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Environmental constrained medium-term energy planning: The case study of an Italian university campus as a multi-carrier local energy community

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ABSTRACT

The European Union defined the ambitious carbon-neutrality goal for 2050. Such a transition must be done gradually to avoid huge investments; therefore, medium-term energy planning of energy supply systems must be performed properly considering both economic and environmental aspects. Sector coupling measures aid to achieve this ambitious target, although they require a remarkable financial investment. This paper presents an innovative methodology for the medium-term energy planning of the university campus “Marche Polytechnic University” located in Italy towards the carbon neutrality, i.e., 50 % of carbon emissions reduction by considering financial investment aspects. The university campus is a multi-carrier local energy community with multiple technologies such as photovoltaic, combined heat and power, gas-fired boilers, absorption, and electric chillers that satisfy the end-users’ energy demand. A different mix of installed and new technologies (e.g., energy storage or hydrogen) are investigated through the Calliope framework. The case studies present the economic-based optimal scenario of a typical year planning, guaranteeing the same 50 % carbon emissions reduction. Results underline the importance of exploiting synergies among multiple carriers and the essential role of i) renewables (e.g., additional 3.3 MW of photovoltaic to be installed), ii) batteries with a capacity of 7 MWh, and (iii) sector coupling technologies.

1. Introduction

The European Union wants to pursue the ambitious plan of making Europe a pioneer in the fight against climate issues, thus being the first climate-neutral continent by 2050. To do this, the European Green Deal was presented by the European Commission in 2019 to achieve such a challenging goal in a short/medium-term plan [1]. Even though the guidelines proposed by the European Commission are more inclined to policymakers, there are still technical aspects of Renewable Energy Systems (RESs) to be addressed since, if on the one hand RESs are the current driving force towards a sustainable transition, on the other hand the uncertain nature of intermittent renewables represents the main issue to be solved. Indeed, the synergic operation of RESs with other technologies such as Energy Storages Systems (ESSs) allows to achieve more energy-efficient scenarios thanks to the greater flexibility offered by these systems, especially at the local level. In this regard, the effects of the high penetration of renewables in local energy systems were widely investigated in the scientific literature [2,3], underlining the strategic importance of storage technologies.

To further contribute to the decarbonization process of local energy systems, sector coupling strategies aim at integrating different energy sectors and exploiting synergies from multiple energy carriers such as electricity, heat, cooling, gas, and mobility [4]. There are two main different approaches to foster the sector coupling [5]: the first approach is based on the electrification of the final uses, thus shifting the end-user’s demand towards the electricity sector fed by renewables [6]. For instance, the use of heat pumps for space heating instead of conventional natural gas boilers, especially in countries that are highly reliant on natural gas, would have a major impact in terms of emissions reduction thanks to the higher conversion efficiency [7]. On the other side, the deployment of electric vehicles can be also seen as a measure to pursue

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Nomenclature

Acronyms:

BAU	Business As Usual
CAPEX	CAPital Expenditure
CHP	Combined, Heat and Power
COP	Coefficient Of Performance
CTES	Cooling Thermal Energy Storage
DER	Distributed Energy Resource
DH	District Heating
DSM	Demand Side Management
DSO	Distribution Service Operator
EC	Electrical chiller
ESS	Energy Storage System
EZ	Electrolyser
FC	Fuel cell
HHV	Higher Heating Value
HP	Heat Pump
IEA	International Energy Agency
LC	Levelized cost
LCOE	Levelized Cost of Energy
LEC	Local Energy Community
MILP	Mixed Integer Linear Programming
MV	Medium Voltage
NG	Natural Gas
O&M	Operation & Maintenance
OPEX	OPErational EXpenditure
PEM	Proton Exchange Membrane
PV	Photovoltaic
RES	Renewable Energy Systems
SPORES	Spatially-explicit Practically Optimal REsultS
TES	Thermal Energy Storage
UNIVPM	Marche Polytechnic University

such a strategy: if the electricity flow between the national grid and the electrical vehicles is bidirectional, the latest will be also used as energy storage by adopting the Vehicle-to-Grid function [8,9]. The second approach is based on cross-sector coupling, which means a synergic coupling of different energy carriers and related networks like the use of hydrogen to couple electrical and gas networks. Indeed, hydrogen can be produced by electrolysers fed by the electrical network, and then it can be injected into the natural gas grid for being stored while being mixed with the natural gas itself. Staffell et al. [10] carried out a comprehensive literature review on the current status of hydrogen applications, demonstrating that a mixture of natural gas-hydrogen blending up to 20% in volume does not require any changes in the current infrastructure. Regarding the sector coupling measures, Victoria et al. [11] addressed the role of different energy storage systems integration at the European level concluding that, while Photovoltaic (PV) systems are preferable to counterbalance their variability with batteries, the fluctuations of wind systems can be tackled with hydrogen storage solutions. Additionally, the coupling of both heat and electricity carriers compensates the thermal energy storage sizes, which otherwise would be overestimated due to the seasonality of the different sources. Malka et al. [12] assessed the energy storage benefits in the case study of Drin Cascade by comparing different technologies, concluding that the most suitable technologies are compressed air energy storage, pumped-hydro energy storage, and sodium-sulphur batteries.

Storage and sector coupling technologies enable the viability of achieving the environmental goal previously mentioned, but they are still economically expensive compared to other fossil fuel-based technologies as reported in a recent technical report [13]. Although RESs are still financially onerous, especially for large-scale plants (multi-MW or GW capacity), a major cost breakdown is currently undergoing thanks to the ongoing research and development activities, leading to specific costs of 310–1,700 €/kWe for PV systems and 830–1,800 €/kWe for wind ones [14]. Compared to 2010, their costs have been reduced by more than 80% and 40%, respectively, as reported in [15]. As for the storage systems, different types of ESSs still require high investment costs, especially Li-ion batteries that are close to 200 €/kWh [16], while thermal energy storage does not have high specific costs (10 €/kWh) [17]. As for the sector coupling technologies, heat pumps require 250–1,700 €/kW$_{th}$ [18], while the hydrogen infrastructure is the most economically intensive due to the lack of maturity, i.e., low technology readiness level. Indeed, low temperature electrolysers operating under 100°C, namely Alkaline and Proton Exchange Membrane (PEM), require 1,000–1,500 €/kW and 2,000–3,000 €/kW, respectively, where the installation costs are included [19]. Hydrogen storage ranges from 200 to 2,000 €/kg$_{H2}$ (the low-temperature fuel cells need an investment cost of around 1,500 €/kW [16]). However, considering the long-term perspective, the energy systems are expected to shift completely towards these technologies to reach the climate-neutrality goal due to the increase of their maturity and economic competitiveness.

The large-scale, i.e., regional-national decarbonization policy, can result in an arduous problem due to its complexity and large numbers of actors involved. For this reason, researchers are now focusing on a bottom-up approach represented by Local Energy Communities (LECs) that are then replicated on a larger scale [20]. A LEC is defined as a Small-Medium Enterprise or a no-profit organization with shareholders or members cooperating in the generation, distribution, storage, and supply of energy at local level [21]. The members of a LEC are called “prosumers”, i.e., consumers that can also produce energy and thus they can actively participate in the electricity market. The optimal planning of LECs is a challenging task due to the presence of multiple energy technologies operating with different carriers that interact one to each other to satisfy the time-varying end-users’ energy demand. In addition, economic aspects are not sufficient to be considered for the optimal planning problem, whereas environmental constraints should be also taken into account. In summary, the most convenient LEC configuration and related operation strategies should be identified in terms of the choice of the energy technologies, their sizes, and their operation by ensuring both the economic and the environmental sustainability of the system. This topic has been widely addressed in the scientific literature. Among others, Doubleday et al. [22] analysed different aspects related to the inclusion of distributed energy resources, district services, and transportation. In particular, they provided an overview on how to deal with the district planning and improve the design tool by including some important features, i.e., power distribution systems in the district planning process. In this regard, two case studies in England and Japan have been analysed and discussed. Dal et al. [23] developed an approach to optimize both the design and the operation of LECs focusing on the Demand Side Management, concluding that these LECs can obtain lower economic expenses and, at the same time, significant emissions reduction. Foiadelli et al. [24] presented a multi-objective optimization model to obtain the optimized configuration of interconnected distributed energy resource systems in a LEC while considering economic and environmental aspects. A Mixed-Integer Linear Programming (MILP) approach was proposed, and the objective was the optimal selection and sizing of distributed energy resources in the LEC with corresponding operation strategies and optimal configuration of the heating pipeline network by minimizing a weighted sum of total annual costs and annual carbon emissions. Mehleri et al. [25] proposed a mathematical programming approach based on the MILP approach for the optimal design of distributed energy systems at the neighborhood level to select the system components among several candidate technologies and design the heating pipeline, thus allowing to have the heat exchange among the different nodes by minimizing the total annual costs. Vu et al. [26] analysed the optimal design of a campus microgrid in South Korea based on a techno-economic analysis that incorporates real market conditions. Various incentives were considered such as those of renewable energy and ESSs to discharge their energy during on-peak hours on weekdays. Comodi et al. [27] assessed the optimal energy planning of a hot-climate university campus in Singapore by exploiting the synergies among five energy hubs connected with an internal district cooling network. Ren et al. [28] proposed a MILP model for an integrated plan and evaluation of distributed energy systems for an eco-campus in Kitakyushu (Japan) to minimize the overall energy cost for a test year by selecting the units to be installed and determining their operating schedules.

From the scientific literature, the energy systems modeling is widely used at the urban district level as a support measure for planning and operating local multi-carrier energy systems, typically through proper optimization algorithms. In such a context, more than 145 models were reviewed by Klemm et al. [29], and they were classified by (i) time resolution, (ii) time horizon, (iii) mathematical formulation, and (iv) assessment criteria. It was concluded that most of the district-level optimization tools have an hourly resolution with a time horizon of at least one year. The MILP approach is the mostly adopted, and economic criteria are typically considered in the optimization problems [30]. Wirtz et al. [31] analysed the influence of the level of detail of the modelling approach for the design optimization problem of local multi-carrier energy systems. From their study, it emerged that the level of detail of the selected modelling approach can significantly vary not only the computation efforts, which range from 10 s to 10 h, but also the value of the objective function resulting from the problem resolution up to 5%.

The selection of the right model for designing a local multi-carrier energy system from scratch, while finding a trade-off between model fidelity and computation efforts, is not a trivial task. Therefore, it is preferable to design LECs starting from a baseline scenario and then analyse further ones with different design possibilities and objectives to be compared with the baseline one. Indeed, since the analysed scenarios share the same level of detail for the modeling approach, their differential evaluation eliminates the uncertainty of the results. Following this latter approach, the aim of this paper is to propose an innovative methodology for the medium-term energy planning of the university campus “Marche Polytechnic University” located in Ancona (Italy) towards carbon neutrality, i.e., 50 % of carbon emissions reduction without neglecting the crucial economic aspect. This university campus fits well the concept of multi-carrier LEC with multiple technologies such as PV, Combined Heat and Power (CHP), gas-fired boilers, absorption and electric chillers aiming at satisfying the users’ energy demand. Starting from this baseline scenario, different mixes among the installed technologies and new ones such as electrolysers, fuel cells, heat pumps, and electric/thermal/hydrogen storage are investigated for the medium-term planning purpose by ensuring the environmental and economic sustainability of the LEC.

