Urban energy hubs economic optimization and environmental comparison in Italy and Vietnam

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Abstract — **This paper aims to perform the minimization of the yearly energy supply cost from the main electricity and natural gas grids related to an energy district, considering the installation of different equipments. The case study refers to energy consumption of a medium density urban district and involves the exploitation of different energy sources and devices (photovoltaic systems, electrical energy storage, heat pumps and cogenerators). The analysis of the district energy supply is accomplished through an energy hub model. After a cost analysis related to the considered energy systems, a MILP algorithm was used for the optimization of a cost function and the simulation of various scenarios. Moreover, a study about CO_2 emissions is reported. The same study is then repeated considering the Vietnamese economic and environmental context, keeping constant the energy losses and performance of the equipment, in order to compare these countries and provide useful conclusions about the improvement of energy supply systems in developed and developing countries.**

Keywords — emissions; energy hub; MILP; optimization

I. Introduction

One of the main problems that mankind has to currently deal with is the global warming related to rising energy consumption demand and Greenhouse Gases (GHG) emissions produced by the exploitation of fossil fuels. The solution currently adopted is the transition from a centralized architecture of the electrical system, composed by big and controllable power plants, to a decentralized or Distributed Generation (DG) system, where many uncontrollable and independent Renewable Energy Sources plants (RESs) are introduced. Moreover, several countries are implementing policies to reduce CO2-eq emissions, improving the energy efficiency of plants and final utilizations and promoting clean energy production. In order to improve the control of energy balance between generation and loads in DGs, the concept of "microgrid" has gained increasing popularity, because it allows to coordinate local generation and loads. Urban energy districts can be seen as sets of energy hubs, defined as "entities consuming energy at their input ports, connected to e.g. power distribution and natural gas grids, and provide certain required energy services such as electricity, heating, cooling, compressed air, etc. at the output ports. Within the hub, energy is converted and conditioned using e.g. combined heat and power technology, transformers, power electronic devices, compressors, heat exchangers and other equipment. The energy hub model can be applied to multiple existing facilities, as buildings (both residential and industrial) or sets of buildings (urban districts), but also to vehicles (trains, ships and aircrafts)" [1], [2]. It can be easily understood that the main infrastructures supporting an energy hub are the heating/cooling infrastructures and the electricity infrastructure. A Microgrid (MG) is an electrical energy system composed by distributed generation and loads, but also converters and Energy Storage Systems (ESS) that can operate either in islanded or grid-connected configuration. Power electronic interfaces allow an easy integration of renewable energy sources (RES) in MGs, which combined with ESSs can provide economic benefits, while ensuring an efficient use of RESs and reliable load supply [1]. Microgrids development can cause several advantages, as they can feed users by adapting to the customers' needs, reducing energy purchase from the grid. MGs serving buildings are justified in areas with lack of transmission and/or distribution lines and, more generally, in areas where constructions are expensive or where transmission and distribution energy costs are relevant.

Three types of issues can arise while studying Urban Energy Hubs:

- Policy: exploring systemic and individual impacts of different choices, as a demand-response policy;
- Analysis: co-simulation approaches to consider the contribution deriving from the different critical infrastructures. The analysis of Urban Energy Hubs refers to the possibility to simulate the behavior of the different parts of the system and to deploy output features, namely thermal and electrical demand trends;
- Design and operation: choosing sizes, typologies and optimal operation of resources and systems. The problem is providing optimized units' sizes and operational dispatch giving as inputs the demand curves of those flows that can be considered as energy carriers, i.e. heat, electricity, mobility and water [1].

The last one is the problem dealt with in the present work. In detail, after an accurate analysis of power and heat demands of a medium density urban district [3], currently satisfied with power and natural gas infrastructures, Authors performed an economic optimization analysis in order to find the set of equipments (cogenerator, heat pumps, electrical storage, photovoltaic plant) that ensures the minimal cost for fulfilling the urban district needs, considering both investment and operation costs. This optimization analysis is presented according to two different cost scenarios: the Italian and Vietnamese contexts. In order to keep the comparability between the results, technical scenarios (efficiencies, operating hours) are considered to be the same. Moreover, optimal energy hub configurations were compared also considering environmental impacts in terms of CO_2 emissions, calculated from the energy mix of these two countries. The optimization has been evaluated by developing a linear mathematical model, involving reals and integer variables, so that a MILP algorithm has been employed for the resolution of the problem.

