese cost and environmental features, in order to understand how the optimization process is affected by different input conditions.**

Index Terms-- **Emissions; Energy hub; Microgrid; MILP; Optimization**

I. INTRODUCTION

The recent rapid increase of energy demand and the transition from “vertically” to “horizontally” integrated energy systems is leading to the search of new cooperative approaches for the different components in the energy system. A very common example is the integration of electricity storage systems into the power grid to optimally exploit the production from non-predictable renewable energy sources, in order to store the excess of energy produced that will be used to cover future loads. Nowadays, the development of technologies such as efficient multi-generation systems have led to realizing the benefits of integrated energy infrastructure such as electricity, natural gas, and district heating networks, thus encouraging a movement towards multi-energy systems. In such systems, different energy carriers and systems interact together in a synergistic way. In 2007, Geidl introduced the concept of energy hub [1], that rapidly gained popularity in the scientific community. An energy hub can be defined as a set of multi-component and multi-carrier energy systems, each component operating in coordination with each other, satisfying the energy demand of a district with the objective of improving the energy efficiency. Cities and urban districts can be represented as microgrids and modelled as self-regulating systems able to manage and generate energy carriers by introducing the energy hub scheme [2], [3].

Many examples are available in literature on the employment of the energy hub model to optimize multi-energy systems, both in single buildings [4] and in microgrids [5]–[9] and applying single-objective [5], [6] or multi-objective [4], [7]–[9] optimizations. Usually, optimizations are aimed at reaching the minimum cost [4]–[9], maximum energy efficiency [4], [7] or minimum environmental impact [8], [9].

The main problem covered in this paper is related to the simultaneous synthesis, design and operation of an urban microgrid with known and fixed requirements. A multi-objective approach was adopted, considering both cost and environmental issues related to the installation of new equipment supplying electricity, heating and cooling to the urban district. An energy hub model was employed to model the microgrid, made up of linear functions only, thus ensuring to obtain an absolute optimal solution through a MILP algorithm. The original contribution provided by this study is the evaluation of cost-related and life cycle impacts related to a large number of different components, accounting for all the energy requirements of a microgrid (electricity, heating and cooling). Moreover, a comparison between Italian and Vietnamese scenarios is provided, keeping constant the number of dwellers and the technical parameters for equipment (e.g. generation efficiencies, storage losses) and comparing Palermo and Hanoi climate features, installation and operating costs for equipments, costs for energy supply and global warming potential related to energy carriers and components.

II. MODEL AND METHODOLOGY

A. *Optimization mathematical model*

The energy hub aims to meet the needs of an energy district. The electrical and thermal (both heating and cooling) demands were considered in the optimization. In order to meet these requirements, a set of converters (Natural Gas Boiler NGB, Heat Pump HP, Combined Heat and Power CHP and Absorbing Chiller AC), renewable generators (Photovoltaic PV and Solar Thermal Collectors STC) and storages (electrical or thermal) can be included. The aim of the optimization study is to identify the optimal combination of equipments (synthesis stage), their optimal sizes (design stage) and their optimal schedule during the analyzed period (operation stage) [10]. The following assumptions were considered in the development of the mathematical model:

- energy balances evaluated in steady state condition;
- constant components efficiencies;
- lines and networks losses were neglected, losses in the system were considered only in components.

As every optimization problem, this model is composed by variables (values to be optimized), parameters (input values, that are kept constant), objective functions, i.e. the function to be optimized (minimized or maximized), equality or inequality constraints (physical balances and component behavior) and variable bounds (physical limits to value assumed by variables). This energy hub optimization is carried out with a multi-objective approach, minimizing a cost function and an environmental function. The mathematical problem is a Mixed Integer Linear Problem (MILP), as it is composed by linear functions and real or integer variables.

Variables of this problem are synthesis variables for components, sizes of components and energy flows from grids, to components and from components. Parameters are values describing equipments (efficiencies, COP, costs, environmental impacts) and energy requirement of the urban district.

The cost objective function takes into account the annualized cost for the fulfillment of the district needs. In detail, the function is given by the sum of the supply cost of energy vectors (e.g. electricity, natural gas, district heating) from the main networks and the investment cost for each component that is a function of the component size. In order to keep the problem linear, the cost function for each k-th component, that is usually considered exponential, was approximated as a linear function, as in Eq. (1):

$$Z_k = z_k \cdot P_k^{\alpha_k} \cong C_k \cdot P_k + C_{0,k} \cdot \delta_k \qquad (1)$$

where Z is the investment cost, z is the unit price, P the equipment size, α the power law exponent, C and C_0 are the extrapolation parameters and δ is a synthesis boolean variable. In detail, to avoid the constant term of the extrapolation to affect the optimization problem, a synthesis boolean variable was adopted for each component, so that if the component is not selected by the optimization problem, the boolean variable is equal to 0 and the constant term is suppressed [10]. These investment cost functions are multiplied by the Capital Recovery Factor (*CRF*, Eq. (2)) of the investment in order to annualize the amount. Maintenance costs were neglected, as were the financial subsidies to energy efficiency and renewable energies.

