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Simulation of Energy Scenarios for the Transition of an Urban Neighborhood into a Renewable Energy Community

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ABSTRACT

The design of renewable energy communities requires multi-disciplinary approaches to identify the most promising solutions from technical, economic, and environmental perspectives. Indeed, different simulations tools can be adopted, ranging from urban modelling to energy planning methods. In this framework, this research focused on the Santa Chiara district in Trento, Italy, to assess the performance of different decarbonization strategies, encompassing fossil and renewable energy systems. To achieve this goal, the district energy balance, CO_2 emissions, total costs, and impact of incentives for energy communities were analyzed for each scenario. Furthermore, the effects of current and future hot climatic conditions were investigated, coupling urban building energy modelling (*umi*) and energy planning codes (*EnergyPLAN*).

Results highlighted major modifications to the energy balance of the district due to climate change, with an important increase of space cooling needs. Heat pumps coupled with photovoltaic and solar thermal panels were identified as the most suitable solution, effectively contributing to the transformation of the considered district into an energy community. Finally, the adopted methodology pointed out the relevant role played by different calculation tools when used in an integrated workflow, allowing for a more comprehensive understanding of the available urban decarbonization strategies and more robust design choices.

Keywords

Renewable energy community;
Energy planning;
umi;
EnergyPLAN;
Climate change

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1. Introduction

In order to reach the goals defined in the Paris Agreement, the European Commission proposed in 2019 the "*Green Deal*", which is an extensive array of policies and strategies aimed at achieving a sustainable and carbon-neutral European economy by 2050 [1]. Among the various sectors involved in these decarbonization initiatives, buildings emerge as pivotal, since they are responsible for 36% of greenhouse gas emissions and represent 40% of overall energy consumption in the European Union (*EU*) [1,2]. Specifically, in order to achieve the goals of the European Commission, it is necessary to reduce the final energy uses for space heating and cooling by 18%, respectively, and to cut greenhouse gas emissions by 60% by 2030 [3]. However, with a meager 0.2% rate of annual renovations to the existing European building stock, new efforts are clearly necessary in order to fulfil the decarbonization

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targets of the European Commission [4]. For example, the "*Renovation Wave*" aims to double the annual rate of deep renovations by 2030 [3,5]. To foster this "*Renovation Wave*", the European Parliament and the Council of the European Union promoted the implementation of different subsidization policies and new legislative strategies, such as those related to renewable energy communities [6]. Indeed, tackling the problem of deep renovation of buildings and local generation of renewable energy at district level can represent an effective solution to get closer to the long-term European goals.

From an operative perspective, however, the design of a renewable energy community from the renovation of an existing urban district can be a challenging task, requiring the adoption of calculation methodologies different from those conventionally used in case of single building analyses. As a first step, the energy demand has to be characterized in detail, not only at a district level but also for the individual buildings in it. Indeed, this is necessary for a more effective design of the in-situ renewable energy production, as well as storage and distribution systems. As a second step, higher spatial (e.g., installed energy production capacity in each building) and time discretization of calculations (e.g., estimates of energy generation at hourly timesteps) are required in order to ensure that the different subsystems can be successfully integrated with each other and contribute to the overall performance optimization. As a matter of fact, this approach can allow for the evaluation of mutual energy exchanges among the buildings in the district, overall self-consumption of generated in-situ renewable energy, and the definition of economically-sustainable public subsidization measures for renewable energy communities, while aiming at a global performance optimization. Furthermore, after an initial period of establishment of new renewable energy communities, the problem of their integration at a larger scale – first regional and then national, will assume a growing relevance. In this perspective, the adoption of calculation methods and approaches pursuing a global optimization since the very design of single renewable energy communities will be essential to anticipate issues which could arise in the future at a larger scale.

As regards the assessment of the building energy performance, the well-established Building Energy Modelling *BEM* approaches are hardly a feasible solution due to the many required inputs to characterize and their high computational costs if applied at a district level. For such reason, Urban Building Energy Modelling *UBEM* has recently been developed, extending the *BEM* capabilities to simulate the energy consumption of large clusters of buildings, as well as assessing issues related to interactions and interdependences among buildings and to economies of scale [7,8].

According to [9], two main groups of urban modelling tools can be found: the first one encompasses *top-down models*, which estimate the energy consumption of buildings by starting from aggregated data at a large scale, while the second one is represented by *bottom-up models*, which calculate energy consumption at the level of individual buildings and subsequently aggregate the results. *Top-down models* can be further distinguished into three subcategories - socio-econometric, technical, and physical models, depending on which main aspect is used in simulation to estimate the energy consumption of the cluster of buildings. Although these models require limited input data and can easily incorporate long-term socio-economic trends, they often lack of sufficient technical details to be effectively exploited in small-scale design applications. On the contrary, *bottom-up models* require a great amount of building-specific information and can be subdivided into data-driven or statistical models, which employ data mining and machine learning techniques to assess the energy demand of buildings, and physics-based (or engineering) models, which are based on detailed modelling and simulation techniques derived from *BEM*. Urban modelling tools available in the literature are many, as reported for instance in [10]. Among them, the Urban Modelling Interface 3.0 *umi*, developed in 2012 by the Sustainable Design Lab at the Massachusetts Institute of Technology, introduced an effective approach based on the definition of thermal "*shoeboxes*", reducing the simulation time while retaining an adequate accuracy in simulating the energy performance of buildings [11]. Even if developed for other purposes, *UBEM* tools can be employed to support the design of renewable energy communities, as done in [12].

As far as energy planning in a whole district is concerned, different codes for the energy systems analysis are available [13, 14] and many of them can be adopted for the design of a renewable energy community, exploring different aspects. Such tools, i.e., *EnergyPLAN* [15–19], *RETScreen* [20], *HOMER* [21,22], etc. can be used for the analysis of energy systems of different sizes and boundaries, encompassing both large scales (e.g., for regional and national energy planning as in [17]) and single city or district levels (as in [23]). They can be used for defining and studying different scenarios supporting the drafting of energy policies and strategies for decarbonization and transition towards renewable energy sources, assessing the impact of environmental and socio-economic factors, as well as the analysis of different energy mixes and combinations of energy production technologies. Focusing on a small and district scale, recently, attention has been paid also on the ability of such tools to model features of smart networks, including last generation district heating and cooling networks [24], as well as to simulate the exchanges between the selected system and its neighboring areas, balancing local generation and consumption [25,26]. Many examples of urban and district energy planning can be found in the literature, ranging from very large cities (e.g., Copenhagen in Denmark [27] and New York in the U.S. [28]) to groups of small settlements [29], and towns of small and medium size (e.g., Aalborg and Frederikshavn in Denmark [30,31] and Bolzano and Brixen in Italy [23,32]).

Furthermore, in a developing context of climate change, the analysis of long-term scenarios is becoming more and more important in order to assess the robustness of the proposed energy policies, as well as the need for their adaptation to a new potential environmental context. The most common approach, in this case, is to scale current data of energy demand and production, determining future trends according to projection scenarios, as done for instance for Shenzhen, China, in 2030 [33], Helsinki, Finland, in 2050 [34], and Bolzano, Italy, again in 2050 [32]. Detailed energy analyses based on future climate projections are typically not part of many codes of the energy systems analysis while they can be easily integrated into *UBEM* simulations, as done for instance in [35].