This paper is organized as follows:

- paragraph II shows mathematical model, assumptions and methodology;
- paragraph III illustrates technical, economic and environmental scenarios;
- paragraph IV provides results comparison;
- paragraph V depicts conclusions and further deepening that will be done in the future.

II. Mathematical Model and Methodology

A. *Background*

Operating sets of equipment as a unique energy hub produces significant benefits in terms of a higher energy efficiency, reduced greenhouse gases emissions and reduced costs. In this light, the scientific community is currently approaching to the analysis and planning of distributed energy resources with characterization, planning, evaluation and optimization of a class of decentralized multi-generation energy systems organized as energy hubs [3].

Generally, energy hubs enclose some fundamental elements: direct connections, converters and storage devices. Direct connections are elements that deliver an input carrier to the output port without converting it into another energy form or changing its quality in a significant way (e.g. electric cables, pipelines). Converter elements transform an energy carrier into another one. They can be of different kind: steam and gas turbines, combustion engines, electric machines, fuel cells. Storage devices are employed to defer energy sources availability in time [2]. The main reason for adopting a storage is either a stochastic behavior of the source (e.g. RES) or economic advantages (e.g. pumped hydro) [3]. Fig. 1 illustrates an example of an energy hub exchanging electricity, natural gas, heat and biomass through converters in order to deliver electricity, heat and cool in output, while two storage devices allow to decouple generation and load.

B. *Mathematical Model*

As the purpose of an energy hub is to fulfill the needs of a district, the analysis is based on balance equations, one for each carrier. The hub is depicted in Fig. 2, it includes energy conversion and storage systems with following assumptions:

- energy balances are evaluated in steady state condition;
- the energy losses in the system are considered only in converters and storage devices.

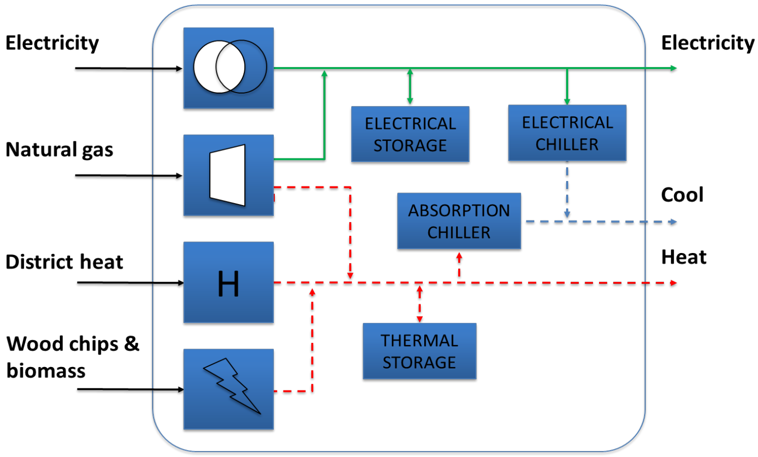

Fig. 1. Example of a microgrid outlined as an energy hub

The energy hub is interfaced with the electrical grid through a transformer, causing small losses. Electricity can also be generated by a cogenerator, fed with natural gas from the local infrastructure, and a RES plant, and can be saved in a storage system. Thermal energy can be recovered from the cogenerator or produced by heat pumps that are modeled as a unique equivalent device.

With reference to Fig. 2 and to previous assumptions, it is possible to write two energy balance equations, the first for the electrical energy (indicated with *E*) and the second for the thermal energy (indicated with *H*). The optimization is evaluated over a standard day, that has been considered as representative of the energy requirement of the urban district.

$$E_{in}(t) - K_{Pj} \cdot E_{in}(t) + E_{cog}(t) + E_{ren}(t) - E_{sto,in}(t) + \\ + E_{sto,out}(t) - E_{HP}(t) = E_{out}(t) \quad (1)$$

$$H_{cog}(t) + H_{HP}(t) = H_{out}(t) \quad (2)$$

where K_{Pj} is a coefficient accounting for the electrical losses in the transformer.