Based on both energy demand and primary energy consumption, a Spatially-explicit Practically Optimal REsultS (SPORES) mode within the Calliope framework [32] has been used to deal with the oscillation of the investment cost without using a stochastic programming approach, thereby reducing the computational efforts. The main contributions to the current literature are highlighted below:

- Proposing a methodology for the optimal expansion plans of a real multi-carrier LEC, thus investigating the involvement of new energy carriers such as hydrogen and emerging ones such as ESSs and sector coupling technologies, and considering both environmental and economic aspects;
- Providing insights on the strategies to be adopted and replicated in similar multi-carrier LECs to achieve medium-term emission goals, which have been set to 50 % emissions reduction, without neglecting economic aspects;
- Investigating the correlations and synergies among the present and candidate emerging technologies to be part of the LEC;
- Classifying the considered emerging technologies by priority based on their size variability in multiple scenarios.

The paper is structured as follows: Section 2 describes the framework and the methodology used in this work. Section 3 presents the case study under investigation considering the different studied scenarios. Section 4 discusses the results of the different scenarios. Finally, Section 5 reports the conclusions of the work.

2. Methods

In this section, both modelling framework (Calliope) and methodology used for carrying on this work, which has been applied to the university campus “Marche Polytechnic University”, are described in detail. The characteristics of the tool are stated; subsequently, the case study’s current status and the possible expansion plans in the medium term have been and described as well.

2.1. Modelling framework and three-phases approach

In this subsection, an overview of the adopted modelling framework, namely Calliope, is reported in Sub-subsection 2.1.1, which describes its customizability and modelling potential required to properly face with the medium-term energy planning of the university campus “Marche Polytechnic University” located in Ancona (Italy). These features are fundamental to apply the methodology specifically adopted in this work that is subsequently presented in Sub-subsection 2.1.2.

2.1.1. Modelling framework

Calliope is an open-source multi-energy system modelling framework: it is user-friendly and highly customizable [32]. Indeed, Calliope allows to evaluate energy systems with user-defined spatial and temporal resolutions, besides their modelling at different levels using a scale-agnostic mathematical formulation based on power nodes modelling framework which has been proposed by Heussen et. al. [33]. Calliope executes many runs based on the same base model and has a clear separation of the framework (code) and model (data): it provides internally coherent scenarios on how the energy is extracted, converted, transported, and used as well as how these processes might change in the future. Calliope adopts a bottom-up approach and a MILP optimization problem formulation to minimize the overall user-defined costs of the whole scenario (Eq. (1)), which is the sum of each technology cost considering multiple energy balance restrictions per each energy carrier. The mathematical modelling of the energy systems and the energy balance constraints can be found in [34].

$$\min : z = \sum_{loc,tech,k} \left(cost(loc : tech, cost = cost_k) \right) \quad [34] \tag{1}$$

where $loc, tech, k$ represents three levels of the model: (i) locations/sites, (ii) technology, and (iii) type of costs, whereas $loc : tech, cost = cost_k$ refers to a specific cost voice related to a specific technology installed in a determined location.

Calliope allows to define different types of costs, namely (i) investment costs related to the capacity of the technology and (ii) Operation and Maintenance (O&M) costs, which are expressed as a fraction of the investment cost or/and an annual capacity-based cost. Furthermore, the depreciation rate is adopted to compare various technologies’ investments as defined in Eq. (2):

$$d_r = \frac{i \cdot (i+1)^{lt}}{(i+1)^{lt} - 1} \quad [34] \tag{2}$$

where d_r is the depreciation rate, lt is the lifetime of the technology (expressed in years), and i is the interest rate. The depreciation rate allows to compare all the technologies considering the same equivalent year, different lifetimes, and interest rates. Hence, the overall cost of a single technology considering a year of reference is the sum of all the cost types:

$$C_{tot} = S \cdot d_r (1 + O\&M_{\%}) + S \cdot O\&M_{year} \quad [34] \tag{3}$$

where S is the capacity of the technology and the design variable of the optimization model.

Regarding the constraints, all the energy carriers coming from the modelled technologies are balanced at each time step and they are mainly divided in five families of systems:

- Energy supply technologies;
- Energy demands;
- Energy storage;
- Energy transmission;
- Energy conversion technologies.

Calliope allows to optimise the multi-carrier LEC considering two different modes, namely planning and operation. In the first mode, the variables of the MILP problem are the sizes of the technologies to be installed to fulfil the energy demand, while the energy of the different carriers is balanced at each time step. In the second mode, the installed size of all the technologies is given as input and the goal is to meet the energy demand optimally through the local management of each energy technology according to their operational constraints.

In this work, only the planning mode is used since the sizes of technologies are unknown and they are evaluated by Calliope as one of the outputs. As output data, Calliope provides the following ones:

- Costs of each technology (CAPEX and OPEX);
- Technologies size;
- Levelised Cost of Energy (LCOE) that is calculated as the ratio between the costs for the energy carrier production (CAPEX and OPEX) and the amount of energy produced in the planning horizon. Considering that the costs can assume different natures, as defined by the modeller, it is possible to have different types of levelised costs. Precisely, in this work there are economic (€/kWh) and environmental levelised costs (gCO$_2$/kWh), where the latter considers the achievement of 50 % emissions reduction.

It is worth noting that the stochastic behaviour is not included in Calliope due to its complexity and computational efforts; however, this can be evaluated using other energy modelling tools such as Temoa [35]. Furthermore, it is possible to obtain any number of optimum alternatives through SPORES mode [36] where not only the best configuration is based on a predefined objective, but also any defined number of alternatives within a range of optimal cost solutions are obtained. Each alternative is called “spore”, whereas the range of acceptance is called “slack”: this mode considers the variability of the costs and provides also a wider perspective of the analysed scenario.

2.1.2. Three-phases approach

The methodology used in this work is divided into three phases, and it allows to achieve a comprehensive overview of the current energy system scenario, which is the benchmark (i). Its environmental cost is used as input for an additional constraint to obtain the (ii) optimal economical solution for energy transition, where the expansion of the existing energy system with sustainable technologies is considered. Furthermore, its economical result is the starting point to assess the (iii) optimal alternatives, where each alternative is a case scenario with the same environmental constraint but different economical costs, i.e., different technologies type and/or sizes.

These three phases must be performed sequentially since each phase result is used as input data for the following one. For each phase, both economic and environmental costs are the results of the optimization problem; indeed, the environmental cost of the first phase (Business As Usual) is used as an additional constraint for the second and third phases.

$$C_{CO_2} \le 0.5 \cdot C_{CO_2,BAU} \tag{4}$$

where C_{CO_2} is the environmental cost of scenarios after the first phase, which must be lower than 50% of the first phase’s ($C_{CO_2,BAU}$).

After the second phase (optimal economical solution), the economic costs are used as input for the third phase (optimal alternatives) and updated at each alternative based on Eq. (5):

$$C_{e,i} \le C_{e,0}\left[i \cdot \frac{(1+m)}{n}\right]; \quad i = 1, \cdots n \tag{5}$$

where $C_{e,0}$ is the economic cost from the second phase, while m and n are acceptance range and the number of optimal alternatives, respectively. The flowchart of all three phases, which highlights the required input data and results together with the additional constraints between phases, are reported in Fig. 1, Fig. 2, and Fig. 3, respectively.

Thanks to the three-phase methodology, the expansion plan of the energy system toward the carbon reduction mission of the LEC is well-defined, thus providing a differential comparison with the BAU scenario (first phase). Furthermore, the best economic configuration (second phase), together with different alternatives (third phase), provides a wide range of possible solutions, including the possibility of assessing the correlation among the technologies.

However, despite the similarity, the proposed methodology is not stochastic, meaning that it does not provide the statistical probability of each alternative. Indeed, the number of alternatives and the acceptance range is user-defined. Both parameters directly impact the possible solutions; however, there is no proper guideline on how to choose them besides the modeler’s experience.

2.2. Case study and scenarios analysis

In this subsection, an overview of the case study’s characteristics has been provided and detailed descriptions of the current status of its energy systems have been reported. Subsequently, the scenarios analysis describes the possible pathways for the expansion plan of the university campus of “Marche Polytechnic University”.

2.2.1. Case study

The case study under investigation is the university campus of “Marche Polytechnic University” (UNIVPM) located in Ancona (Italy). It is a medium-scale campus that accounts for almost 17,000 people among students and academic, administrative, and technical staff.

It hosts different faculties, namely Engineering, Agriculture, and Natural Sciences. The UNIVPM campus is divided into several buildings that are dedicated to offices, classrooms, and laboratories which are shown in Fig. 4 and it covers an area of around 31,000 m^2.

The UNIVPM campus is connected to the national electrical grid with a Medium Voltage (MV) cabin, being a single node of connection with the local Distribution System Operator, and one connection node for the natural gas network.

The UNIVPM campus is configured as a multi-energy LEC where several types of energy demands must be satisfied; in particular, there are (i) electrical energy demands for offices appliance, lighting, and laboratory equipment plus (ii) thermal energy and cooling demands for the space heating and space cooling. The electrical energy demand is satisfied by Distributed Energy Resources (DERs) and the national electrical grid, while the thermal energy demand is fulfilled by natural gas boilers located in the thermal power plant. The overall energy is distributed through the District Heating (DH) infrastructure within the UNIVPM campus. Lastly, the cooling energy demand is provided mainly

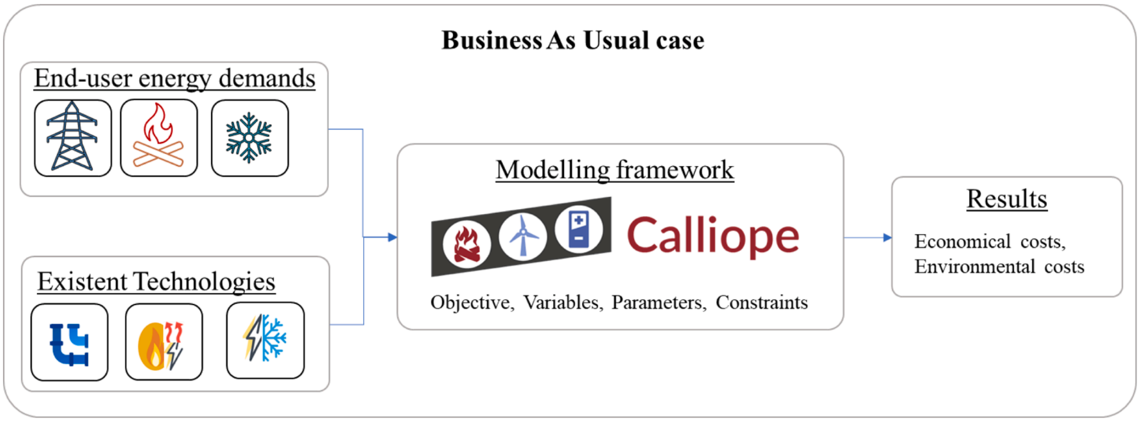


Fig. 1. First phase flowchart.