1.1 Aim and scope of the research

As described in the previous paragraphs, the optimal design and operation of renewable energy communities require the use of methods and calculation tools different from those conventionally adopted for either Building Energy Modelling or energy planning. On the one hand, indeed, an effective design requires the characterization of the energy demands of each building part of the renewable energy community, with at least an hourly time-discretization. On the other hand, the optimized design task can benefit also from a comprehensive and global perspective, typical of tools for energy planning and energy systems analysis, which can allow for aggregated energy balances exploiting those quantities generated at single building scale. Nevertheless, Building Energy Modelling tools require a level of detail of inputs often incompatible with renewable energy communities comprising numerous buildings. In that context, however, the Urban Building Energy Modelling codes, developed specifically to face the challenges of urban- and district-scale simulation, can help by simplifying the number and the types of required inputs.

Given these premises, in this research we present a workflow combining both *UBEM* and energy planning codes to design the transition of an existing district into a renewable energy community. The adopted approach allowed to investigate the impact of different decarbonization strategies encompassing several renewable energy technologies, compared in terms of energy balance, CO_2 emissions, total costs, and profitability of incentives for energy communities. Moreover, to further discuss the flexibility provided by *UBEM* simulations, the performance of different decarbonization strategies were analyzed in two climate scenarios, one of which accounting for the an increase of ambient temperature.

As an example of the implementation of the proposed workflow, we focused the Santa Chiara district in Trento, Italy, one of the case-studies considered in the Horizon Europe project InCUBE, which aims to develop tools and methodologies to accelerate the rate of deep renewal of the existing building stock to achieve the decarbonization goals of the European Commission [36–38].

2. Case-study District

The Santa Chiara neighborhood in Trento, Italy, (Figure 1) has been in a status of progressive abandonment since the end of the 1990, with social marginality, building decay, lack of space protection, and crime episodes. It is composed of:

I. five public buildings, namely buildings *B1* (floor area: 1872 m^2), *B2* (floor area: 796 m^2), *B3* (floor area: 5854 m^2), *B4* (floor area: 130 m^2), and *B6* (subdivided into three units of 5400 m^2, 1607 m^2, and 1128 m^2 of floor area, respectively),
II. a private building complex with two building units with combined residential and commercial uses, namely building *B5* (floor area: 7776 m^2), and
III. a large green space.

In 2016 the Municipality of Trento has started the *"Program for re-functionalization and sustainable reuse of the area Santa Chiara"*, involving initially buildings *B1* to *B5*, as well as the green park, and, more recently, building *B6* [39]. The main renovation activities in the Santa Chiara district, which encompass both refurbishment of the existing buildings and demolishment and reconstruction, are related to (1) the improvement of the

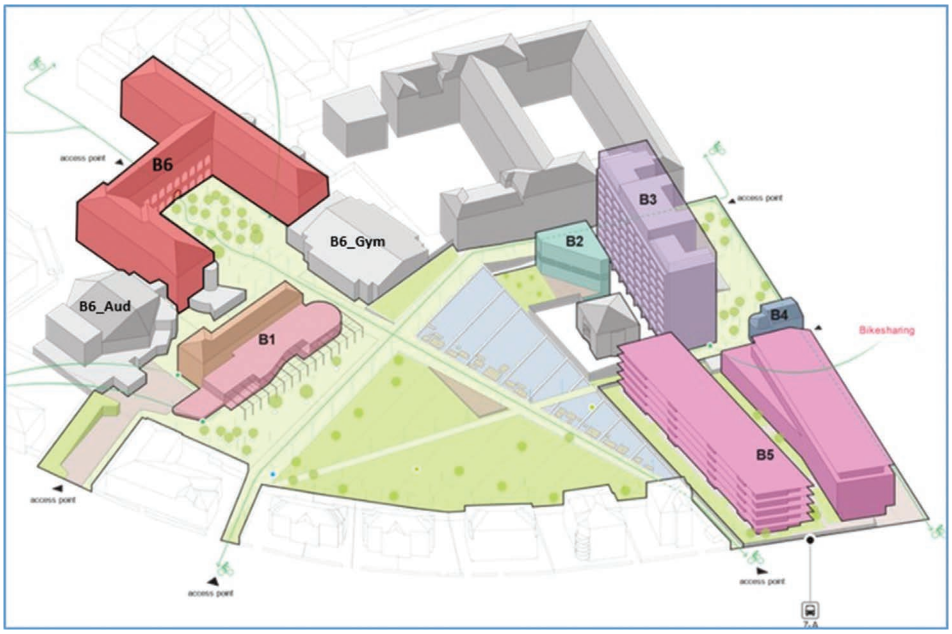

Figure 1: Sketch with the buildings involved in the Santa Chiara district deep renovation project.

Table 1: Intended use and characteristics of the building envelope of the Santa Chiara buildings according to the deep renovation plan proposed by the Municipality of Trento.

Building ID	External wall [W m^{-2} K^{-1}]	Ground floor [W m^{-2} K^{-1}]	Roof [W m^{-2} K^{-1}]	Internal partitions [W m^{-2} K^{-1}]	Internal slab [W m^{-2} K^{-1}]	Window type	Intended use
B1_Bar	0.22	0.16	0.18	0.53	1.37	Triple glazing	Community area
B1_Off	0.23	0.54	0.19	0.96	1.30	Triple glazing	Office
B2	0.21	0.23	0.20	0.70	0.51	Triple glazing	Community area
B3	0.29	0.54	0.16	0.71	0.20	Triple glazing	Office
B4	0.70	2.20	0.50	1.60	2.00	Double glazing	Community area
B5_Ret	0.18	0.80	0.20	0.71	0.20	Triple glazing	Retail
B5_Res_s	0.11	0.80	0.12	0.56	0.20	Triple glazing	Residential
B5_Res	0.11	0.80	0.12	0.56	0.20	Triple glazing	Residential
B6	0.70	2.20	0.50	1.60	2.00	Double glazing	Community area
B6_Gym	0.70	2.20	0.50	1.60	2.00	Double glazing	Community area
B6_Aud	0.70	2.20	0.50	1.60	2.00	Double glazing	Community area

Table 2: Type of systems and designed capacities according to the deep renovation plan by the Municipality of Trento.

Building unit	Heat pump (heating capacity) [kW]	Heat pump (cooling capacity) [kW]	Natural gas boiler [kW]	PV panels [kW]	Solar thermal panels [kWh]
B1	136.8	45.9	–	24.4	–
B2	108.6	–	–	6.0	–
B3	304.2	226.4	–	20.0	9620
B4	–	–	25.0	–	–
B5	145.0	165.0	163.2	43.0	77600
B6	–	120.0	1118.0	77.0	–
District	694.6	557.3	1307.6	170.4	87220

building envelope through external insulation and installation of new high-performance windows (Table 1), and (2) the installation of new *HVAC* building systems, such as heat pumps and *PV* and solar thermal panels (Table 2).