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \qquad (2)$$

where i is the interest rate and n the useful life of the component.

The environmental objective function takes into account the environmental impacts on the global warming related to the production of electricity from the grid and equipment. In detail, Global Warming Potential (GWP) related to the manufacture and dismission of components were considered, while a simplified approach was adopted for the impact of electricity, considering only the average CO_2 emissions from the national electricity production system, thus neglecting the life cycle impact related to the manufacture of the power plants. Life cycle impact related to extraction and distribution of natural gas was also neglected.

Cost and environmental objective functions were combined in a multi-objective objective function *O.F.*, adopting the Scalarization Technique, where the objective functions are combined in a weighted sum single-objective function, properly normalized in order to take into account the order of magnitude of different objective. Objective function is reported in Eq. (3), where f are the single-objective functions, w are the weights and n are the normalization factors.

$$O.F. = w_{cost} \cdot \frac{f_{cost}}{n_{cost}} + w_{env} \cdot \frac{f_{env}}{n_{env}} \qquad (3)$$

As linear optimization problems are inherently convex, every local minimum is also a global minimum, thus the scalarization technique applied to linear problems is able to identify the global minimum. For the normalization of objective functions, worst cases values were adopted, i.e. values related to $w_{cost} = 0$ and $w_{cost} = 1$, respectively for n_{cost} and n_{env}.

To optimize the system, balance equations for each energy flow have been considered as equality constraints, linking input and output of the system. Balance were written referring to the schematic reported in Figure 1, with acronyms already explained in Paragraph II.A.

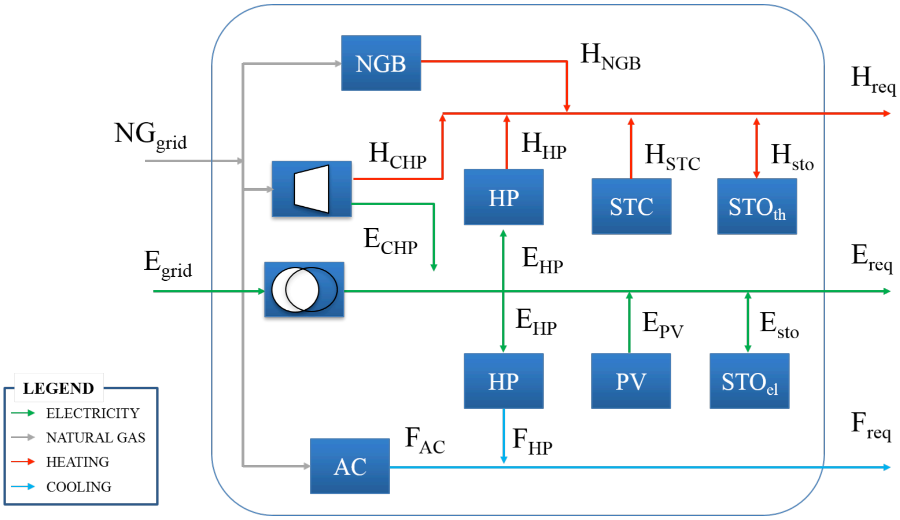

Figure 1 - Schematic of the urban energy hub analyzed in this study

Energy balance equations were imposed for electrical energy (indicated with E in Eq. (4)), for thermal energy (the balance of heating indicated with H in Eq. (5) and the balance of cooling indicated with F in Eq. (6)), while a mass balance was imposed for the natural gas supply (indicated with NG in Eq. (7)):

$$E_{grid}(t) - K_{TR} \cdot E_{grid}(t) + E_{CHP}(t) - E_{HP}(t) + \\ + E_{PV}(t) - E_{sto,in}(t) + E_{sto,out}(t) = E_{req}(t) \qquad (4)$$

$$H_{CHP}(t) + H_{HP}(t) + H_{NGB}(t) + H_{STC}(t) + \\ - H_{sto,in}(t) + H_{sto,out}(t) = H_{req}(t) \qquad (5)$$

$$F_{HP}(t) + F_{AC}(t) = F_{req}(t) \qquad (6)$$

$$NG_{grid}(t) = NG_{CHP}(t) + NG_{NGB}(t) + NG_{AC}(\qquad (7)$$

where K_{TR} is a coefficient accounting for the electrical losses in the transformer on top of the line feeding the district.