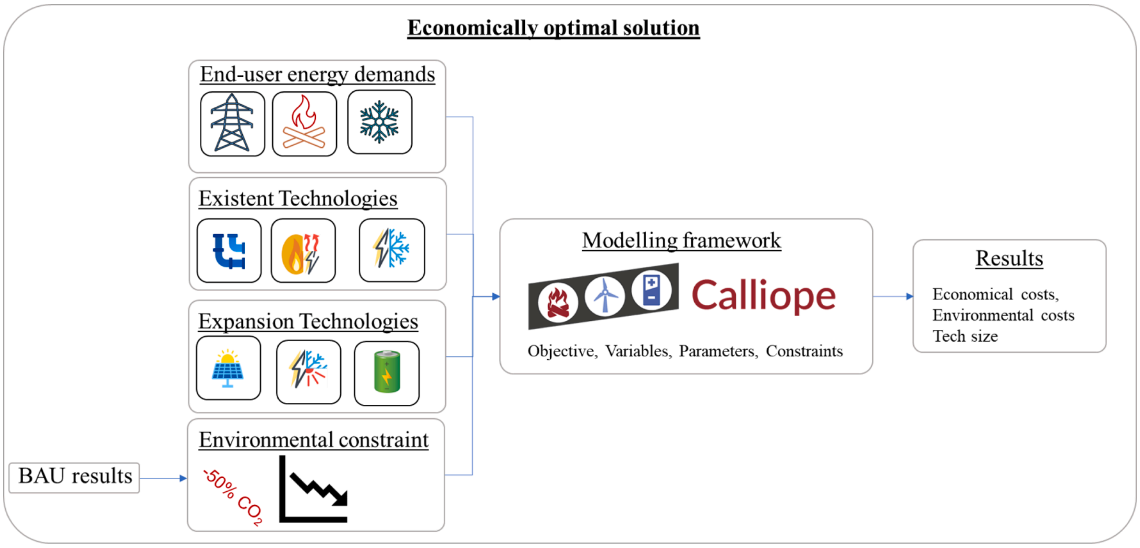


Fig. 2. Second phase flowchart.

by the dislocated absorption chillers installed in each building; indeed, four buildings (e.g., “Science 1”, “Science 2”, “Science 3”, and “South block”) receive the cooling energy from two absorption chillers whose thermal energy for their supply comes from the local DH network.

Currently, the energy technologies already installed in the UNIVPM campus are:

- A PV system with a peak power of 20 $kW_{p;}$
- A CHP system, which is fed by the natural gas coming from the national network, with a rated power of 575 kW_{el}/610 kW_{th} connected to the DH network. Its yearly average electrical and thermal efficiency are equal to 0.415 and 0.44, respectively;
- Eight natural gas boilers, each of them having a rated capacity of 1 MW_{th} and an average thermal efficiency of 0.91;
- Two absorption chillers with an overall capacity of 500 kW_{th} and an average efficiency of 0.80;
- Three electrical chillers with 900 kW_{th} of total capacity and an average Coefficient Of Performance (COP) of 3.

The historical data used in this study, which have been monitored, refers to the year 2019. Such data regards the natural gas consumption, which is taken from the national gas grid, and the electricity withdrawn from the national electric network as reported in Fig. 5. Considering that the UNIVPM campus has a single connection with both the natural gas grid and the electric network, it can be considered as a single final user. To provide a better overview of the energy carriers involved in the UNIVPM campus, Fig. 6 shows the energy demand calculation process.

Additional case study characteristics are listed below:

- Thermal energy is provided by a natural gas-fueled CHP, supported by natural gas boilers, while no electricity is used for the thermal energy production;
- The CHP has the objective to operate always more than 50% of its rated condition;
- The cooling energy is produced in June-July; if electric chillers are adopted, the electricity withdrawal from the national electric grid will be subjected to a huge variation compared to the one that occurred in May, thus spotting the electricity dedicated to produce the cooling energy;
- The thermal energy produced by the CHP plant in June-July is directly used to supply the absorption chiller.

On the other hand, the energy demands of the three carriers like electricity, thermal, and cooling energy are simulated with an hourly resolution for the entire year as reported in Fig. 7, Fig. 8, and Fig. 9, respectively.

In 2019, the overall electrical energy consumption was equal to 5.0 GWh with a peak power of 1,368 MW as reported in Fig. 7.

The thermal energy demand was related to space heating purposes only in the cold months; in particular, around 4.0 GWh of thermal

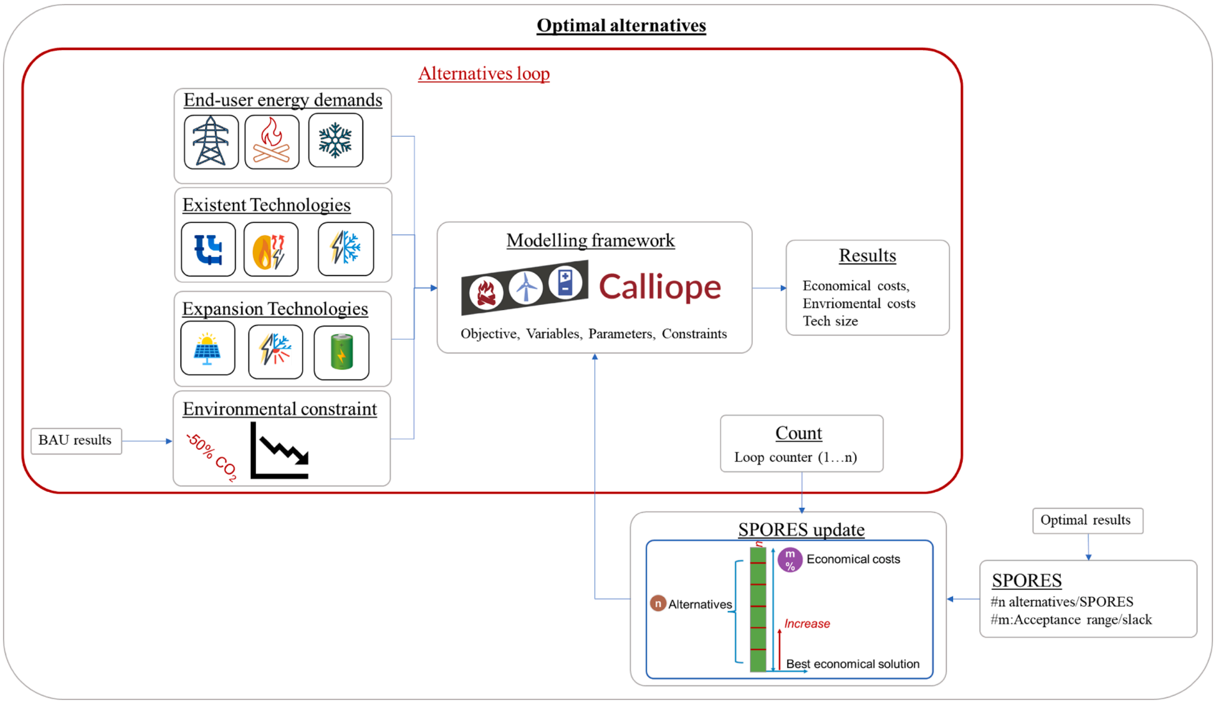


Fig. 3. Third phase flowchart.

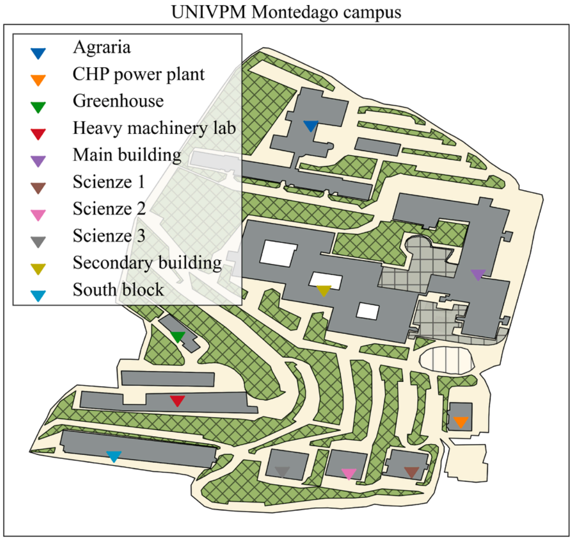


Fig. 4. UNIVPM Campus map created with Geopandas [37].

energy have been consumed with a power peak request of 4.4 MW, which occurred on the 4th of January as reported in Fig. 8. This power peak was due to the “rebound effect” caused by powering up the space heating infrastructure that remained inactive during the Christmas holidays; thus, a considerable amount of heat was needed to restore the temperature setpoint of the internal spaces.

On the other hand, the cooling energy demand was present only in July-September when 0.5 GWh of cooling power have been consumed with a power peak of 1.3 MW as shown in Fig. 9.

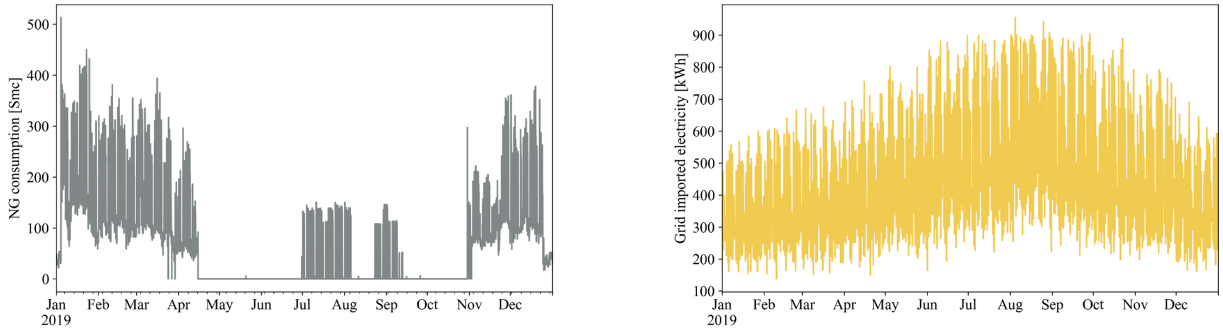
2.2.2. Scenarios analysis

Regarding the scenarios analysis, the planning horizon is based on a typical year. The current technologies and the new ones considered for the potential expansion plans sorted by the energy nature are the following:

1. Energy supply: national electric network and natural gas grid;
2. RES: PV systems whose input is the solar irradiance. The irradiance data, which are adjusted with the panel efficiency, has been reconstructed with Renewables Ninja [38] that is an online tool that allows to perform an estimation of the PV system production based on the location of the installation site;
3. Energy conversion technologies: CHP unit, natural gas boilers, PEM electrolyser (EZ), PEM fuel cell (FC), absorption chiller, electrical chiller (EC), and heat pump (HP);
4. Energy storage technologies: thermal and cooling energy storage, battery, and hydrogen storage;
5. A mixer that is a conversion system that allows to have natural gas-hydrogen blending. This energy carrier, named “blend”, can be used as input for the CHP unit and boilers. It is worth noting that the mixer is a figurative conversion system with no financial cost and with 100 % efficiency since its function is to supply hydrogen-natural gas blends [2].