Table 1 reports the main features of the envelope of the buildings in the Santa Chiara district, as well as their intended use according to the deep renovation plan of the Municipality of Trento. Most interventions are designed to reduce the average *U*-values of external walls and roofs below 0.26 $W\ m^{-2}\ K^{-1}$ and 0.22 $W\ m^{-2}\ K^{-1}$, respectively, in agreement with the current national prescriptions for the climate zone E, i.e., the one in which the city of Trento is located [40]. As regards windows, new triple glazing windows with an average *U*-value of 1.51 $W\ m^{-2}\ K^{-1}$ and solar heat gain coefficient *SHGC* of 0.42 are chosen. As it can be seen, some of the buildings (*B4* and *B6*, which are protected under the Italian legislative framework for Architectural Heritage and Landscape) are characterized only by minor interventions to the building envelope. Indeed, the average *U*-values of the opaque elements of the building envelope are larger than those prescribed for Trento [40] and building *B4* and *B6* present double glazing (average *U*-value equal to 3.16 $W\ m^{-2}\ K^{-1}$ and *SHGC* equal to 0.60) instead of triple glazing windows.

Table 2 focuses on the systems designed by the Municipality of Trento in its deep renovation plan for the Santa Chiara district. As it can be seen in the table, although natural gas boilers still constitute the largest share of the installed capacity for space heating and domestic hot water production, the strategy adopted by the Municipality of Trento includes a significant installed capacity of heat pumps (more than half megawatt) and *PV* solar systems (about 170 kW), as well solar thermal panels expected to generate more than 87 MWh per year.

In the context of the current research, the deep renovation plan of the Municipality of Trento represents the starting point of the analysis – i.e., a Business As Usual scenario. Despite being a specific configuration, it is in agreement with the current Italian legislative framework on high-performance buildings and is representative of state-of-the-art and most widespread off-the-shelf technologies (heat pumps, fossil fuel boilers, and solar renewable energy systems). As mentioned in Section 1.1., the challenge of this work is to combine different calculation methods and tools to allow for a more in-depth assessment of alternative decarbonization strategies based of different mixes of renewable energy technologies. Since the building envelope is already highly insulated, at least where feasible, our focus was put on the active building systems, still largely supplied by fossil fuels as reported in Table 2.

3. Methods

The research follows a three-step methodology (Figure 2). The initial phase has involved collecting and analyzing building information about the district and the characterization of the local climate conditions. In the second phase, the collected inputs, along with standard variables and parameters, have been used to develop an urban building energy model of the district with the MIT software *umi*, in order to generate hourly profiles of the district energy needs. These latter ones, eventually, have been included as inputs for the preparation of an *EnergyPLAN* model, adopted to characterize the performance of different *HVAC* and renewable energy systems in terms of CO_2 emissions, energy costs, and efficacy of energy community incentives. As regards the adopted tools, *umi* and *EnergyPLAN* were both selected in consideration of the many examples of their applications in the literature, as for instance [41,42] and [15,16,19,43], respectively.

3.1 Characterization of climatic conditions

With the goal of developing an analysis also robust to long-term climate change, two climate conditions have been modelled: the first one pertains to the current typical climate conditions for Trento, while the other one is based on the identification of an extreme climate scenario which could be encountered in the future.

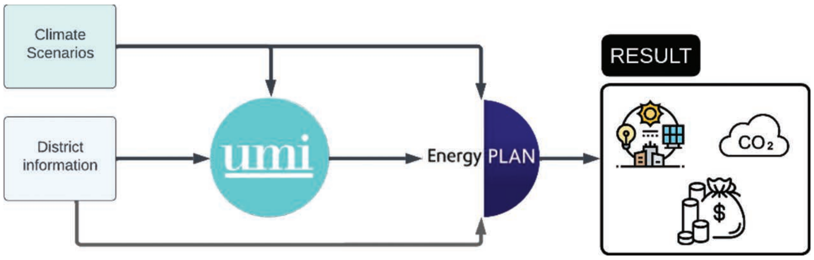

Figure 2: Study workflow.

The typical reference year TRY_{EN} made available for Trento by the *Comitato Termotecnico Italiano CTI* according to the technical standard UNI 10349-1 has been used to represent the current climatic condition [44]. On the other hand, the hot Extreme Reference Year ERY_h^I proposed in [45] has been adopted as a hot climatic condition which could be more frequently found in the future due to climate change effects. The ERY_h^I climate conditions do not refer to a specific climatologic projection and are a collection of actual historical weather data series of exceptionally hot months recorded in Trento in the last decades.

The two climate conditions, TRY_{EN} and ERY_h^I, demonstrate substantial variations in key climatic parameters. According to the TRY_{EN}, the average annual temperature is 11.2 °C, while, with the ERY_h^I, it rises to 14.9 °C. The Heating Degree Days with base-temperature of 18 °C (HDD_{18}) show a decrease from 2791 K d to 1852 K d, switching from the TRY_{EN} to the ERY_h^I weather file. Conversely, the Cooling Degree Days with the same base temperature (CDD_{18}) exhibit an opposite trend, increasing from 313 K d to 730 K d. This implies a shift in climate conditions towards a reduced demand for space heating but an increased demand for space cooling in the extreme context, which could be representative of the long-term effect of climate change. Furthermore, the ERY_h^I weather file is characterized by an annual global horizontal irradiation higher than the TRY_{EN}. file, respectively equal to 1344 kWh m^{-2} yr^{-1} and 1126 kWh m^{-2} yr^{-1}.

3.2 The developed *umi* model

The energy demand of the district has been simulated with a *umi* model (Figure 3). Although six main buildings are included in the district, due to the diverse utilization of some of them, it has been necessary to divide them into multiple blocks. More specifically, the *B1* building underwent a partitioning into two separate blocks: an office block (*B1_Off*) and a bar zone block (*B1_Bar*). Similarly, the *B5* building was partitioned into a retail zone block (*B5_Ret*) alongside two residential blocks (*B5_Res* and *_B5 Res_s*). Finally, building *B6* was separated into three distinct components: *B6*, *B6_Gym* (a gym), and *B6_Aud* (the Auditorium of Santa Chiara).

The initial step in the process has involved creating a 3D model of the buildings using Rhinoceros as a 3D modelling software. Special attention has been paid to accurately representing the relative distances between buildings to effectively evaluate shading interactions. Together with the 3D model of the district, a *umi* library has been created, characterizing building envelope elements, schedules, and other pieces of information for each building block.

The library definition process has required the creation of schedules, which serve as time-dependent representations of the building use and are related to occupancy, equipment load, Domestic Hot Water *DHW* usage, ventilation, and profiles of space heating and space cooling setpoints. Given that most of these buildings are currently not occupied and their renovation is in the construction phase, standard schedule profiles from the ASHRAE technical standards and the U.S. Department of Energy's references have been used [46].