Further equality and inequality constraints were considered, describing the behavior of the CHP, heat pump, gas boiler, absorption chiller (powered by natural gas only), renewable sources and storage.

COMBINED HEAT AND POWER

$$E_{CHP}(t) = K_{CHP,e} \cdot NG_{CHP}(t) \qquad (8)$$

$$H_{CHP}(t) = K_{CHP,h} \cdot NG_{CHP}(t) \qquad (9)$$

$$K_{CHP,e} + K_{CHP,h} < 1 \qquad (10)$$

where E_{CHP} is the electricity generated by cogenerator at time t, NG_{CHP} is the natural gas supply, H_{CHP} is the heat flow from the cogenerator, $K_{CHP,e}$ and $K_{CHP,h}$ are the electrical and thermal efficiencies of the cogenerator, respectively.

HEAT PUMP

$$H_{HP}\left(t\right)=K_{HP,h}\cdot E_{HP}\left(t\right) \tag{11}$$

$$F_{HP}\left(t\right)=K_{HP,f}\cdot E_{HP}\left(t\right) \tag{12}$$

where H_{HP} and F_{HP} are the heating and cooling flows from the heat pump, respectively, E_{HP} is the corresponding absorbed electricity, $K_{HP,h}$ and $K_{HP,f}$ are the conversion coefficients from electricity to heating and from electricity to cooling, respectively, commonly known as *COP* (Coefficient Of Performance) and *EER* (Energy Efficiency Ratio).

NATURAL GAS BOILER

$$H_{NGB}\left(t\right)=K_{NGB}\cdot NG_{NGB}\left(t\right) \tag{13}$$

where H_{NGB} is the heating flow from the boiler, NG_{NGB} is the natural gas flowing into the boiler and K_{NGB} is the boiler efficiency.

ABSORBING CHILLER

$$F_{AC}\left(t\right)=K_{AC}\cdot NG_{AC}\left(t\right) \tag{14}$$

where F_{AC} is the cooling flow from the absorbing chiller, NG_{AC} is the natural gas flowing into the chiller and K_{AC} is the chiller efficiency.

PHOTOVOLTAIC

$$S_{PV}\leq K_{PV}\cdot I_{sun}\cdot A_{PV\_MAX} \tag{15}$$

where S_{PV} is the energy output from the renewable plant in a day, K_{PV} is the conversion efficiency of the photovoltaic plant, I_{sun} is the daily average solar radiance availability, $A_{PV,MAX}$ is the maximum available surface for photovoltaic plant.

SOLAR THERMAL COLLECTOR

$$S_{STC}\leq K_{STC}\cdot I_{sun}\cdot A_{STC\_MAX} \tag{16}$$

where S_{STC} is the energy output from the solar collector in a day, K_{STC} is the conversion efficiency of the solar collector, I_{sun} is the daily average solar radiance availability, $A_{STC,MAX}$ is the maximum available surface for solar collectors.

ELECTRICAL STORAGE

$$E_{sto}\left(t+1\right)=E_{sto}\left(t\right)\cdot\left(1-E_{sto,loss}\right)+ \tag{17}$$

$$+K_{e,sto,ch} \cdot E_{sto,ch}\left(t+1\right) - E_{sto,disch}\left(t+1\right) / K_{e,sto,di}$$

$$E_{sto}\left(1\right) = E_{sto}\left(end\right) \tag{18}$$

$$E_{sto,ch}\left(t\right) \le \delta_{e,sto,ch}\left(t\right) \cdot Q_{e,sto,ch} \tag{19}$$

$$E_{sto,disch}\left(t\right) \le \delta_{e,sto,disch}\left(t\right) \cdot Q_{e,sto,disch} \tag{20}$$

$$\delta_{e,sto,ch}\left(t\right) + \delta_{e,sto,disch}\left(t\right) \le 1 \tag{21}$$

$$DoD \cdot S_{e,sto} \le E_{sto}\left(t\right) \le S_{e,sto} \tag{22}$$

$$E_{sto,ch}\left(t\right) \le S_{e,sto} \cdot \left(1 - DoD\right) \tag{23}$$

$$E_{sto,disch}\left(t\right) \le S_{e,sto} \cdot \left(1 - DoD\right) \tag{24}$$