Additional equations can be written to describe the cogenerator, the heat pump, the electrical storage and the renewable plant (assumed as a photovoltaic system), in order to account efficiencies, energy production and physical constraints.

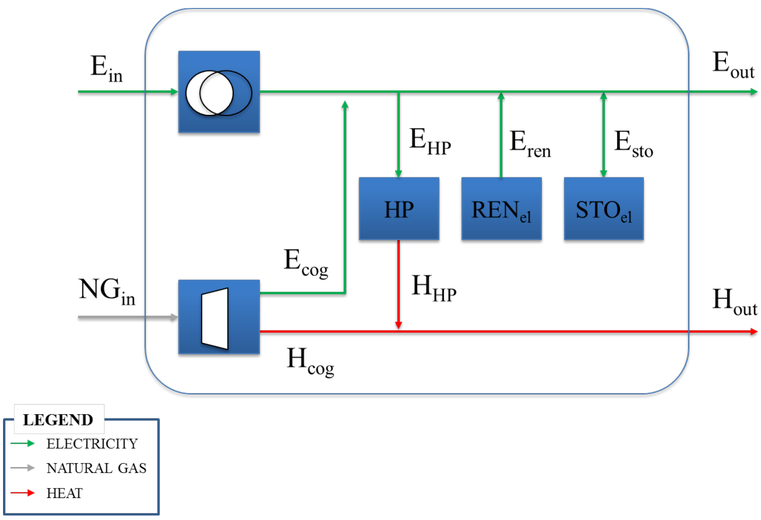

Fig. 2. Schematic of the urban energy hub analyzed in this paper

COGENERATOR

$$E_{cog}(t) = K_{ele} \cdot NG_{in}(t) \tag{3}$$

$$H_{cog}(t) = K_{heat} \cdot NG_{in}(t) \tag{4}$$

$$K_{ele} + K_{heat} < 1 \tag{5}$$

$$S_{cog} = \frac{24}{K_{day}} \cdot \sum_{t=1}^{K_{day}} E_{cog}(t) \tag{6}$$

where E_{cog} is the energy generated by cogenerator at time t, NG_{in} is the natural gas supply, H_{cog} is the heat flow from the cogenerator, K_{ele} and K_{heat} are the electrical and thermal efficiencies of the cogenerator, respectively.

HEAT PUMP

$$H_{HP}(t) = K_{HP} \cdot E_{HP}(t) \tag{7}$$

$$S_{HP} = \frac{24}{K_{day}} \cdot \sum_{t=1}^{K_{day}} H_{HP}(t) \tag{8}$$

where H_{HP} is the heat flow from the cogenerator, E_{HP} is the corresponding electricity, K_{HP} is the conversion coefficient between electrical and thermal energy in the heat pump, commonly known as *COP* (Coefficient Of Performance).

ELECTRICAL STORAGE

$$\begin{aligned} E_{sto}(t+1) &= E_{sto}(t) + \eta_{ch} \cdot E_{sto,in}(t+1) + \\ &- E_{sto,out}(t+1)/\eta_{disch} - E_m \end{aligned} \tag{9}$$