The CHP unit and the boilers can be fed either by natural gas or natural gas-hydrogen blend based on their economic convenience and availability. The natural gas-hydrogen blend is a feasible measure to reduce the carbon impact due to the conventional natural gas-based technologies, and it has been proven by experimental tests that this application does not require any technical adjustment up to 20% of hydrogen volume concentration [39]. In this work, the hydrogen volume concentration is equal to 15% since this level has been widely used and validated by numerous real-life demonstrators like the one of SNAM S.p.A. project in Italy [40] and the Hydeploy project in the United Kingdom [41]. A bottleneck for the natural gas-hydrogen blend applications is due to the lower energy content per unit of volume compared to the natural gas as reported in Table 1. Indeed, the natural gas-hydrogen blend provider must supply more volume depending on the hydrogen content to reach the same amount of energy that would have been provided to the end-users using only natural gas [42].

It is worth noting that there are no transmission technologies because, in the proposed scenario, the campus has been modelled as an aggregated consumer without considering each building in detail. The functional scheme of all the technologies is reported in Fig. 10. This



a) Hourly trend of natural gas consumption

b) Hourly trend of electricity import

Fig. 5. Monitored data of both natural gas consumption and electricity withdrawn from the national network.

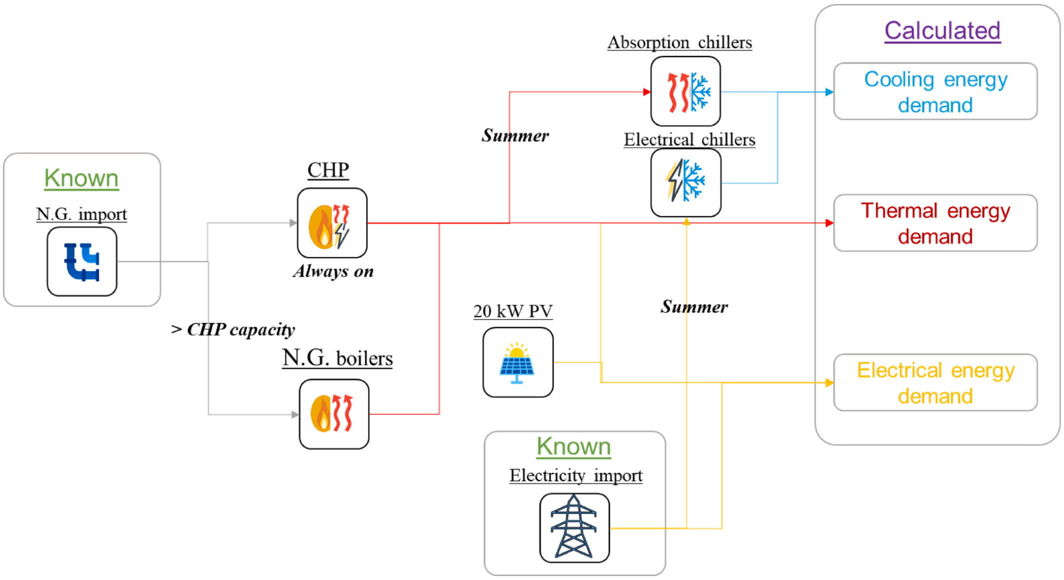


Fig. 6. Energy demands calculation process.

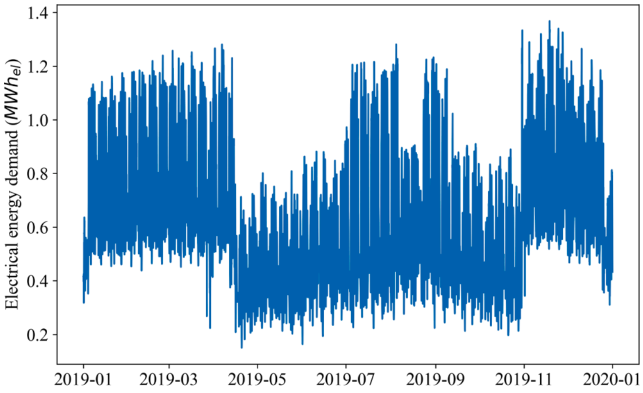


Fig. 7. Electrical energy demand in the year 2019 (hourly resolution).

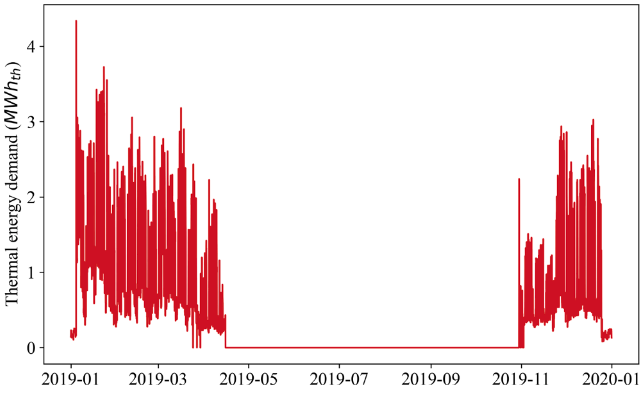


Fig. 8. Thermal energy demand in the year 2019 (hourly resolution).

scenario presents six energy carriers and a RES plant, two energy supply technologies, eight conversion technologies, four types of ESSs, and three kinds of energy demand.

Once the energy technologies involved in the baseline scenario have been established, their technical and cost parameters must be defined. For the existent technologies, which are listed in Table 2, their CAPital EXpenditure (CAPEX) costs are ignored, and the OPerational EXpenditure (OPEX) ones are strictly based on the primary energy consumption. As for the supply networks, their financial import cost and export revenue [45], along with their carbon footprint [46], are presented in Table 3. In this study, carbon emissions are attributed only to energy supply technologies.

The new technologies that are considered for the expansion plans of the campus are listed in Table 4 and Table 5 along with their performance and financial data. All the technologies share a common financial interest rate that is set equal to 2 %. Going into detail, the Li-ion

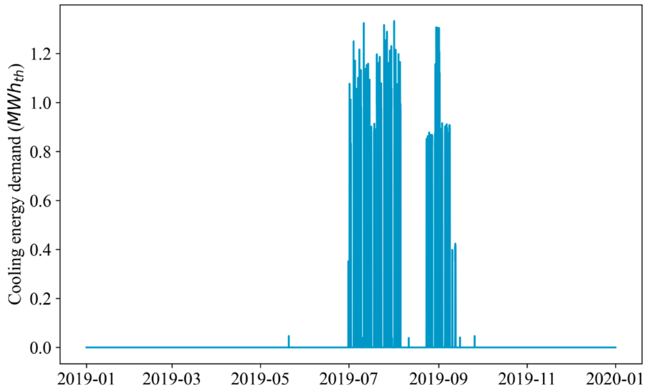


Fig. 9. Cooling energy demand in the year 2019 (hourly resolution).

Table 1
Natural gas and hydrogen properties.

	Natural gas [43]	**Hydrogen** [44]
Density [kg/Nm^3]	0.679–0.98	0.089
Higher Heating Value (HHV) [MJ/Nm^3]	34.95–45.28	12.7
Wobbe Index range [MJ/Nm^3]	47.31–52.33	46

batteries suffer a “self-discharge” loss behaviour over time, dropping nearly 5 % of the stored energy in a month [47]. Such a trend has been also considered in the proposed scenario. No hydrogen compression unit has been included in the study since the chosen electrolyser type produces high-pressure hydrogen [48] to be directly stored in a tank. Moreover, a hydrogen storage tank deals with a gas mass flow and thus no losses are considered.

3. Results and discussion

In this section, the results obtained by the studied scenarios are reported and discussed. Firstly, the baseline scenario assesses the year 2019 and it is the starting point of this analysis. Then, the economical optimal scenario, which reaches the environmental goal of 50% emissions reduction as well as twenty optimal alternatives with a cost acceptance range of 50 %, has been investigated.

Table 2
Conversion systems size and efficiency (equipment already installed onsite).

	Size	Efficiency
Cogeneration plant	575 kWel / 611 kWth	0.415 (el) / 0.44 (th)
Boiler	8 MW	0.91
Electrical chillers	900 kWth	3
Absorption chillers	455 kWth	0.8

Table 3
Energy supply cost and export revenue.

	Import cost	Import emission cost	Export revenue	Reference
Electrical grid	0.2 €/kWh	281.4 gCO_2/kWh	0.095 €/kWh	[45]
Natural gas network	0.095 €/kWh	201 gCO_2/kWh	N/A	[45]

3.1. *Baseline scenario*

In the baseline scenario, which refers to the case with the technologies already installed (see Table 2 and Table 3), the UNIVPM campus must withstand 1.39 M€ due to the import of the energy carriers from the national supply, and therefore it has an annual carbon emission of 2.4 ktons. In this scenario, the UNIVPM campus is dependent on the supply grids despite the DERs installed on site; however, the CHP unit plays a crucial role in the energy demand fulfilment. As reported in

Table 4
Conversion technologies parameters.