where E_{sto} *(t)* is the electrical energy stored in the device, $K_{e,sto,ch}$ and $K_{e,sto,disch}$ are the charge and discharge efficiencies of the electrical storage, respectively, $E_{sto,ch,}$ *(t)* and $E_{sto,disch,}$ *(t)* 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 stored electrical energy, $\delta_{e,sto,ch}$ *(t)* and $\delta_{e,sto,disch}$ *(t)* are boolean variables that indicate whether the electrical storage is charging or discharging at time *t*, respectively, $Q_{e,sto,ch}$ and $Q_{e,sto,disch}$ are upper limits to $E_{sto,ch,}$ *(t)* and $E_{sto,disch,}$ *(t)*, *DoD* is the Depth of Discharge of the electrical storage, $S_{e,sto}$ is the capacity of the electrical storage.

THERMAL STORAGE

$$\begin{aligned} H_{sto}\left(t+1\right) &= H_{sto}\left(t\right) \cdot \left(1 - H_{sto,loss}\right) + \\ &+ K_{h,sto,ch} \cdot H_{sto,ch}\left(t+1\right) - H_{sto,disch}\left(t+1\right) / K_{h,sto,di} \end{aligned} \tag{25}$$

$$H_{sto}\left(1\right) = H_{sto}\left(end\right) \tag{26}$$

$$H_{sto,ch}\left(t\right) \le \delta_{h,sto,ch}\left(t\right) \cdot Q_{h,sto,ch} \tag{27}$$

$$H_{sto,disch}\left(t\right) \le \delta_{h,sto,disch}\left(t\right) \cdot Q_{h,sto,disch} \tag{28}$$

$$\delta_{h,sto,ch}(t) + \delta_{h,sto,disch}(t) \le 1 \qquad (29)$$

$$H_{sto}(t) \le S_{h,sto} \qquad (30)$$

where $H_{sto}(t)$ is the thermal energy stored in the device, $K_{h,sto,ch}$ and $K_{h,sto,disch}$ are the charge and discharge efficiencies of the thermal storage, respectively, $H_{sto,ch,}(t)$ and $H_{sto,disch,}(t)$ are the heating flows in input and output of the storage, respectively, $H_{sto.loss}$ is the self-discharge coefficient, assumed as a fraction of the stored thermal energy, $\delta_{h,sto,ch}(t)$ and $\delta_{h,sto,disch}(t)$ are boolean variables that indicate whether the thermal storage is charging or discharging at time t, respectively, $Q_{h,sto,ch}$ and $Q_{h,sto,disch}$ are upper limits to $H_{sto,ch,}(t)$ and $H_{sto,disch,}(t)$, $S_{h,sto}$ is the capacity of the thermal storage.

Further, synthesis variables were linked to power of each component with a relation as reported in Eq. (31):

$$P_k \le \delta_k \cdot Q_k \qquad (31)$$

where Q_k is the upper limit to available power (or capacity, for storages) of each component.

B. *Methodology*

The illustrated mathematical model allows assessing the economic and environmental feasibility of the installation of equipment for the fulfillment of energy needs of a microgrid. It was implemented as a script in MATLAB 2018a. Since variables in the model are real or integer, and the objective functions and all the constraints are linear functions, an integer linear programming algorithm, MILP, was adopted. Cost and environmental objective functions were combined into a weighted sum single-objective function, through the so-called *Scalarization Technique*. In order to compare the Italian and Vietnamese contexts, representative average values were employed for economic and environmental parameters, while the values of the technical parameters, such as average operating hours and efficiencies, were kept constant in the comparison. Hourly values of energy requirement should be adopted to provide accurate results, thus requiring 8760 values for each variable. With 8 components depicted above (one for each kind), the problem should evaluate 157,696 variables, with equality constraints having 52,568 rows and 157,696 columns (61.8 GB of memory) and inequality constraints having 113,888 rows and 157,696 columns (133.8 GB of memory). As this level of accuracy may be useless for an optimization problem, where relations are simplified in order to obtain an optimal solution, the optimization problem was solved by using a standard seasonal day, hence a sequence of 4 standard days, reducing the number of variables to 1,744. In this way, the optimal solution was evaluated on a good approximation of the energy demands of the urban district, while reducing the computational burden for the computer.