$$E_{sto,in}(t) \leq \delta_{ch}(t) \cdot Q_{\max,ch} \tag{10}$$

$$E_{sto,out}(t) \leq \delta_{disch}(t) \cdot Q_{\max,disch} \tag{11}$$

$$\delta_{ch}(t) + \delta_{disch}(t) \leq 1 \tag{12}$$

$$E_{sto}(1) = E_{sto}(K_{day}) \tag{13}$$

$$DoD \cdot S_{sto} \leq E_{sto}(t) \leq S_{sto} \tag{14}$$

$$E_{sto,in}(t) \leq S_{sto} \cdot (1 - DoD) \tag{15}$$

$$E_{sto,out}(t) \leq S_{sto} \cdot (1 - DoD) \tag{16}$$

where η_{ch} and η_{disch} are the charge and discharge efficiencies of the storage, respectively, $E_{sto,in}(t)$ and $E_{sto,out}(t)$ are the electrical flows in input and output of the storage, respectively, $E_{sto}(t)$ is the energy stored in the device, E_m is the self-discharge coefficient, assumed as a constant term in the model, $\delta_{ch}(t)$ and $\delta_{disch}(t)$ are boolean variables that indicate whether the storage is charging or discharging at time t, respectively, $Q_{max,ch}$ and $Q_{max,disch}$ are two values necessary to avoid that the solver indicates infinite values of energy flow into or from the storage, *DoD* is the Depth of Discharge of the storage device.

RENEWABLE PLANT (PHOTOVOLTAIC)

$$S_{el,ren} \leq \eta_{ren} \cdot I_{sun} \cdot A_{PV} \tag{17}$$

$$S_{el,ren} = \frac{24}{K_{day}} \cdot \sum_{t=1}^{K_{day}} E_{ren}(t) \qquad (18)$$

where E_{ren} is the energy in output from the renewable plant, η_{ren} is the conversion efficiency of the photovoltaic plant, I_{sun} is the daily average solar radiance availability, A_{PV} is the photovoltaic plant surface.

In (6), (8), (14)-(18), the symbol *S* indicates the energy size of the equipment, i.e. the energy production over a day for cogenerator, heat pump and photovoltaic plant and the maximum amount of energy that can be saved in the storage. In (6), (8), (13) and (18), K_{day} is a coefficient used to reduce the computational burden of the algorithm by collecting groups of hours and assuming that the requirement in that number of hours can be considered as uniform. As example, $K_{day} = 6$ means that the standard day can be represented through 6 groups of hours (24/6 = 4 hours per group).

The objective function of the model is the sum of investment cost for the equipment and the operating costs for the electricity and natural gas supply over a year, as illustrated in (19). Maintenance costs have been neglected in this analysis, as also financial subsidies for the exploitation of renewable energies or for high efficiency cogeneration and penalties for CO_2 emissions.

$$\min \left\{ \frac{8760}{K_{day}} \sum_{t=1}^{K_{day}} \left[C_{op,E} \cdot E_{in}(t) + C_{op,NG} \cdot NG_{in}(t) \right] + \right.$$
$$+ C_{el,ren} \cdot \frac{S_{el,ren}}{\bar{h}_{el,ren}} \cdot CRF_{el,ren} + C_{cog} \cdot \frac{S_{cog}}{\bar{h}_{cog}} \cdot CRF_{cog} + \qquad (19)$$
$$\left. + C_{HP} \cdot \frac{S_{HP}}{\bar{h}_{HP}} \cdot CRF_{HP} + C_{el,sto} \cdot S_{el,sto} \cdot CRF_{el,sto} \right\}$$

where the symbol *C* indicates the cost for energy carrier supply or for investment, the symbol $\bar{h}$ indicates the average operating daily hours and *CRF* is the Capital Recovery Factor of the investment, that is used to distribute investments over a year, and is equal to:

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \qquad (20)$$

where *i* is the interest rate and *n* the useful life of the component. The ratio *S/h* is used to transform the energy into power and to determine the components' sizes. In (1)-(20), the variables are the energy fluxes flowing at each time, the energy stored in the electrical storage, the total energy produced over the standard day by each component and the state of the energy storage, identified by boolean variables $\delta_{ch}(t)$ and $\delta_{disch}(t)$. The other quantities are considered as parameters, which values will be specified in the next paragraphs.

C. *Methodology*

The mathematical model illustrated in (1)-(20) was used to assess the economic convenience deriving from the implementation of a hybrid energy hub to fulfill the energy requirements of an urban district. The optimization problem has been implemented in MATLAB 2018a, considering (19) as objective function, (1)-(4), (6)-(9), (13), (18) as equality constraints and (10)-(12), (14)-(17) as inequality constraints (Eq. (5) involves parameters only, which values are reported in Table II). As (1)-(20) are all linear equations, with all real variables except for $\delta_{ch}(t)$ and $\delta_{disch}(t)$, a Mixed-Integer Linear Programming (MILP) algorithm was selected in order to solve the depicted optimization problem.