Technology	Efficiency < 1 / COP greater than 1	Lifetime (years)	Investment cost (€/kW)	O&M cost	Reference
PV	N/A	30	1,473	10 €/kW	[15]
Heat pump	3 (heat) / 3.5 (cold)	20	1,600	4 % CAPEX	[18]
Electrolyser	0.71	15	1,295	3.5 % CAPEX	[17]
Fuel cell	0.50 (el) / 0.34 (th)	14	1,500	3.8 % CAPEX	[17]

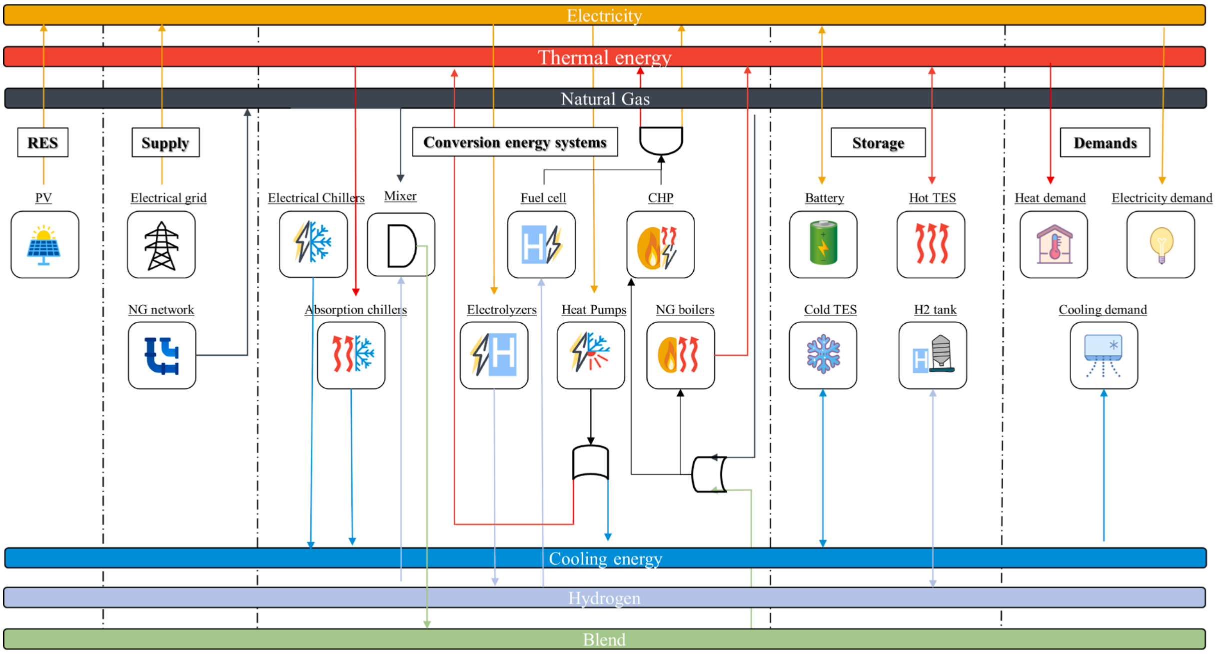


Fig. 10. Functional scheme of the energy carriers and technologies involved in all the scenarios.

Table 5

Energy storage parameters.

Technology	Efficiency	Lifetime (years)	Investment cost (€/kWh)	O&M cost (%CAPEX/year)	Minimum SOC (%)	Reference
Battery	0.95	15	1,000	2	20	[49]
Hot TES	0.81	24	10	1.5	0	[17]
Cold TES	0.81	24	10	1.5	0	[17]
H_2 Tank	0.99	23	10	2.3	0	[17]

Fig. 11, the CHP unit does not only contribute to 38.5% of the overall electricity production, but it also provides thermal energy that covers 54.8 % of the overall thermal energy demand. As for the cooling energy, both the absorption and the electric chillers share almost the same percentage of energy production.

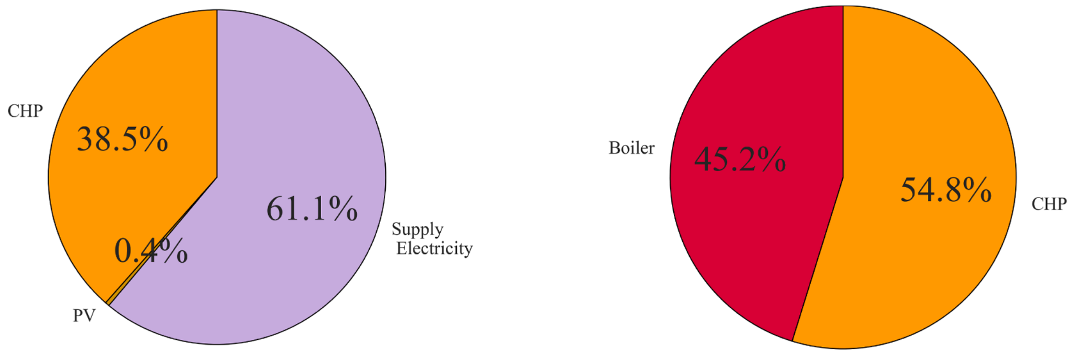
In this case, the monetary LCOE of both thermal and electrical energy depends on the cost of natural gas and electricity supply, in addition to the technical efficiencies of the CHP plant, which is equal to 0.33 and 0.25 €/kWh, respectively.

Since the LCOE is the ratio between the costs of an energy carrier and the effective produced energy, the levelised cost of cooling energy is huge compared to others because it needs to be produced from either electricity or thermal energy, hence also the technology investment of producing thermal or electrical energy carriers must be considered. In addition, its demand is lower than the other two carriers and thus the produced energy is limited. As a result, the levelized cost of the cooling energy of the baseline scenario reaches 2.92 €/kWh.

As for the emissions LCOE, even though the cost nature is different, the relationships among the energy carriers remain the same where the cooling energy is the most environmentally expensive one since it reaches the value of 5 kg_{CO2}/kWh, while the other two have comparable values (around 0.2–0.3 kg_{CO2}/kWh).

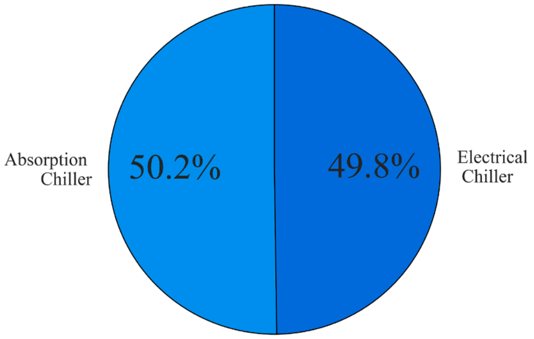
3.2. Optimal scenario

The optimal planning scenario is economically based on the constraint of reaching the pre-set environmental goal, i.e., 50 % of carbon emissions reduction in the multi-carrier LEC. Such a goal is based



a) electricity

b) thermal energy



c) cooling energy

Fig. 11. Energy share of the baseline scenario.

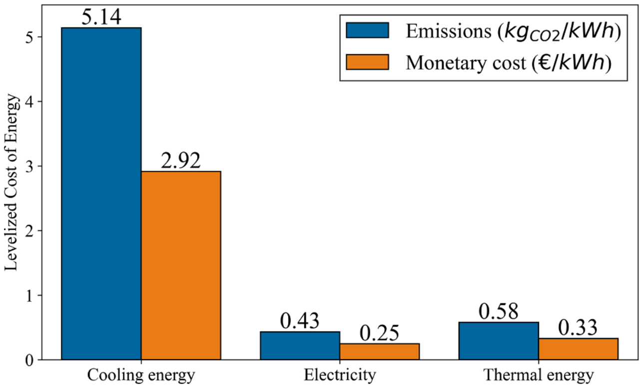
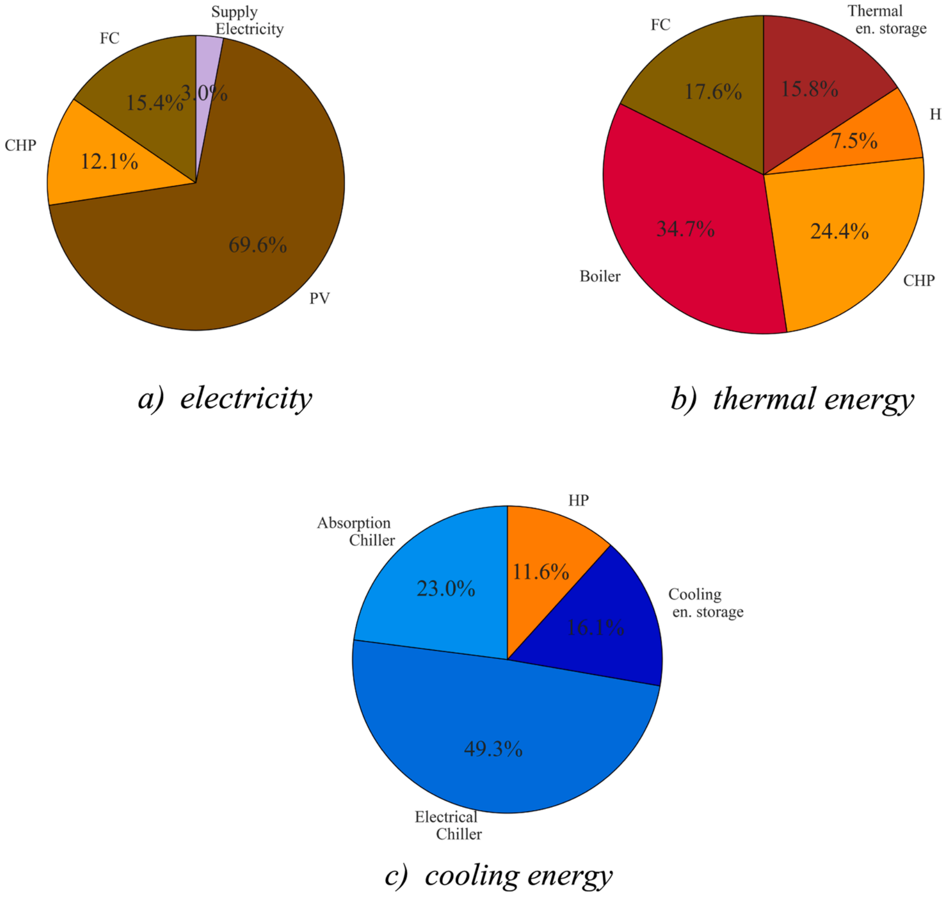


Fig. 12. LCOE of the energy carriers.



a) electricity

b) thermal energy

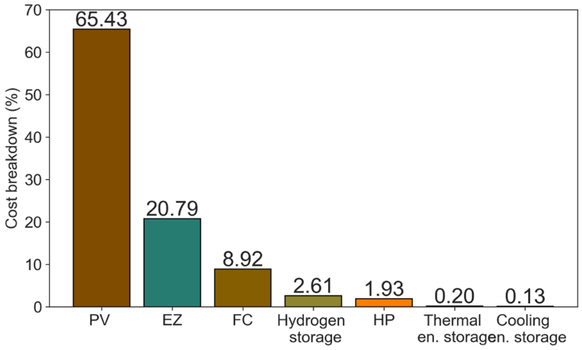
c) cooling energy

Fig. 13. Energy matrixes of the optimal scenario.