For each building type and library schedule, distinct profiles for working days and weekends have been generated. Subsequently, the daily profiles have been grouped to prepare weekly and yearly profiles, reflecting the temporal variations in energy demand and occupant behavior over different time spans. As an example,

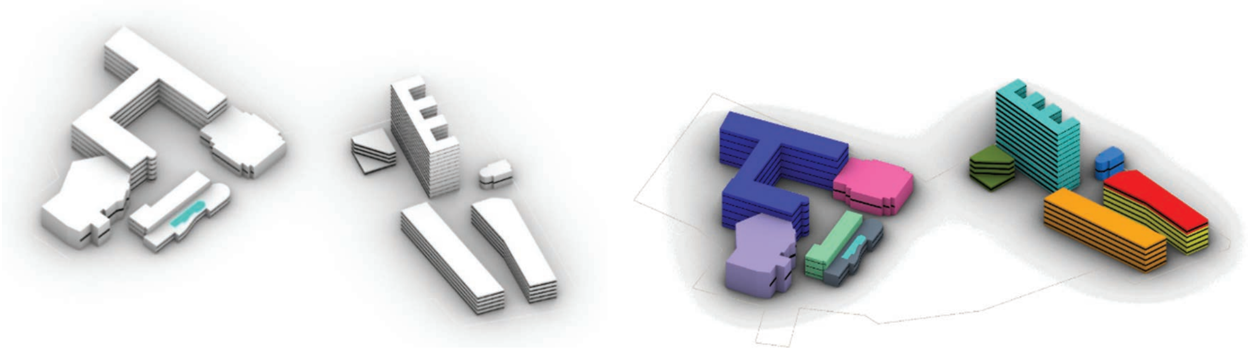

Figure 3: The *umi* model of the district.

Figure 4 shows the daily occupancy profile for the residential building.

Internal loads and *DHW* demand profiles have been sourced from the Italian technical specification UNI/TS 11300-1:2014 [47] and the ventilation airflow rates set in agreement with the minimum rates recommended by the technical standard UNI 10339:1995 [48] (Table 3). Finally, space heating and space cooling setpoints have been set equal to 20 °C and 26 °C, respectively.

3.3 The *EnergyPLAN* scenarios

In this section, the process of creating scenarios in *EnergyPLAN* to assess the environmental and economic impact of the renovated district is outlined. Besides analyzing different technologies, current and future contexts have been taken into account in the considered scenarios. While the current context focuses on technological efficiencies and costs available at the moment in the location of Trento, Italy, the future one accounts also for potential improvements in the performance of *HVAC* and renewable energy systems, as well as for changes in the economic conditions. From the climatic perspective, the current context has been matched with the current climatic condition (TRY_{EN} weather file) and the future one with the hot climatic condition (ERY_h^I weather file) described in Section 3.1.

3.3.1 HVAC systems and renewable energy technologies

As regards the *HVAC* and renewable energy systems, they have been based on the actual system configurations

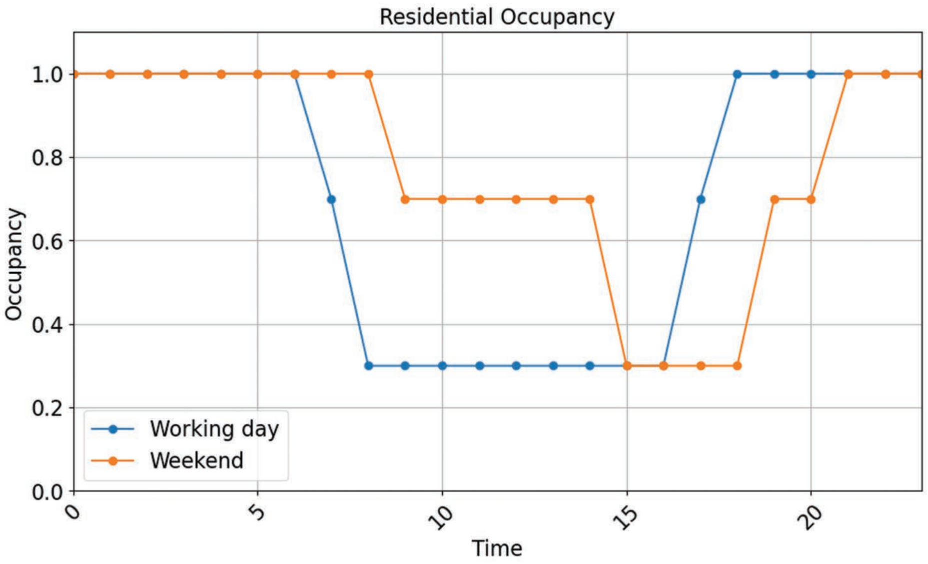

Figure 4: Occupancy profile for residential building.

Table 3: Settings of each building block.

Building ID	Occupancy density [p m^{-2}]	Internal loads [W m^{-2}]	Ventilation airflow rate [l s^{-1} p^{-1}]	DHW demand [l h^{-1} m^{-2}]
B1_Bar	0.10	10	11	0.1160
B1_Off	0.06	6	11	0.0376
B2	0.10	6	6	0.0261
B3	0.06	6	11	0.2420
B4	1.20	8	6	0.0332
B5_Ret	0.15	8	6.5	0.0592
B5_Res_s	0.03	4	11	0.0736
B5_Res	0.03	4	11	0.1160
B6	0.10	6	6	0.2040
B6_Gym	0.20	5	6.5	0.2530
B6_Aud	1.50	8	12.5	0.1160

designed by the Municipality of Trento for the deep renovation of the district as described in Section 2, with the addition of other technologies. Multiple scenarios have been defined, some of them describing the current planned configurations (Table 2) and some other ones accounting on other renewable energy technologies as shown in [49–53] for the design and optimization of renewable energy communities. As a whole, the considered heat generation systems have been (1) boilers (both natural gas and hydrogen-fueled boilers), (2) solar thermal panels, and (3) heat pumps. As regards the in-situ power production, *PV* panels represent the only feasible technology for this case-study. Furthermore, to better exploit the local *PV* generation, electrical storage technology (i.e., batteries with capacities chosen to match the power generated by the *PV* panels installed in the district, see Section 3.3.3 for more details) have also been included among the possible solutions.

The maximum *PV* installable capacity and generation yielded from solar thermal panels have been analyzed in both climate conditions described in Section 3.1 (current with the TRY_{EN} weather file and hot climatic conditions with the ERY_h^I weather file), assuming to cover all available flat or south-oriented roof areas, with the exception of the *B4* and *B6* buildings, which are listed under the national Fine Arts Commission and do not allow this kind of intervention. Since the Santa Chiara district is surrounded by other buildings with similar heights and the city of Trento is located in the Adige Valley, with significant natural obstacles on both east and west-sides, the installation of *PV* systems on the vertical façades was not taken into account in simulations. The efficiency of the panels has been also considered in determining the maximum *PV* capacity and the solar thermal generation, distinguishing state-of-the-art efficiencies (associated to the current context) and potential future improvements (accounted for in the future context). As regards the *PV* panels, it has been assumed a 20% efficiency for the current context and 22% for the future one [54]. Likewise, a +6% technology improvement is expected for solar thermal panels in the future [54]. Table 4 summarizes the maximum installed capacity of *PV* panels and the annual generation of solar thermal panels in the two different climate conditions for each building and the whole district.