III. CASE STUDY

A. *Energy demand calculation*

In order to obtain reliable data on microgrid energy requirements, a single-family house was modelled in *SketchUp*, shown in Figure 2. This model was used as input file for *EnergyPlus* thermophysical simulator, considering climate files for Palermo (Italy) and Hanoi (Vietnam) as outdoor conditions. For thermal transmittance of building components, default values form EnergyPlus database were adopted. Simple schedules were prepared to model occupants, lighting and electrical equipments, assuming the house to be inhabited by a family of four. A detailed simulation was conducted on this model, evaluating the energy requirement for electricity, heating and cooling for each hour of the year (8760 values per requirement).

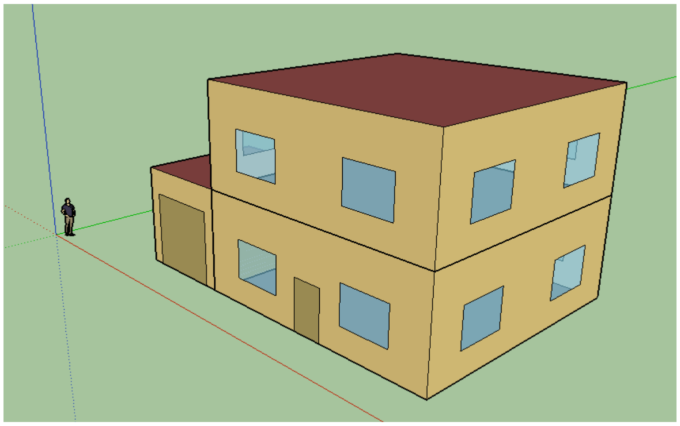

Figure 2 - SketchUp model adopted for energy requirement calculation

A standard day for each season was extrapolated from yearly simulation, with each hour of the standard day being the average value of the same hour for a three-months period. This led to 96 values for each energy requirement, allowing each optimization to be solved in few minutes. To simulate an urban district with terraced houses, assuming to have 35 residential units, data obtained from *EnergyPlus* simulations were multiplied by 35, neglecting simultaneity factors. The deriving energy demands employed in this case study are reported in Figure 3 to Figure 7. As the electricity demand only depends on lighting and internal equipments, it is the same for Italian and Vietnamese scenarios.

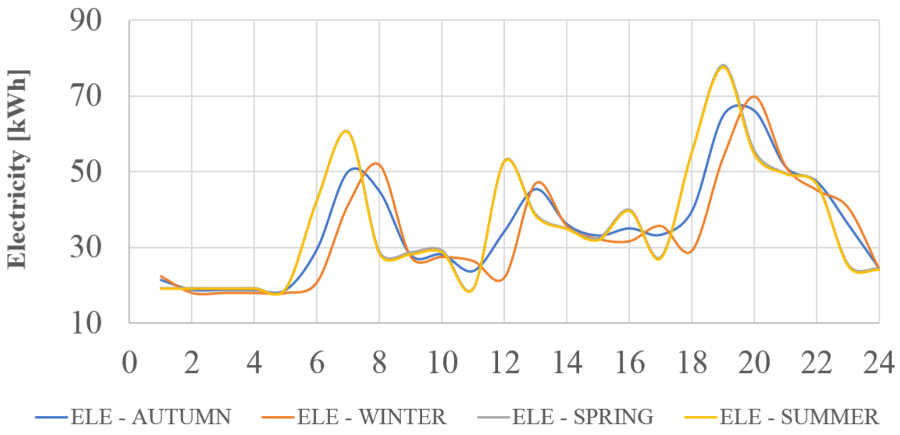

Figure 3 - Electricity demand for Palermo's and Hanoi's climate in different standard seasonal days

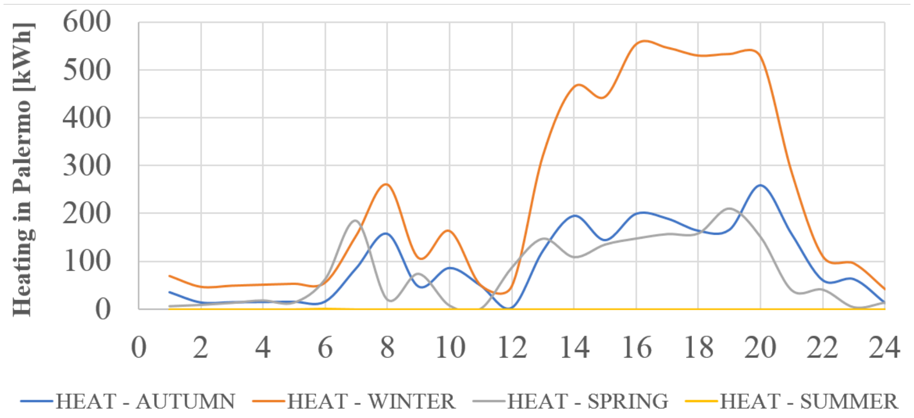

Figure 4 - Heating demand for Palermo's climate in different standard seasonal days