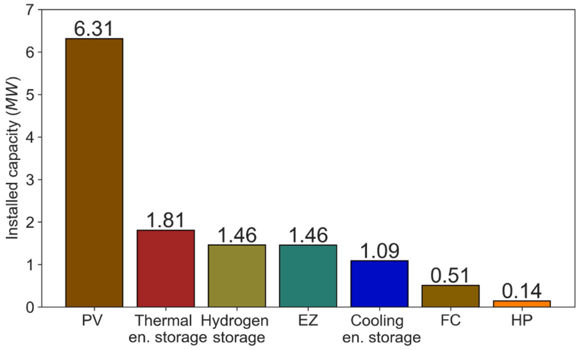
on the baseline results; thus, the scenario must have annual carbon emissions lower than 1.2 kton$_{CO2}$.

Knowing that CO_2 reduction measures usually come with an increase in economical investment, the maximum level of CO_2 emissions is always reached because of an economic-focused objective. In this scenario, even though it has an environmental benefit, it does not come with the same increasing percentage of expenses in economic costs. Conversely, the economic total costs decrease accounting for 1.31 M€ throughout the planning horizon in a single year. The best economic solution has been reached by installing new energy technologies: positive results are obtained not only from an environmental point of view (-50% of CO_2 emissions), but also from an economical point of view (-6%). Indeed, the LCOEs of every single carrier face a significant decrease: such changes are due to the use of new technologies that allow to drastically lower supply dependence. As it can be noticed in Fig. 13, the energy demand matrix experiences an important change compared to the baseline scenario. For instance, the supply of both electricity and natural gas, which have both considerable economic and environmental expenses, is drastically reduced compared to the baseline scenario due to the use of newly installed technologies. The natural gas supply value can be derived by the share of the CHP unit and natural gas boilers for thermal energy production since they are only natural gas consumers.

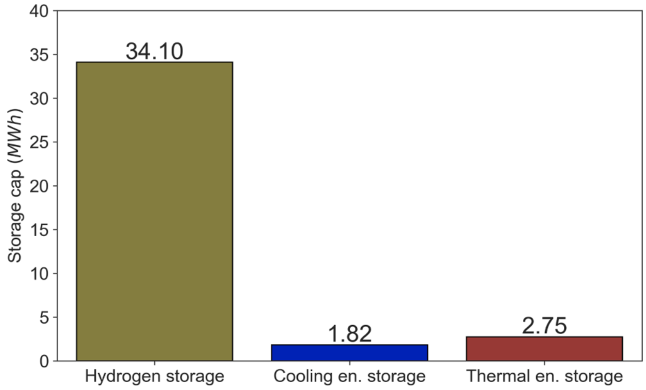
It is worth noting that all the investment costs of the new technologies are discounted in a single year based on their lifetime by using Eq.s 4 and 5. The overall cost of the new technologies is equal to 0.7 M€/year. Fig. 14 *a)* shows the technology investment breakdown: as it can be



a) Technologies investment breakdown



b) New technologies capacity



c) New storages capacity

Fig. 14. Optimum scenario overview.

noticed, the investments in the heat pumps are like those of the hydrogen storage, while the thermal storage requires significantly lower investments.

This distribution depends on a combination of two factors, namely (i) the sizes to be installed (Fig. 14 *b)* and *c)*) and (ii) the CAPEX. Indeed, the PV system holds the largest share due to its required size (about 6.3 MWp) and its CAPEX (1,473 €/kWp). On the other hand, even though thermal energy storage needs a considerable energy storage capacity (around 2–3 MWh), its investment cost is negligible compared to the other technologies because of their lower CAPEX (10 €/kWh). The hydrogen infrastructure, namely the PEM electrolyser, hydrogen storage tank, and PEM fuel cell contributes to nearly 30% of the energy systems investment due to their higher CAPEX.

The levelised cost of each energy carrier is notably dropped compared to the baseline scenario (see Fig. 12), while the cooling energy is the most expensive carrier with monetary and emission expenses of 2.5 €/kWh and 2.1 kg_{CO2}/kWh, respectively.

Compared to the BAU case, the configuration of the technologies involved in this scenario includes i) a wider expansion of the already installed technology (PV) and ii) the inclusion of new ones like heat and cooling energy storages, fuel cell, electrolyser, hydrogen storage, and heat pumps: this information can be found in Fig. 15, while Fig. 16 shows the LCOEs of the optimal scenario.

The electricity, because of the significant size of the PV system, is the least expensive carrier. The hydrogen cost is usually expressed in terms of mass considering that it has a lower heating value of 33.3 kWh/kg in standard conditions, which means that in this case the hydrogen has a monetary LCOE of 14.3 €/kg_{H2} that is aligned to the values reported in the scientific literature [50]. However, it is still far from the hydrogen cost reduction expectations [51]; furthermore, in this scenario, it not an emission-free carrier because the electricity supply to the electrolysers is not solely provided by the PV system. Indeed, hydrogen has a levelised

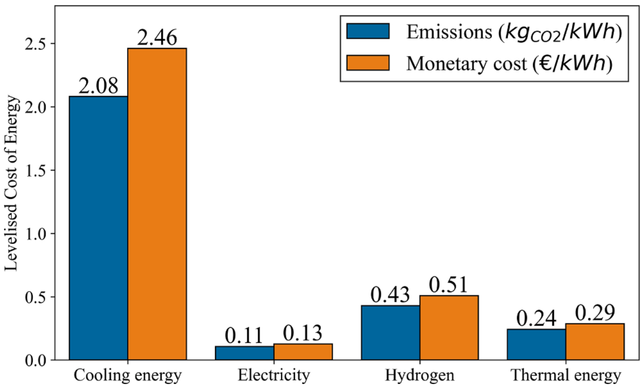


Fig. 16. LCOE of the optimal scenario.

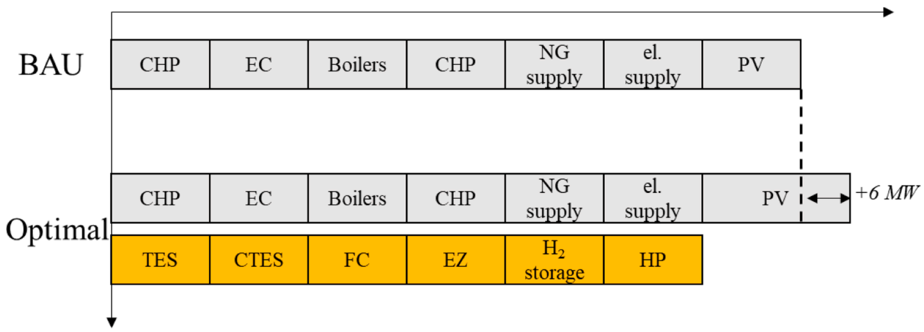


Fig. 15. Technologies adopted comparison.

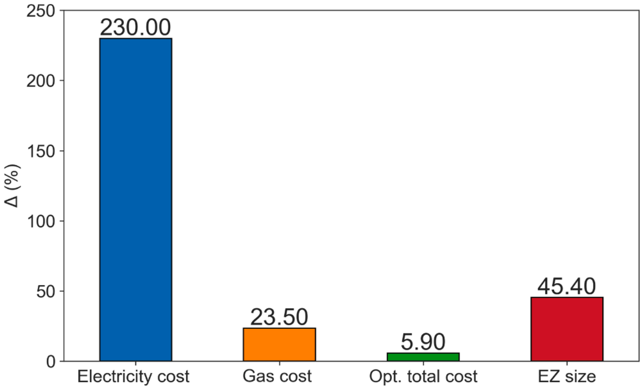


Fig. 17. Variation due to energy cost increase.

cost of emission equal to 0.51 kg_{CO2}/kWh, thus overtaking both the electricity and the thermal energy due to (i) the electricity supply from the grid, (ii) lower efficiencies of the hydrogen conversion systems, and (iii) lower amount of the hydrogen request/production.

Due to the undergoing energy crisis, both natural gas and electricity costs, which are supplied by the respective national grid and network, have tremendously increased; indeed, the electricity cost had + 230% of increase, while the natural gas cost had an increase of 23.5% compared to 2019 levels [52]. Despite of these fluctuations, the results show that the technologies to be used are unchanged, but an increase in the electrolyser size of 45.4% is obtained as shown in Fig. 17. In this case, hydrogen has become more economically suitable with the skyrocketing energy costs; also, the community is now more grid independent and less subjected to the overall energy costs increase as well (+5.9%).

3.3. Optimal alternatives scenarios

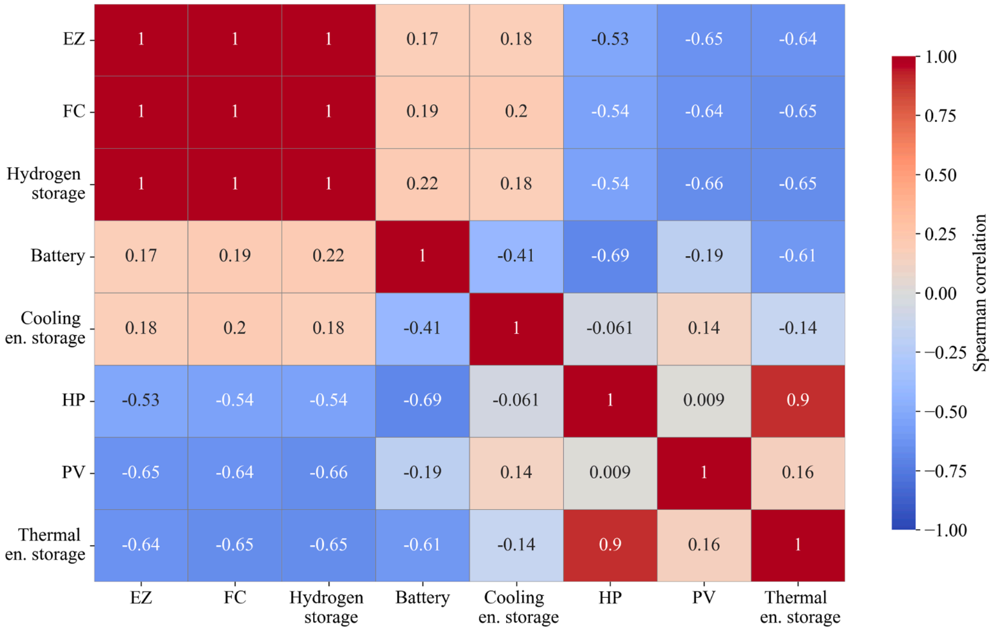
Starting from the optimal scenario, which is economically based, twenty alternatives (or SPORES, as previously discussed in Subsection 2.1) have been analysed. In particular, the objective of the problem is still economically driven by the environmental limitations and the acceptance range ("slack") of the objective value (monetary costs), which is set equal to 50% to consider the variability of the costs of the different systems. Each alternative can have different results of planning if they do not exceed 50% of the economic costs addressed to the optimal scenario. The large acceptance range is required to assess the large cost variability of the different energy systems; indeed, these alternatives can assume a wide range of size values since the equipment has not been installed yet and the objective is to find their optimal size, whereas the existent technologies cannot vary.