3.3.2 Current and future economic contexts

EnergyPLAN facilitates the comprehensive assessment of a system's total annual cost, encompassing both actualized investment prices and running energy costs.

Each technology has been characterized by means of its Capital Expenditure (*CAPEX*), Operating Expense (*OPEX*), and lifetime, obtained from a pre-existing cost database established through prior researches on the CEIS district in the Province of Trento [29,54]. With this information, the annualized investment cost A_c has been calculated.

Energy vector costs have been computed on a per-unit basis, and, for electricity from the grid, the hourly price distribution has been considered. For the current context, running electricity costs have been computed as an average derived from the national electricity prices *PUN* observed over the last five years in the *Gestore Mercati Elettrici GME* database [55]. As

Table 4: Maximum installed capacity of *PV* panels and annual generation of solar thermal panels in the two different climate conditions.

		Current context with current climatic condition (TRY_{EN})		**Future context with hot climatic condition (ERY_h^I)**	
Building ID	**Area [m^2]**	**PV panels [kW$_p$]**	**Solar thermal panels [MWh yr^{-1}]**	**PV panels [kW$_p$]**	**Solar thermal panels [MWh yr^{-1}]**
B1	1285.2	257.0	616	289.9	884
B2	220.0	44.0	105	49.6	151
B3	269.9	54.0	129	60.9	186
B4	–	–	–	–	–
B5	2049.0	409.8	981	462.2	1410
B6	–	–	–	–	–
B6_gym	482.0	96.4	231	108.7	332
B6_aud	543.0	108.6	260	122.5	374
District	4849.1	989.8	2320	1113.8	3340

regards the year 2023, whose data are available only for the first six months, a predictive model based on the historical data of the previous five years has been adopted. The final consumer electricity price has been determined adding the dispatching and meter management costs (equal to 36% of the national electricity price, i.e., the mean value over the last 13 years in Italy), and Value Added Tax (equal to 22% [56]). A similar approach has been applied to estimate the natural gas price for the final consumer, starting from data provided by ARERA and including the current Italian taxation [56].

Regarding the future context, attributed for sake of simplicity to the year 2050 to be coherent with the *EU* reference, energy prices have been extrapolated from future scenarios outlined by TERNA and SNAM [57]. Table 5 summarizes the price values adopted in the analysis.

3.3.3 Investigated scenarios

We investigated six scenarios, differing primarily in terms of renewable capacity, storage capacity, and use of hydrogen, for both current and future climate and economic contexts:

- The Business As Usual (*BAU*) scenario emulates the system configuration described in Section 2 and presented in Table 2.
- The High Penetration *PV* (*HPPV*) scenario considers the full electrification of the heating systems through the installation of new heat pumps, along with a full potential capacity of *PV* systems presented in Table 4.
- The High Penetration Renewable (*HPR*) scenario accounts for both solar thermal and *PV* panels (Table 4); specifically, the installed solar thermal capacity aligns with the *DHW* demand, with any remaining heating requirements fulfilled by heat pumps.
- The High Penetration Hydrogen (*HPH*) scenario considers the replacement of gas boilers of the *BAU* scenario with hydrogen boilers and the maximization of the installed *PV* capacity (Table 4). Furthermore, hydrogen generation is thought to take place in-situ through electrolysis, including also a hydrogen storage unit. The capacity of the installed electrolyzer has been tailored to meet the minimum power requirements for hydrogen production and assumes an efficiency equal either to 70% (current context) or to 75% (future context). As regards the storage unit, its capacity is thought to be three times the average daily demand.
- Finally, two storage scenarios (*HPPVS* and *HPRS*) further develop *HPPV* and *HPR* scenarios, integrating electrical storages to eliminate electricity export for the district. The electrical storage has a capacity equal to the one of the installed *PV* panels in the district and it is assumed to have the same efficiency for both charging and discharging, respectively equal to 89% in the current context and to 94% in the future context. Electrical storages have a capacity of 7 and 5 MWh, respectively for *HPPVS* and *HPRS* in the current context, and of 116 and 79 MWh, respectively for *HPPVS* and *HPRS* in the future context.

A comprehensive overview of the *HVAC* and renewable energy technologies accounted for in the six different scenarios is provided in Table 6. In all scenarios,

Table 5: Energy prices.

	Unit	**Current context**	**Future context**
National electricity price *PUN*	€ MWh^{-1}	134	89
Electricity distribution cost	€ MWh^{-1}	109	163.5
Gas price	€ GJ^{-1}	22.65	17.55

Table 6: *HVAC* and renewable energy systems adopted in the different scenarios.

Scenario	**Natural gas boilers**	**Heat pumps**	**Hydrogen boilers**	**Solar thermal panels**	**PV panels**	**Electrical storage**
BAU	✓	✓	✗	✓	✓	✗
HPPV	✗	✓	✗	✗	✓	✗
HPR	✗	✓	✗	✓	✓	✗
HPH	✗	✓	✓	✗	✓	✗
HPPVS	✗	✓	✗	✗	✓	✓
HPRS	✗	✓	✗	✓	✓	✓

electricity can be exchanged among buildings, as explained in the next Section 3.3.4 as regards the assessment of the subsidization measures.

3.3.4 Simulation outputs

One of the outputs of *EnergyPLAN* simulations are the CO_2 emissions of the district, adopted in this research as a direct gauge of the advancement towards decarbonization objectives. To increase the representativeness of this metric, in addition to the *EnergyPLAN* evaluation of CO_2 emissions from fossil fuels directly burned in the district, a post-processing corrective methodology has been implemented. First, imported electricity has been distinguished into regional [54] and national [55] categories, assuming the 2021 energy mix (Table 7) as representative of the current conditions. Then, efficiency of power generation has been considered for both regional and national systems. For the former, it has been prudently approximated at 35% for the current conditions, progressing to a 40% benchmark in the future. For the latter one, instead, it has been projected to grow from 48.5% to 56% [54].

Table 7**:** National and regional primary energy mix of electricity generation adopted for current and future analyses [54,55].