The economic parameters used for the resolution of the problem were average market values representative of the Italian and Vietnamese contexts, in order to compare how the optimal solution can change between these two countries. Technical parameters, as efficiencies and average operating hours, were kept the same in the comparison. The energy needs of the urban district are kept the same as well, and they are relative to an energy audit carried out on a medium population density district in the city of Agrigento (Italy) [3], and are provided in Tab. I. Optimized hubs were compared according to technical and environmental features, considering the size of components and the CO_2 emissions related to the use of electrical energy in these two cost-optimal microgrids, calculated considering electricity emission factors. CO_2 emissions related to components building and transportation were neglected, assuming that values are very similar between these two countries.

III. Italian and Vietnamese Scenarios Comparison

The aim of this paper is to compare the cost-optimal solution for a microgrid in two different countries, Italy and Vietnam, for a given technology scenario. In this paragraph are recapped values and assumptions done in the development of the model.

A. *Technology scenario*

In both cases the considered energy hub is the one depicted in Fig. 2. The urban district is supplied by an electricity and a natural gas grid, that are exploited for electricity and thermal needs, respectively. In order to fulfill the energy requirements in a cheaper way, a cogenerator, a heat pump (it may be considered both as a heat pump feeding a district heating system or an equivalent heat pump representing small systems installed in the dwellings), an electrical renewable energy plant (assumed to be a photovoltaic plant), and an electrical storage system. These components are characterized by parameters reported in Tab. II. Another parameter that was kept constant among scenarios is K_{day}, that was set equal to 6.

B. *Cost scenarios*

Economic parameters required for this optimization analysis are the cost for electricity and natural gas supply, the investment costs for components (cogenerator, heat pump, photovoltaic plant and electrical storage system) and their Capital Recovery Factors. Cost values were derived manly from catalogues and national reports [3]–[9] or by professional experience wherever it is not specified. For CRFs calculation, interest rate values were assumed equal to $i = 5\%$ for Italy [10], $i = 6{,}25\%$ for Vietnam [11] and useful life values equal to 20 years, 15 years, 25 years and 8 years, respectively for cogenerator, heat pump, photovoltaic plant and electrical storage system. Useful life has been set equal both for Italy and Vietnam's scenarios, as the useful life is considered to be a technical rather than an economic parameter. Numerical values used for the simulations are reported in Tab. III.

C. *Environmental scenarios*

Environmental scenario has been characterized using 2 parameters:

- CO_2 emission related to the production of electricity, that was selected as environmental indicator to evaluate the potential impact of the energy mix on the greenhouse effect;
- Daily average solar radiation, used to evaluate hub PV production capability.

Although detailed emissions data related to the production of electricity in Italy was available [12], a similar figure for the Vietnamese generation asset was not found in literature. For this reason, specific emissions factors were calculated for both countries, in order to keep comparability of data, considering the 2016 energy mixes [13], that are reported in Fig. 5, and the emission factors standard table used for the emissions calculation for the EU Emission Trading System [15]. In order to evaluate the photovoltaic production, average daily solar radiation for Agrigento (Italy) [16] and Hanoi (Vietnam) [17] were used. Environmental parameters are reported in Tab. IV.

IV. Optimization Results

The optimization model developed for this study allowed to obtain the cost-optimal daily schedule of energy fluxes from networks and equipment for Italian and Vietnamese scenarios. A histogram of electrical fluxes is provided in Fig. 3 and 4, that are referred to Italian and Vietnamese scenarios, respectively.