Precisely, the technologies that are allowed to vary their size in the different scenarios are:

- Electrolyser;
- Fuel cell;
- Hydrogen storage;
- Battery;
- Cooling energy storage;
- Heat pumps;
- Photovoltaic systems;
- Thermal storage;
- Mixer.

No solution has shown the use of a mixer, meaning that the blended energy carrier is not economically feasible in the acceptance range due to the lower density of hydrogen. Indeed, a 15% of natural gas-hydrogen blending volume leads to a 5.13% of emissions reduction as already stated in [53]. For this reason, rather than using the natural gas-hydrogen blend, the model chooses a more economically efficient decarbonisation path using hydrogen or heat pumps. Among these alternatives, the results regarding both the emissions and the economic levels are the same and equal to 1.11 $kton_{CO2}$ and 1.96 M€, respectively, where the latter value corresponds exactly to the maximum allowable cost that is 1.5 times higher than the one obtained in the optimal scenario. However, the size of the technologies can change significantly because of the high slack (50%).

The analysis of different alternatives allows to assess the dependency among the energy technologies, which is carried out through the Spearman correlation. It is a correlation indicator of the monotonic relationship for two generic parameters (x and y), ranging from −1 to + 1, where 0 stands for no correlation. Correlations of −1 or + 1 imply an exact monotonic relationship, while positive correlations indicate that, as the parameter × increases, the parameter y increases as well. On the

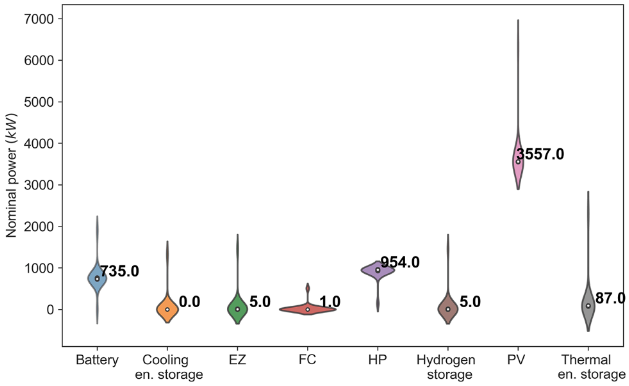


	EZ	FC	Hydrogen storage	Battery	Cooling en. storage	HP	PV	Thermal en. storage
EZ	1	1	1	0.17	0.18	-0.53	-0.65	-0.64
FC	1	1	1	0.19	0.2	-0.54	-0.64	-0.65
Hydrogen storage	1	1	1	0.22	0.18	-0.54	-0.66	-0.65
Battery	0.17	0.19	0.22	1	-0.41	-0.69	-0.19	-0.61
Cooling en. storage	0.18	0.2	0.18	-0.41	1	-0.061	0.14	-0.14
HP	-0.53	-0.54	-0.54	-0.69	-0.061	1	0.009	0.9
PV	-0.65	-0.64	-0.66	-0.19	0.14	0.009	1	0.16
Thermal en. storage	-0.64	-0.65	-0.65	-0.61	-0.14	0.9	0.16	1

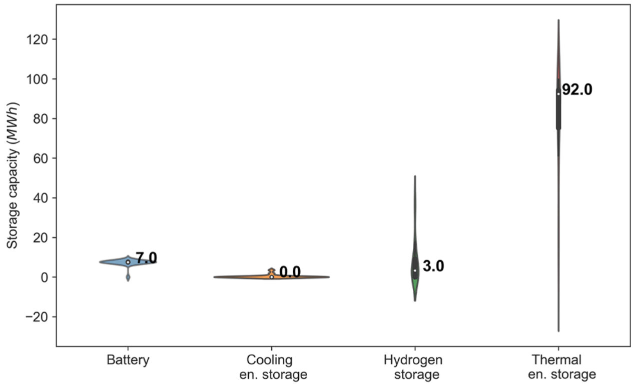
Fig. 18. Spearman correlation matrix.

contrary, negative correlations suggest that as × increases, y decreases.

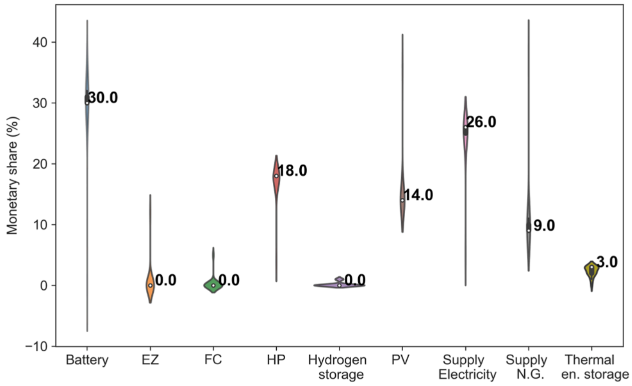
The energy conversion technologies use the power capacity as a parameter, while the energy capacity is used for storage systems. The Spearman correlations are illustrated in Fig. 18 where two parameters are considered remarkable only if the absolute value of the correlation indicator exceeds the value of 0.4. Indeed, three hydrogen technologies are strictly connected. The same behaviour occurs for the heat pumps and thermal energy storage with a correlation of 0.9. Furthermore, the whole hydrogen infrastructure has a notable negative correlation with PV, heat pumps, and thermal storage. The increase of the battery capacity does not only allow to achieve a slight reduction of the PV system size, but also the deployment of heat pumps and thermal energy storage capacity as well.



a) Power capacity variability range



b) Storage capacity variation range



c) Monetary share variation range

Fig. 19. Variation of the main parameters in the analysis of the optimal alternatives.

It is also interesting to investigate the variability of the different parameters obtained by the results from the analysed scenarios. The fluctuation of the sizes of the technologies and their monetary share is reported and discussed in Fig. 19.

In terms of capacity, the PV system plays a crucial role in achieving the environmental goal previously mentioned, while all the other technologies can have a null capacity. The PV system, batteries, heat pumps, and thermal storage have an essential role with average power and energy capacity values of 735 kW/7 MWh, 954 kW, and 87 kW/92 MWh, respectively. Other technologies have average values nearly close to zero, thus they are not considered crucial ones.

From an economic point of view, the battery is the most expensive technology because of its higher CAPEX; the same situation occurs for the heat pumps. The electricity and the natural gas supply contributes to a significant share of the overall costs in most scenarios, while in some of them the electricity supply monetary share can reach a null value. This trend does not occur in the natural gas supply that contributes, at least, for 9% of the overall costs. Furthermore, the PV system has a minimum monetary share value of 8%.

4. Conclusions

In this study, a multi-carrier LEC planning problem has been established and solved to achieve the goal of 50% emissions reduction without neglecting the crucial economic factor. The investigated system, which is related to a university campus “Marche Polytechnic University” (UNIVPM) in Ancona (Italy), holds different types of energy technologies. This study has analysed the mix among the already installed and new technologies instead of deploying solely brand-new technologies. There are two main advantages deriving from this approach: (i) new technologies can have smaller sizes since they are backed up by the existent ones and, therefore, the investment costs are lower compared to the complete replacement of the installed assets, and (ii) the exploitation of the whole lifetime of the installed technologies.

The results, which is replicable in similar LECs, showed that the monetary cost-optimal scenario does not only reduce the emitted emissions, but also leads to a significant economic benefit (-6% compared to the baseline scenario), meaning that some expenses are avoided (e.g., costs related to the energy withdrawal of the energy from national supply infrastructures). Such avoided expenses exceed also the discounted investment costs of all the new technologies. Even though the integrated system cannot be completely independent of the national grid in this scenario, it is anyway highlighted the importance of having a LEC that leads to both economic and environmental advantages.

Nevertheless, to reach the environmental goal, the energy matrixes face a quite radical change due to the new technologies installation and, as a result, the levelised costs of each energy carrier dropped. Despite these reductions, the cooling energy levelised cost remains high with a relevant scarcity of its demand throughout the year. The same trend is faced by the hydrogen that has a monetary LCOE of 14.3 €/kg_{H2}, but it is still too high to proceed with the hydrogen cost reduction pathway that has the goal to reach a value lower than 2 €/kg_{H2}. From these results, both the levelised cost of cooling energy and hydrogen carriers can be reduced if their production increases. Furthermore, hydrogen cannot be considered totally “green” since its production is not solely provided by the PV system, and the choice of rather use PV or supplying electricity is purely based on an economical perspective because of the economical-driven modelling objective.

The optimal alternatives result assesses (i) the variability, (ii) the priority, and (iii) the correlation among the new technologies. Indeed, to achieve the modeling goal, the PV system capacity increases from 3 MWp to 6.3 MWp, then battery, heat pumps, and thermal storage are embedded since they are technologies downstream of the PV system. The electricity surplus generated by the PV system can be either stored in the battery or used in heat pumps to produce thermal energy. Lastly, the thermal storage has the role to absorb the excess thermal energy from the heat pump production.

All the three hydrogen-related energy technologies are correlated one to each other, as well as with the PV system and the heat pumps. The negative correlation between the hydrogen technologies and the PV system implies the role of hydrogen in absorbing the variability of the PV system, whereas their correlation with the heat pumps and the thermal energy storage entails that they are exchangeable sector coupling solutions.

In terms of monetary costs, the battery holds for 30% of overall costs in most of the scenarios due to its high CAPEX; then, there are heat pumps and the PV system that contribute by 18% and 14% of the overall cost, respectively. The costs related to the electricity and natural gas supply are quite remarkable, especially the electricity-one that contributes by 26% of the costs, but it can be also reduced to zero in some cases. On the other hand, the natural gas supply cannot achieve this target since it is used in all the optimal alternative scenarios.

Nevertheless, different technical solutions of the expansion plan can be assessed: they are highly dependent on the number of alternatives and the acceptance range, and this represents a limitation of the presented methodology. Thus, future studies will consider surely the use of other technologies that can be easily embedded in the university campus “Marche Polytechnic University” (UNIVPM) taking into account other energy conversion technology and storage systems, the internal grids, and the integration of stochastic aspects (statistical distributions). This analysis will be important for analysing possible energy costs fluctuation, and thus have a possible overview of a LEC to cut down the costs and being as much as possible self-sufficient from an energy point of view. The future development of the energy sector is a priority and, looking to the future, the main environmental targets to be reached in 2030 and 2050 will be also analysed.