National energy mix				
Conditions	**Coal**	**Oil**	**Natural gas**	**Renewable**
Current context	5.03%	0.89%	48.01%	46.07%
Future context	–	0.00%	12.00%	88.00%
Regional energy mix				
Conditions	**Import**	**Biomass**	**Natural gas**	**Renewable**
Current context	0.58%	0.73%	17.05%	81.64%
Future context	5.38%	0.75%	10.86%	83.00%

The final aspects under consideration involve the assessment of costs and energy communities' incentives. Although with *EnergyPLAN* it is currently unfeasible to calculate the amount of electricity self-consumed by individual buildings, such piece of information is integral in determining the electricity bought and sold by each building, as well as for calculating shared electricity, the associated incentives, and the network-related charges. For such reason, a post process calculation has been performed (Figure 5). First, the energy costs calculated by the *EnergyPLAN* district model have been deducted from the total costs, thereby computing only the annual expenses specifically associated with the installed systems. Then, knowing the installed capacity in each individual building, a dedicated single-building *EnergyPLAN* model has been prepared and run for each one of the buildings in the district. When present an energy storage, integration from stored energy has also occurred at individual building level. The results obtained from each single-building simulation have provided valuable insights into the patterns of electricity import and export, allowing for the calculation of the shared electricity within the

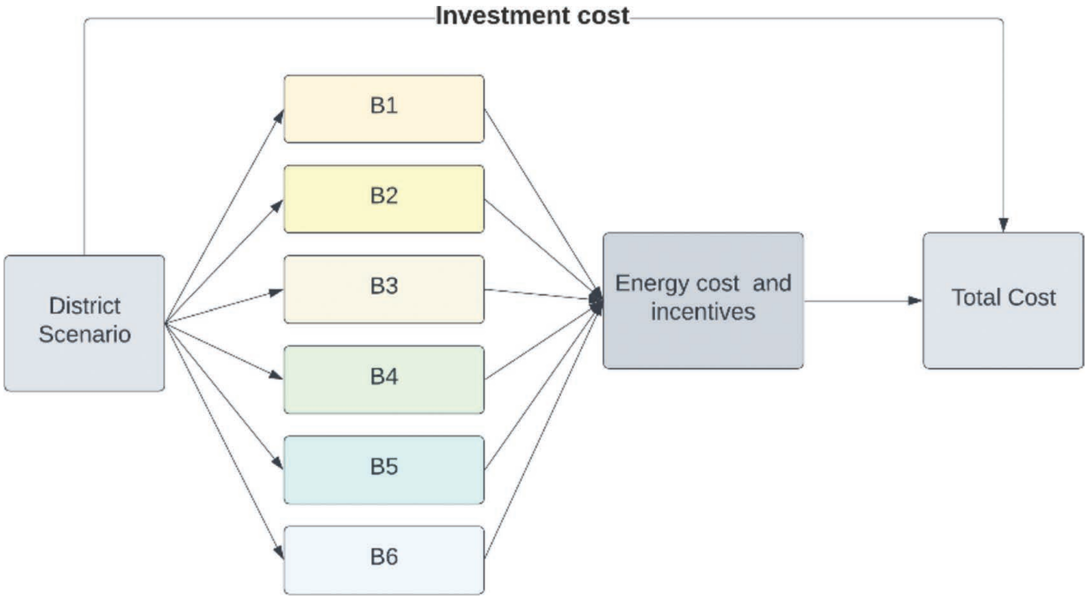

Figure 5: Energy cost post-process.

district energy community and, thus, the relevant energy community incentives.

The calculation of incentivized electricity sharing has been performed according to Equation 1, considering only electricity exchanges occurring within the same primary substation of the power grid where the Santa Chiara district is located. Electricity shared has been estimated on an hourly basis as the minimum value between the sum of the electricity exported by each k prosumer user (E_{exp}) and the sum of the imported electricity by all n members of the energy community (E_{imp}, equivalent to the hourly demand of the community) [58].

$$E_{shared} = \sum_{i=1}^{8760} min\left(\sum_{n} E_{imp\,n}, \sum_{k} E_{exp\,k} \right) \qquad \text{Eq. 1}$$

Shared electricity is valued at an incentive rate of 110 EUR MWh^{-1} for northern Italy, along with an additional valuation of approximately 9 EUR MWh^{-1} for grid loss reduction attributed to the energy community. Incentive quantities are fixed, while valuation rates are periodically updated by ARERA. In addition to the incentive mechanism, all energy injected into the grid is valued at the prevailing market rate [55,56].

4. Results and Discussion

In this section the obtained results are presented and discussed, with the same structure as in the methods: first, the *umi* simulation results are presented and, then, the findings of the *EnergyPLAN* scenarios are outlined.

4.1 *umi* results

Concerning the heating demand at district level, it reveals a substantial reduction, from 2158 MWh yr^{-1} to 1546 MWh yr^{-1} (equal to 28%), when comparing the current and the future hot climatic conditions. As expected (Table 8 and Figure 6), the buildings with the lowest energy efficiency in the district (*B1*, *B4* and *B6*) are the most affected by the different climatic conditions and show the largest decrease in the energy demand for space heating. A similar trend can be observed by

Table 8: *umi* annual energy needs and peak loads for space heating.

	Space heating needs (current climatic condition) [MWh yr^{-1}]	**Space heating needs (hot climatic condition) [MWh yr^{-1}]**	**Δ %**	**Space heating peak load (current climatic condition) [kW]**	**Space heating peak load (hot climatic condition) [kW]**	**Δ %**
B1	54.8	37.3	–32%	81.5	55.5	–32%
B2	30.8	24.7	–20%	14.5	14.2	–2%
B3	155.4	119.4	–23%	351.8	275.7	–22%
B4	16.4	9.1	–45%	12.5	10.5	–15%
B5	240.8	177.6	–26%	137.6	127.2	–8%
B6	1659.9	1178.0	–29%	1156.4	1101.5	–5%
District	2158.2	1546.0	–28%	1718.9	1375.2	–20%

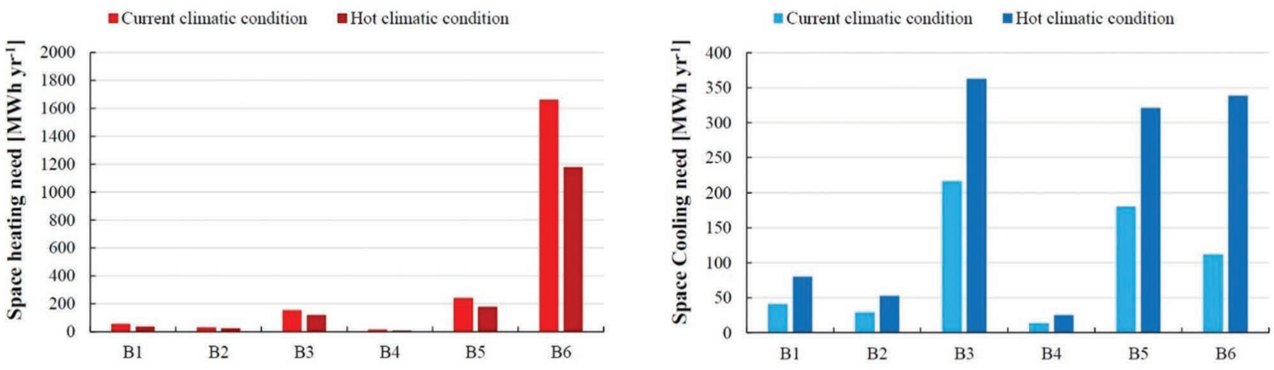

Figure 6: Space heating (left) and cooling (right) annual energy needs for the six buildings in the district, in both current and hot climatic conditions.

comparing the peak loads. *DHW* consumption, on the contrary, is the same in both climatic conditions, resulting equal to 324 MWh yr^{-1}.