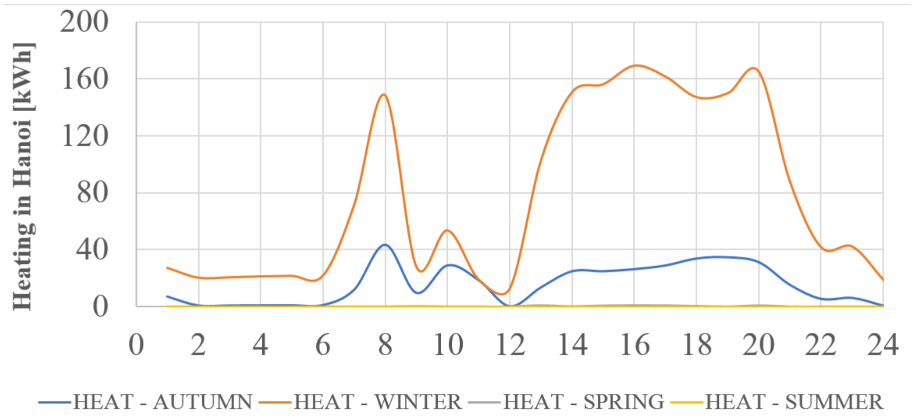

Figure 5 - Heating demand for Hanoi's climate in different standard seasonal days

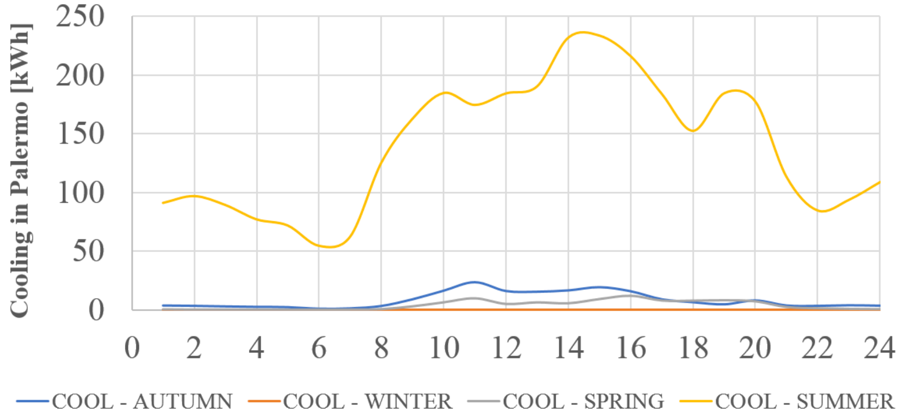

Figure 6 - Cooling demand for Palermo's climate in different standard seasonal days

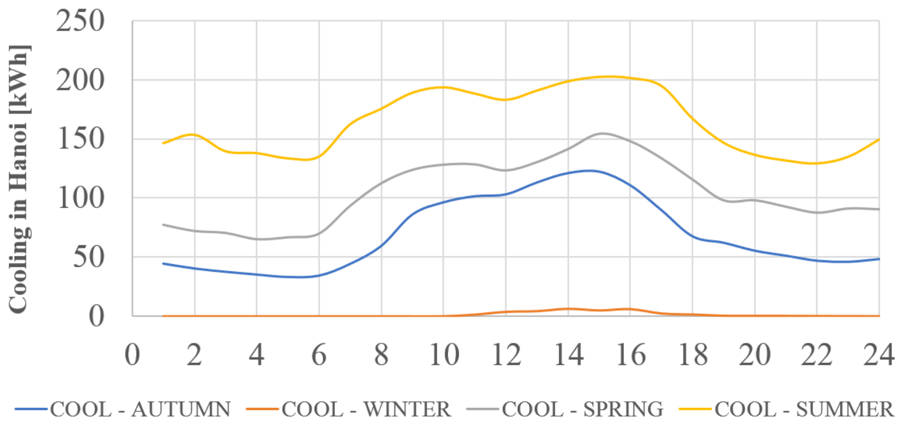

Figure 7 - Cooling demand for Hanoi's climate in different standard seasonal days

B. *Technical Scenario*

The analyzed energy hub for both Palermo and Hanoi studies is depicted in Figure 1. The district is supplied by a natural gas and an electricity grid, representing the unique way to fulfill energy needs in the AS-IS scenario. In order to investigate whether cheaper or cleaner ways exist, the installation of a set of components is proposed. Efficiencies of these equipments were derived from datasheets [10]–[12] or assumed, while useful life of equipment were derived from the same datasheets or from reports and literature [9], [13]–[15].