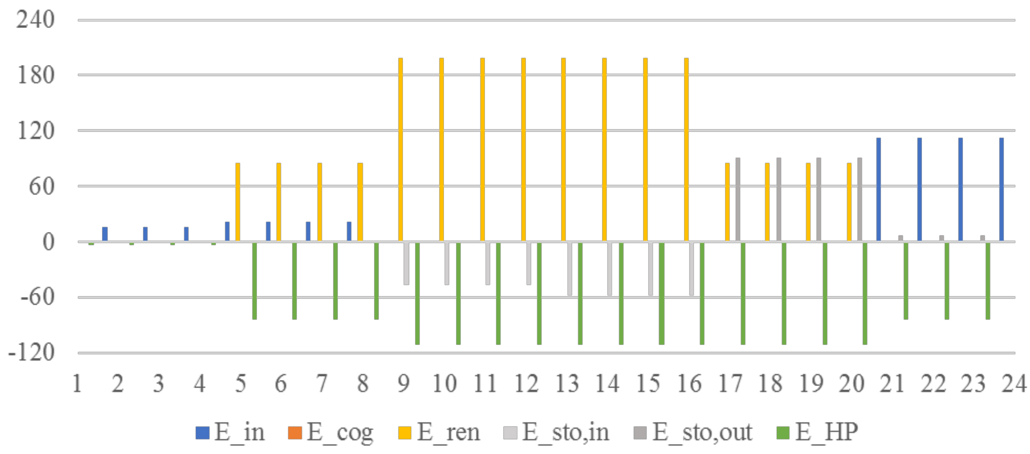

Fig. 3. Cost-optimal schedule of electrical fluxes for the standard day in the Italian scenario

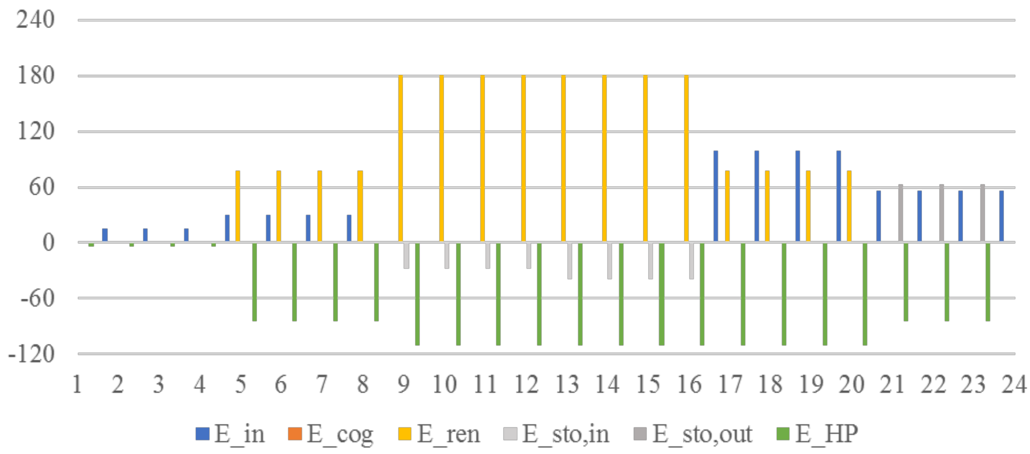

Fig. 4. Cost-optimal schedule of electrical fluxes for the standard day in the Vietnamese scenario

The trends are quite similar, but some important differences can be identified. The higher PV production in Italy allows to have a higher size for the electrical storage, in order to exploit part of the RES production during the evening and reduce the electricity import from the grid, that is used only by night. In both scenarios the heat requirement is totally covered through the heat pump, that is more efficient and economical than the cogenerator, so that this component has not been selected. The output of the two optimized scenarios is provided in Table V.

The environmental analysis of the two scenarios has been evaluated considering the electricity imported from the grid by the optimized energy hub, that has been multiplied by the emission factors provided in Table IV. Results are provided in Table VI. Vietnamese environmental scenario, unfavorable compared to the Italian one, reduces the combined PV and storage exploitation, producing a minor electricity saving from the grid. This aspect, combined with the high value of emission factor (Vietnam produces 35% of electricity from coal, as in Fig. 5), leads to very low CO_2 reduction for the system, that would also be nullified if embodied carbon of equipment were taken into account. On the opposite, Italian optimized microgrid allows to reach an energy saving from the grid higher than 200 kWh/year and an emission reduction higher than 25 kg/year. Considering economic aspects, as Vietnamese scenario costs are lower than in the Italian one, the yearly cost for the operation of the optimized Vietnamese microgrid is almost the half of the cost for the Italian microgrid. This feature may bring investors to be less attracted by energy efficiency investments.