CRediT authorship contribution statement

Lingkang Jin: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Mosè Rossi:** Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Lucio Ciabattoni:** Data curation, Writing – original draft, Writing – review & editing. **Marialaura Di Somma:** Funding acquisition, Visualization, Writing – original draft, Writing – review & editing. **Giorgio Graditi:** Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. **Gabriele Comodi:** Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] Commission E. The European Green Deal 2019;vol. 53. https://doi.org/10.1017/CBO9781107415324.004.
[2] Bartolini A, Carducci F, Muñoz CB, Comodi G. Energy storage and multi energy systems in local energy communities with high renewable energy penetration. Renew Energy 2020;159:595–609. https://doi.org/10.1016/j.renene.2020.05.131.
[3] Wang C, Lv C, Li P, Song G, Li S, Xu X, et al. Modeling and optimal operation of community integrated energy systems: A case study from China. Appl Energy 2018; 230:1242–54. https://doi.org/10.1016/j.apenergy.2018.09.042.
[4] Di Somma M, Graditi G. Challenges and Opportunities of the Energy Transition and the Added Value of Energy Systems Integration. Technologies for Integrated Energy Systems and Networks 2022:1–14. https://doi.org/10.1002/9783527833634.CH1.
[5] Comodi G, Spinaci* G, Di Somma M, Graditi G. Transition Potential of Local Energy Communities. Technologies for Integrated. Energy Systems and Networks 2022: 275–304. https://doi.org/10.1002/9783527833634.CH11.
[6] Van Nuffel L, Gorenstein Dedecca J, Smit T, Rademaekers K. Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise? 2018:1–151.
[7] Abd Alla S, Bianco V, Scarpa F, Tagliafico LA. Electrification of the residential heat demand: An analysis of the power market potential to accommodate heat pumps. Thermal Science and Engineering Progress 2022;27:101173. https://doi.org/10.1016/j.tsep.2021.101173.
[8] Wang M, Craig MT. The value of vehicle-to-grid in a decarbonizing California grid. J Power Sources 2021;513:230472. https://doi.org/10.1016/j.jpowsour.2021.230472.
[9] Di Somma M, Ciabattoni L, Comodi G, Graditi G. Managing plug-in electric vehicles in eco-environmental operation optimization of local multi-energy systems. Sustainable Energy Grids Networks 2020;23:100376. https://doi.org/10.1016/J.SEGAN.2020.100376.
[10] Staffell I, Scamman D, Velazquez Abad A, Balcombe P, Dodds PE, Ekins P, et al. The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 2019;12:463–91. https://doi.org/10.1039/c8ee01157e.
[11] Victoria M, Zhu K, Brown T, Andresen GB, Greiner M. The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. Energy Convers Manag 2019;201:111977. https://doi.org/10.1016/j.enconman.2019.111977.
[12] Malka L, Daci A, Kuriqi A, Bartocci P, Rrapaj E. Energy Storage Benefits Assessment Using Multiple-Choice Criteria: The Case of Drini River Cascade. Albania Energies (Basel) 2022;15:4032. https://doi.org/10.3390/EN15114032/S1.
[13] IEA International Energy Agency. Projected costs of generating electricity. 2020.
[14] Vellini M, Bellocchi S, Gambini M, Manno M, Stilo T. Impact and costs of proposed scenarios for power sector decarbonisation: An Italian case study. J Clean Prod 2020;274:123667. https://doi.org/10.1016/j.jclepro.2020.123667.
[15] Taylor M, Ralon P, Anuta H, Al-Zoghoul S. Renewable Power Generation Costs in 2019:2020.
[16] Monforti Ferrario A, Bartolini A, Segura Manzano F, Vivas FJ, Comodi G, McPhail SJ, et al. A model-based parametric and optimal sizing of a battery/hydrogen storage of a real hybrid microgrid supplying a residential load: Towards island operation. Advances in Applied Energy 2021;3:100048. https://doi.org/10.1016/j.adapen.2021.100048.
[17] Petkov I, Gabrielli P. Power-to-hydrogen as seasonal energy storage: an uncertainty analysis for optimal design of low-carbon multi-energy systems. Appl Energy 2020; 274:115197. https://doi.org/10.1016/j.apenergy.2020.115197.
[18] Cooper W, Roccatagliata F, Comodi G, Bartolini A, Nadeem A, Ragni L, et al. Multi Utilities Smart Energy GRIDS WP1 – “Synergies between grids and MUSE GRIDS technologies assessment” D1. 1 – “Catalogue for technologies that enable grid interactions.” 2022.
[19] Yue M, Lambert H, Pahon E, Roche R, Jemei S, Hissel D. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. Renew Sustain Energy Rev 2021;146:111180. https://doi.org/10.1016/j.rser.2021.111180.
[20] Koirala BP, Koliou E, Friege J, Hakvoort RA, Herder PM. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. Renew Sustain Energy Rev 2016;56:722–44. https://doi.org/10.1016/j.rser.2015.11.080.
[21] Green Tech Cluster. Local Energy Communities. Green Tech Magazine 2018;16.
[22] Doubleday K, Hafiz F, Parker A, Elgindy T, Florita A, Henze G, et al. Integrated distribution system and urban district planning with high renewable penetrations. Wiley Interdiscip Rev. Energy Environ 2019:8. https://doi.org/10.1002/WENE.339.
[23] Dal E, Carraro G, Volpato G, Lazzaretto A, Danieli P, Co EM. A multi-criteria approach to optimize the design-operation of Energy Communities considering economic-environmental objectives and demand side management. Energy Convers Manag 2022;263:115677. https://doi.org/10.1016/j.enconman.2022.115677.
[24] Foiadelli F, Nocerino S, Di Somma M, Graditi G. Optimal Design of der for Economic/Environmental Sustainability of Local Energy Communities. In: Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018; 2018. https://doi.org/10.1109/EEEIC.2018.8493898.
[25] Mehleri ED, Sarimveis H, Markatos NC, Papageorgiou LG. A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level. Energy 2012;44:96–104. https://doi.org/10.1016/j.energy.2012.02.009.

[26] Vu BH, Husein M, Kang HK, Chung IY. Optimal Design for a Campus Microgrid Considering ESS Discharging Incentive and Financial Feasibility. JEET 2019;14: 1095–107. https://doi.org/10.1007/S42835-019-00142-9.

[27] Comodi G, Bartolini A, Carducci F, Nagaranjan B, Romagnoli A. Achieving low carbon local energy communities in hot climates by exploiting networks synergies in multi energy systems. Appl Energy 2019;256:113901. https://doi.org/10.1016/j.apenergy.2019.113901.

[28] Ren H, Gao W. A MILP model for integrated plan and evaluation of distributed energy systems. Appl Energy 2010;87:1001–14.

[29] Klemm C, Vennemann P. Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. Renew Sustain Energy Rev 2021;135:110206. https://doi.org/10.1016/j.rser.2020.110206.

[30] Chang M, Thellufsen JZ, Zakeri B, Pickering B, Pfenninger S, Lund H, et al. Trends in tools and approaches for modelling the energy transition. Appl Energy 2021: 290. https://doi.org/10.1016/j.apenergy.2021.116731.

[31] Wirtz M, Hahn M, Schreiber T, Müller D. Design optimization of multi-energy systems using mixed-integer linear programming: Which model complexity and level of detail is sufficient? Energy Convers Manag 2021;240:114249. https://doi.org/10.1016/j.enconman.2021.114249.

[32] Pfenninger, Stefan and Pickering B. Calliope: a multi-scale energy system modelling framework. The Journal of Open Source Software n.d.

[33] Heussen K, Koch S, Ulbig A, Andersson G. Energy storage in power system operation: The power nodes modeling framework. IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT Europe 2010:1–8. https://doi.org/10.1109/ISGTEUROPE.2010.5638865.

[34] Calliope n.d. https://calliope.readthedocs.io/en/stable/index.html (accessed December 8th, 2022).

[35] Hunter K, Sreepathi S, DeCarolis JF. Modeling for insight using Tools for Energy Model Optimization and Analysis (Temoa). Energy Econ 2013;40:339–49. https://doi.org/10.1016/J.ENECO.2013.07.014.

[36] Lombardi F, Pickering B, Colombo E, Pfenninger S. Policy Decision Support for Renewables Deployment through Spatially Explicit Practically Optimal Alternatives. Joule 2020;4:2185–207. https://doi.org/10.1016/j.joule.2020.08.002.

[37] GeoPandas 0.12.1 — GeoPandas 0.12.1+0.g195f70b.dirty documentation n.d. https://geopandas.org/en/stable/ (accessed December 8th, 2022).

[38] Renewables ninja n.d. https://www.renewables.ninja/.

[39] Melaina M, Antonia O, Penev M. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. Contract 2013;303:275–3000. https://doi.org/10.2172/1068610.

[40] SNAM S.p.A. SNAM: HYDROGEN BLEND DOUBLED TO 10% IN CONTURSI TRIAL n.d. https://www.snam.it/it/media/news_eventi/2020/Snam_immissione_sperimentale_idrogeno_Contursi_raddoppiata.html.

[41] HyDeploy. HyDeploy Project. 2018.

[42] Haeseldonckx D. Concrete transition issues towards a fully-fledged use of hydrogen as an energy carrier. 2009.

[43] SNAM S.p.A. Attachment 11 / a Technical Specification of the Chemical-Physical Characteristics and of the Presence of Other Components in Natural Gas and Biomethane 2007.

[44] Quintino FM, Nascimento N, Fernandes EC. Aspects of Hydrogen and Biomethane Introduction in Natural Gas Infrastructure and Equipment. Hydrogen 2021;2: 301–18. https://doi.org/10.3390/hydrogen2030016.

[45] ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale. Fattori di emissione atmosferica di gas a effetto serra nel settore elettrico nazionale e nei principali Paesi Europei. 2019.

[46] Zimmerman AH. Self-discharge losses in lithium-ion cells. IEEE Aerosp Electron Syst Mag 2004;19:19–24. https://doi.org/10.1109/MAES.2004.1269687.

[47] Rohland B, Eberle K, Ströbel R, Scholta J, Garche J. Electrochemical hydrogen compressor. Electrochim Acta 1998;43:3841–6. https://doi.org/10.1016/S0013-4686(98)00144-3.

[48] European Association for Storage of Energy. Lithium-ion Battery Report. 2016.

[49] Gallardo FI, Monforti Ferrario A, Lamagna M, Bocci E, Astiaso Garcia D, Baeza-Jeria TE. A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan. Int J Hydrogen Energy 2020. https://doi.org/10.1016/j.ijhydene.2020.07.050.

[50] IRENA. GREEN HYDROGEN COST REDUCTION. 2020.

[51] ARERA - Andamento del prezzo del gas naturale per un consumatore domestico tipo in regime di tutela n.d. https://www.arera.it/it/dati/gp27new.htm (accessed December 8th, 2022).

[52] Jin L, Monforti Ferrario A, Cigolotti V, Comodi G. Evaluation of the Impact of Green Hydrogen Blending Scenarios in the Italian Gas Network: Optimal Design and Dynamic Simulation of Operation Strategies. Renewable and Sustainable Energy Transition 2022;2:100022. https://doi.org/10.2139/ssrn.3957992.