C. *Cost Scenarios*

In this study, required economic parameters are the prices for natural gas and electricity supply, the investment costs for equipment (CHP, heat pump, gas boiler, absorbing chiller, photovoltaic plant, solar collector, electrical and thermal storage systems) and their Capital Recovery Factors. Cost values and interest rates were derived from catalogues, websites and national reports [10]–[12], [16]–[21].

D. *Environmental Scenarios*

Environmental scenarios parameters are the daily average solar radiation of the location and the specific CO_2 emissions related to the electricity production. Solar radiation data, used for the estimation of PV and STC producibility, were derived from the climate files adopted for the energy demand simulation in EnergyPlus. Electricity-related emissions were estimated from local energy mix production, according to the methodology developed by the Italian Institute for Environmental Protection and Research (ISPRA) [22]. This value, that is used in the environmental objective function with GWP of equipments, is not the correct value of electricity GWP, as the calculation should take into account also for other aspects, as the supply of fuels, the manufacture of power plants and the emission of other greenhouse gases. Moreover, the methodology adopted by ISPRA is very site specific for Italy. Nevertheless, as more accurate data were not available for the Vietnamese scenario, authors preferred to adopt the same methodology for both countries. Further environmental parameters, common for both Italian and Vietnamese scenarios, are the Global Warming Potential (GWP) related to the manufacture and dismission of components, derived from literature Life Cycle Assessment (LCA) studies [9], [23]–[27].

IV. SIMULATION AND OPTIMIZATION RESULTS

The optimization model allowed to obtain a set of optimal solutions according to cost and environmental criteria for both locations. This set was evaluated changing weights reported into the multi-objective function, in order to cover the whole interval between $w_{cost} = 0$ (environmental optimization) and $w_{cost} = 1$ (economical optimization). Optimization results are reported in Figure 8.

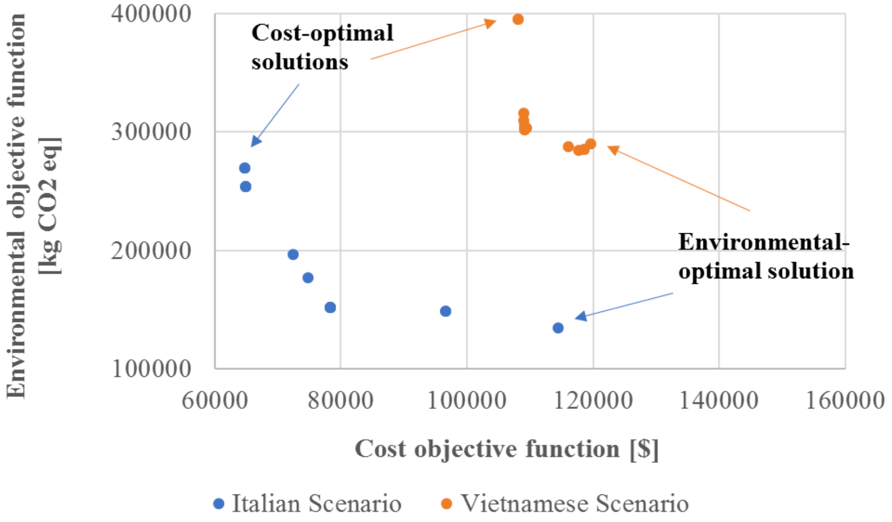

Figure 8 – Output of optimization for Italian and Vietnamese scenarios

The main outcome that can be derived is that Italian scenario presents a widespread set of solution, while Vietnamese scenario related solutions are much more concentrated, allowing a simpler process into the identification of a compromise solution. In detail, a small increment in investment leads to a huge reduction into the annual $CO_{2\text{-eq}}$ emissions. This is caused by the higher impact related to the electricity production in Vietnam (513 g/kWh against 325 g/kWh for Italian electricity), as Vietnamese power production is mainly based on fossil fuels.