TABLE I. ENERGY REQUIREMENT OF THE URBAN DISTRICT IN THE STANDARD DAY [3]

Hour of the day	Energy Requirement	
	Electrical energy [kWh]	***Thermal energy [kWh]***
1:5	11.78	10.75
6	19.88	333.33
7	23.19	333.33
8	36.44	333.33
9	39.76	333.33
10	43.42	333.33
11	43.42	333.33
12	39.76	333.33
13	28.4	333.33
14	23.91	333.33
15	23.91	333.33
16	46.38	333.33
17	59.64	333.33
18	66.26	333.33
19	72.89	333.33
20	59.64	333.33
21	46.38	333.33
22	46.38	333.33
23	33.13	333.33
24	11.78	10.75

TABLE II. TECHNOLOGY SCENARIO ADOPTED FOR SIMULATIONS

Parameter	Symbol	Value
Transformer efficiency	K_{Pj}	99%
Cogenerator electrical efficiency	K_{ele}	35%
Cogenerator thermal efficiency	K_{heat}	42%
Cogenerator equivalent operation hours at rated power	$\overline{h}_{cog}$	20 hours
Heat pump COP	K_{HP}	3
Heat pump equivalent operation hours at rated power	$\overline{h}_{HP}$	10 hours
Electrical storage charging efficiency	η_{ch}	97%
Electrical storage discharging efficiency	η_{disch}	97%
Electrical storage Depth of Discharge	DoD	20%
Electrical storage maximum allowable input	$Q_{\max,ch}$	1000 kWh
Electrical storage maximum allowable output	$Q_{\max,disch}$	1000 kWh
Electrical storage self-discharge coefficient	E_m	0.01 kWh
Photovoltaic plant global conversion efficiency	η_{ren}	12%
Photovoltaic plant available surface	A_{PV}	1000 m^2
Photovoltaic plant equivalent operation hours at rated power	$\overline{h}_{el,ren}$	5 hours

TABLE III. COST SCENARIOS ADOPTED FOR SIMULATIONS

Parameter	Symbol	*Italian scenario*	*Vietnamese scenario*
Electrical energy supply cost	$C_{op,E}$	0.28 \$/kWh [3]	0.12 \$/kWh [5]
Natural gas supply cost	$C_{op,NG}$	0.18 \$/kWh [3]	0.10 \$/kWh [4]
Cogenerator investment cost	C_{cog}	1961.32 \$/kW$_{el}$ [6]	1000 \$/kW$_{el}$ [8]
Cogenerator CRF	CRF_{cog}	8.02%	8.90%
Heat pump investment cost	C_{HP}	158.94 \$/kW$_{th}$	162.08 \$/kW$_{th}$
Heat pump CRF	CRF_{HP}	9.63%	10.47%
Electrical storage investment cost	$C_{el,sto}$	79.03 \$/kWh [7]	191.64 \$/kWh [9]
Electrical storage CRF	$CRF_{el,sto}$	15.47%	16.26%
Photovoltaic plant investment cost	$C_{el,ren}$	1557 \$/kW	1000 \$/kW [8]
Photovoltaic plant CRF	$CRF_{el,ren}$	7.10%	8.01%

TABLE IV. ENVIRONMENTAL SCENARIOS ADOPTED FOR SIMULATIONS

Parameter	Symbol	*Italian scenario*	*Vietnamese scenario*
Daily average solar radiance	I_{sun}	4.74 kWh/(m^2 day) [16]	4.3 kWh/(m^2 day) [17]
Electricity CO_2 emission factor	EF_{CO2}	121.31 gCO_2/kWh	177.00 gCO_2/kWh