As regards the cooling demand, results indicate a doubling of energy needs in the hot climatic condition, from 592 MWh yr^{-1} to 1181 MWh yr^{-1}. *B6* building, in particular, shows an increase larger than 200% due to its high ventilation requirements and its lower efficiency compared to the other buildings in the district (Table 9 and Figure 6). The cooling peak load slightly increases for all buildings, except for the *B4* building.

Electricity consumption (not for HP) remains the same in both climatic contexts. The annual consumption figures are comprehensively presented in Table 10.

The whole energy demand, as illustrated in Figure 7, indicates the growing share of the cooling needs, almost equal to those for space heating. Considering hot climatic conditions, space heating, space cooling, and electricity demands (not for HP) are expected to attain similar shares, emphasizing the need for a holistic approach. Moreover, Figure 8 shows that, while in the current climatic context space heating and space cooling peak loads are comparable, in the hot climatic context the latter ones are significantly larger. This fact, coupled with demand shifting, suggests potential variations in electricity consumption for HP throughout the year, which have been later explored in detail thanks to the *EnergyPLAN* scenarios.

Table 9: *umi* annual energy needs and peak loads for space cooling.

	Space cooling needs (current climatic condition) [MWh yr^{-1}]	**Space cooling needs (hot climatic condition) [MWh yr^{-1}]**	**Δ %**	**Space cooling peak load (current climatic condition) [kW]**	**Space cooling peak load (hot climatic condition) [kW]**	**Δ %**
B1	41.0	80.3	96%	103.8	117.9	14%
B2	29.2	52.8	81%	67.0	69.3	3%
B3	216.5	363.2	68%	408.6	521.5	71%
B4	13.6	25.0	84%	33.2	28.5	–14%
B5	179.9	321.0	78%	559.4	695.3	24%
B6	111.8	338.7	203%	603.7	962.9	59%
District	591.9	1181.0	100%	1574.4	1949.1	24%

Table 10: Annual electrical consumptions.

		B1	**B2**	**B3**	**B4**	**B5**	**B6**	**District**
Electric Consumption	MWh yr^{-1}	83.7	27.1	222.1	4.9	225.1	401.2	964.2

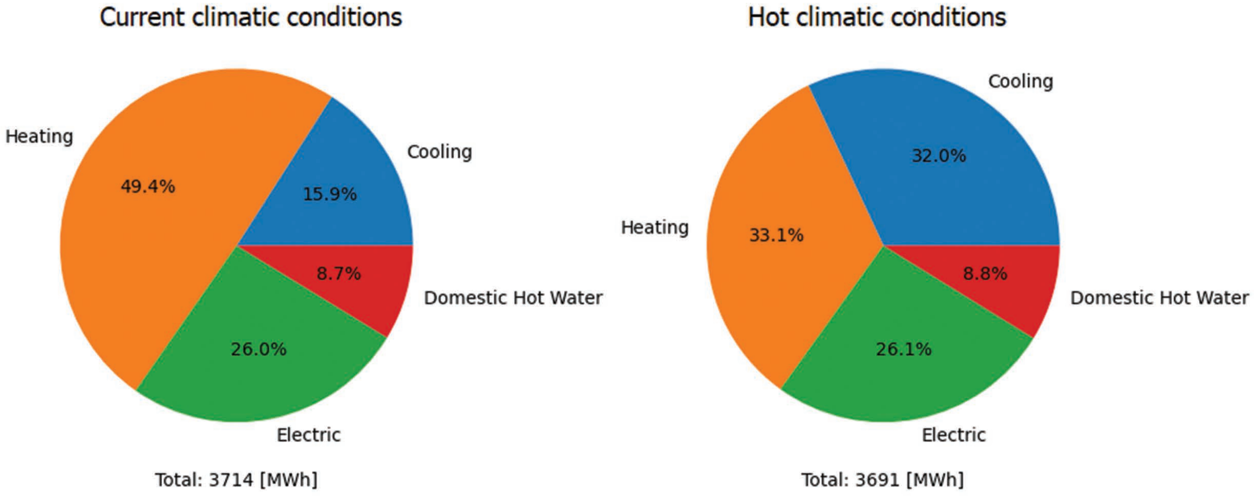

Figure 7**:** Breakdown of energy demand in both current (left) and hot (right) climatic conditions.

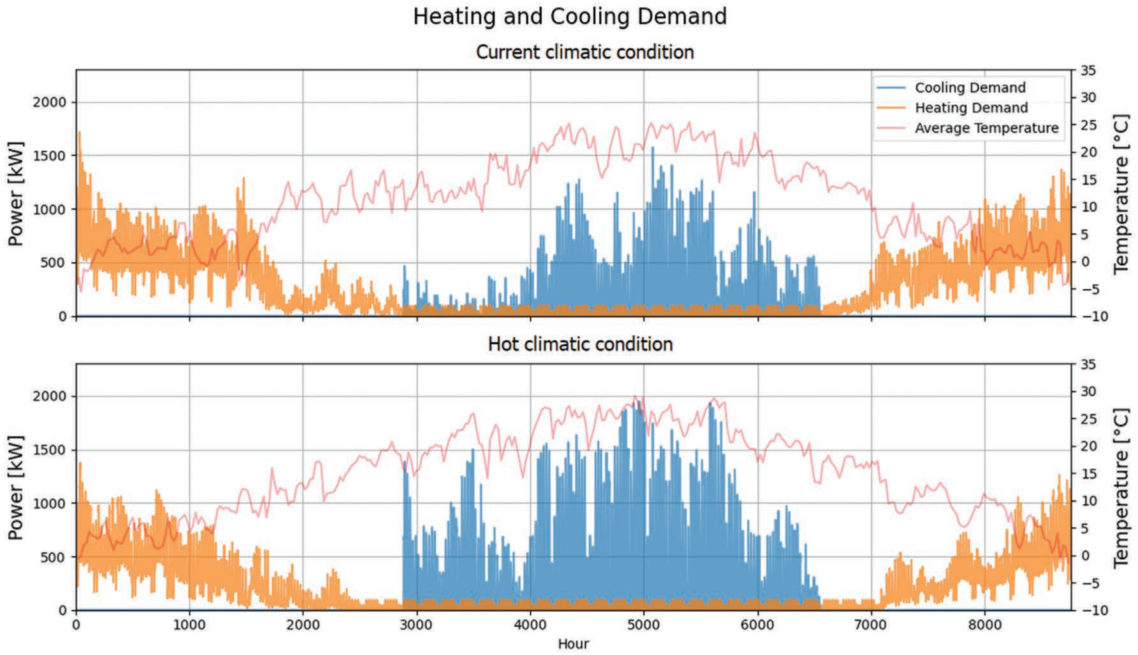

Figure 8: Hourly space heating and cooling loads in both climate conditions.

Table 11: Outputs of *EnergyPLAN* scenarios.