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

This study showed a methodology to compare costs and environmental impacts related to the energy demand of an urban district, using an energy hub model. Different economic and environmental conditions showed to affect significantly the optimal solution. The comparison was evaluated considering the same families and a hypothetical urban district. However, as Italian and Vietnamese contexts have different architectural features, a further improvement of this study will take into account different spacing and heights of buildings, that tend to shade each other, causing a reduction in the effective energy that photovoltaic panels may produce. Also, the higher pollution present in Hanoi may reduce direct solar radiation collected by photovoltaic panels, furtherly reducing their production. Other possible improvements of the study, related to the methodology, concern a more accurate analysis of costs and environmental impacts related to the microgrid, accounting also for subsidies for energy efficiency and for a reliable Life Cycle Assessment of components and energy flows.

ACKNOWLEDGMENT

The authors wish to thank the Italian Ministry of Foreign Affairs and International Cooperation and the General Directorate for the promotion of the Italian economic System for their support to the research activity within the frame of the scientific cooperation Italy-Vietnam 2017-2019 project: “Greening the power systems with solar power for GreenHouse Gas emission reduction in Vietnam”.

REFERENCES

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

[2] 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.

[3] E. Riva Sanseverino *et al.*, “Urban Energy Hubs and Microgrids: Smart Energy Planning for Cities,” in *From Smart Grids to Smart Cities: New Challenges in Optimizing Energy Grids*, 2017, pp. 129–175.

[4] 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.

[5] 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.

[6] 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.

[7] 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.

[8] A. Maroufmashat, S. Sattari, R. Roshandel, M. Fowler, and A. Elkamel, “Multi-objective Optimization for Design and Operation of Distributed Energy Systems through the Multi-energy Hub Network Approach,” *Ind. Eng. Chem. Res.*, vol. 55, no. 33, p. 8950−8966, 2016.

[9] 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.

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

[11] “Enel X web page.” [Online]. Available: https://www.enelxstore.com/it/it/prodotti/.

[12] “IRCI Impianti ed Energia web page.” [Online]. Available: https://www.ircispa.com/.

[13] ASHRAE, “ASHRAE Equipment Life Expectancy chart.”

[14] J. Fan, Z. Chen, S. Furbo, B. Perers, and B. Karlsson, “Efficiency and lifetime of solar collectors for solar heating plants,” in *Proceedings of the ISES Solar World Congress 2009*, 2009, pp. 331–340.

[15] K. Smith *et al.*, “Life Prediction Model for Grid- Connected Li-ion Battery Energy Storage System Preprint,” in *2017 American Control Conference (ACC)*, 2017, pp. 1–6.

[16] “Italian Energy Markets Manager (GME) web page.” [Online]. Available: http://www.mercatoelettrico.org/.

[17] "Vietnam Electricity web page." [Online]. Available: http://en.evn.com.vn/d6/gioi-thieu-d/RETAIL-ELECTRICITY-TARIFF-9-28-252.aspx.

[18] "Vietstock web page." [Online]. Available: https://vietstock.vn/2018/01/thang-02-2018-gas-giam-20000-dongbinh-768-581118.htm.

[19] D. Dapice, "Counting all of the Costs: Choosing the Right Mix of Electricity Sources in Vietnam to 2025," 2017.

[20] A. Biancardi, "The cost of capital in the energy and water sectors in Italy." 2016.

[21] "Trading economics web page." [Online]. Available: https://tradingeconomics.com/vietnam/interest-rate.

[22] ISPRA, "Atmospheric emission factors of greenhouse gases and other gases in the electricity sector - in Italian (Fattori di emissione atmosferica di gas a effetto serra e altri gas nel settore elettrico)," 2018.

[23] M. Beccali, M. Cellura, S. Longo, B. Nocke, and P. Finocchiaro, "LCA of a solar heating and cooling system equipped with a small water – ammonia absorption chiller," *Sol. Energy*, vol. 86, no. 5, pp. 1491–1503, 2012.

[24] O. Gökulu, F. Kadırgan, and M. A. N. Kadırgan, "Life cycle assessment (LCA) of a solar selective surface produced by continuous process and solar flat collectors," vol. 135, pp. 284–290, 2016.

[25] M. C. Mcmanus, "Environmental consequences of the use of batteries in low carbon systems : The impact of battery production," *Appl. Energy*, vol. 93, pp. 288–295, 2012.

[26] H. SCHAEFER and G. HAGEDORN, "Hidden energy and correlated environmental characteristics of P.V. power generation," *Renew. Energy*, vol. 2, no. 2, pp. 0–7, 1992.

[27] T. M. Gulotta, F. Guarino, M. Cellura, and G. Lorenzini, "A Constructal Law optimization of a boiler inspired by Life Cycle thinking," *Therm. Sci. Eng. Prog.*, vol. 6, no. January, pp. 380–387, 2018.