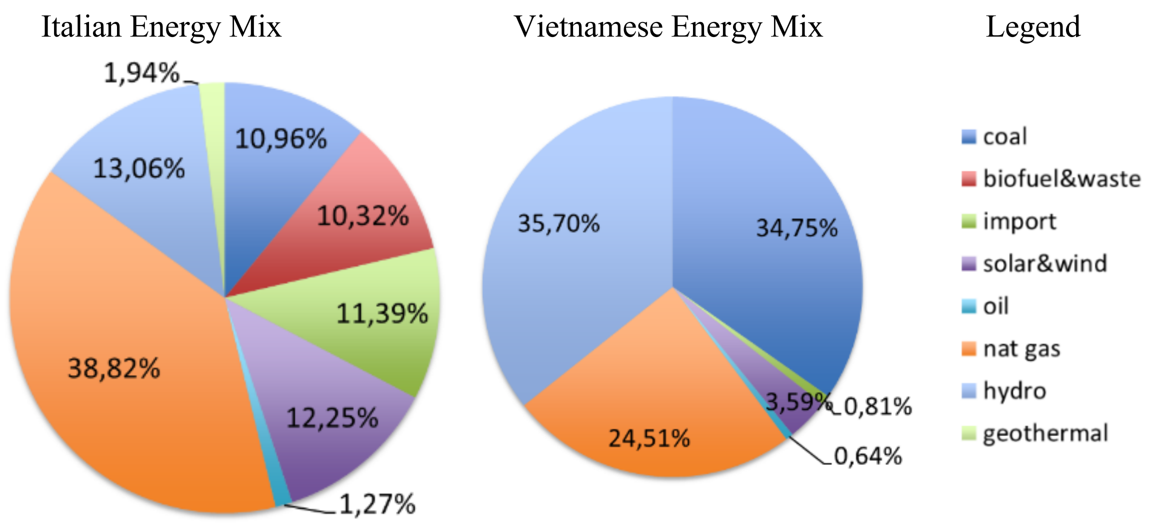

Fig. 5. Energy mixes in Italy and Vietnam in 2016

TABLE V. OPTIMAL SIZE OF EQUIPMENT AND ANNUALIZED COST FOR MICROGRID

Parameter	*Italian scenario*	*Vietnamese scenario*
Photovoltaic plant rate power [kW]	199	181
Cogenerator rate electrical power [kW]	0	0
Heat pump rate thermal power [kW]	333	333
Electrical storage capacity [kWh]	126	81
Annualized cost for microgrid requirements fulfillment [\$]	90,932	58,527

TABLE VI. ELECTRICITY CONSUMPTION FROM THE GRID AND RELATED CO_2 EMISSIONS

Electricity from the Grid [kWh/year]	**Italy**	**Vietnam**
Urban district (before optimization)	823.47	823.47
Energy hub (after optimization)	600.51	805.01
CO_2 Emissions [kg/year]	**Italy**	**Vietnam**
Urban district (before optimization)	99.9	145.8
Energy hub (after optimization)	72.8	142.5

V. Conclusions and Future Developments

This paper outlines a methodology to obtain the cost-optimal energy hub supply for an urban district considering electricity and heat requirements. The mathematical model is based on the assumption of negligible losses in power distribution and district heating networks and steady state energy balances for each time step and can be easily implemented in an optimization tool. The economic analysis has been based only on investment and operating costs of main components, neglecting maintenance costs, CO_2 emissions penalties or financial subsidies for energy efficiency or RES exploitation.

The analysis shows that the optimized microgrids show the same architecture and similar sizes for equipment, while economic, energy and environmental aspects are very different between these two countries. In detail, Vietnam is favored by low supply costs of energy, that are, on the opposite, very high in Italy. This aspect implies that energy savings are more cost-effective in Italy, although the running costs for the operation of the optimized microgrid is quite double than the costs for the Vietnamese case study. Considering environmental aspects, Italy shows higher carbon emissions savings, as the energy mix is "greener" in this country.

In future works, Authors will further improve the mathematical model, in order to account also for the cooling demand of an urban district and including other equipment. In order to deepen the environmental analysis of the energy hub, the application of the Life Cycle Assessment methodology will be applied. Environmental aspects may be considered as new objective function to be included in the optimization, leading to a multi-objective optimization analysis.

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