Scenario	Natural gas boilers [GWh yr^{-1}]	Heat pumps [GWh yr^{-1}]	Hydrogen boilers [GWh yr^{-1}]	Solar thermal panels [GWh yr^{-1}]	PV panels [kW]	Electrical storage [MWh]
			Current context			
BAU	1.453	0.749	–	0.087	170	–
HPPV	–	2.158	–	–	990	–
HPR*	–	1.836	–	0.324	834	–
HPH	–	0.749	1.453	–	990	–
HPPVS	–	2.158	–	–	990	7
HPRS*	–	1.836	–	0.324	834	5
			Future context			
BAU	1.030	0.536	–	0.087	170	–
HPPV	–	1.546	–	–	1113	–
HPR*	–	1.222	–	0.324	993	–
HPH	–	1.546	1.030	–	1113	–
HPPVS	–	1.546	–	–	1113	116
HPRS*	–	1.222	–	0.324	993	79

* Solar thermal needs a daily storage to provide the target energy

4.2 *EnergyPLAN* results

The results of *EnergyPLAN* simulations for the different scenarios are detailed in Table 11 and in Figure 9. Furthermore, the *EnergyPLAN* outputs are reported in Table 12 and in Figures 10 and 11, detailing results for both contexts and for the set of technology scenarios (12 scenarios in total).

4.2.1 Analysis of the scenarios in the current context

In the current context, the *BAU* configuration appears unfavorable due to higher CO_2 emissions due to natural gas boilers (Figure 10) and insufficient *PV* power generation, which covers a limited amount of the electrical energy demand (Figure 11). The limited export and energy-sharing aspects further imply the presence of

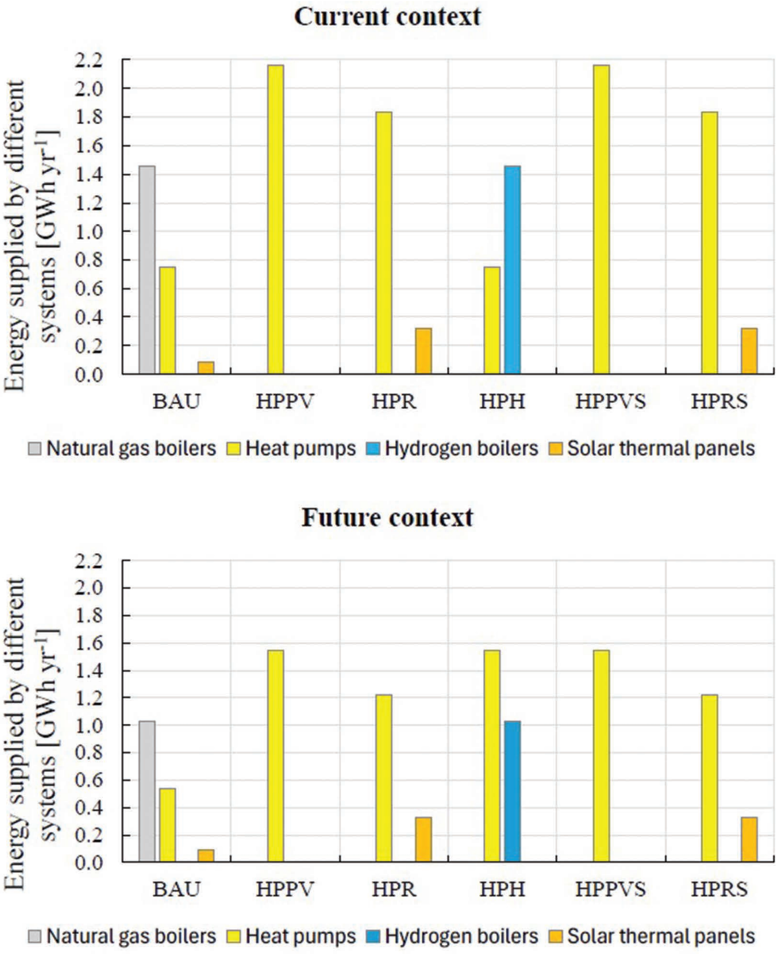

Figure 9: Energy supplied by the different technologies in the considered scenarios, for both current (top) and future contexts (bottom).

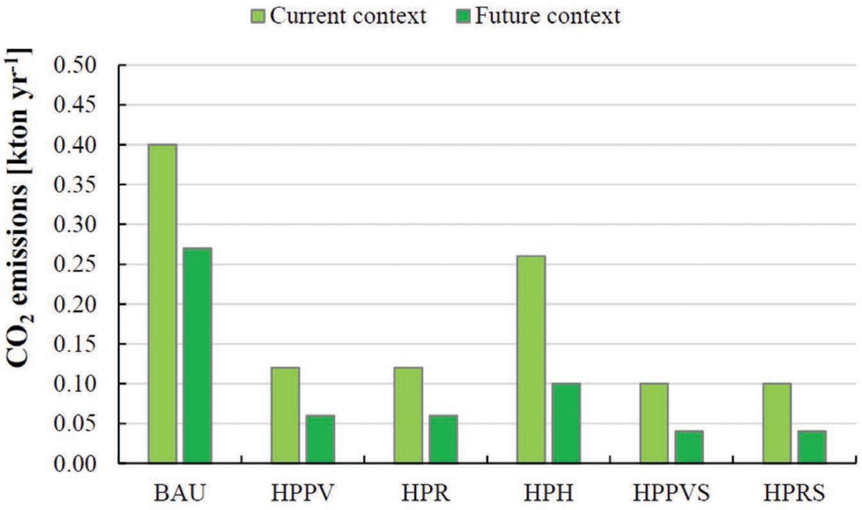

Figure 10: CO$_2$ emissions in both current and future contexts.

self-consumption by individual buildings (i.e., low energy community incentives as shown in Figure 11).

Comparing scenarios *HPPV* and *HPR* in the current context, both exhibit comparable CO$_2$ emissions, about 70% lower than the *BAU* scenario (Figure 10), with a small increase in total costs, respectively +12% and +5% (Table 12 and Figure 11). In *HPPV*, the annual *PV* power production exceeds the electrical demand for space heating and space cooling (0.83 GWh yr^{-1}). In contrast, in the *HPR* scenario in the current context, the installed *PV* capacity covers only the needs for space heating and cooling (0.77 GWh yr^{-1}), with solar thermal production able to satisfy the *DHW* needs. Despite these results, none of *HPPV* and *HPR* system configurations is able to optimally

Table 12: Outputs of the simulations of *EnergyPLAN* scenarios.

	CO$_2$ Emissions [kton yr^{-1}]	**PV power generation [GWh yr^{-1}]**	**Imported power [GWh yr^{-1}]**	**Exported power [GWh yr^{-1}]**	**Incentives [k€ yr^{-1}]**	**Electrical Net Costs [k€ yr^{-1}]**	**Other Costs [k€ yr^{-1}]**	**Total Costs [k€ yr^{-1}]**
				Current context				
BAU	0.40	0.16	1.19	0.00	0.31	265.50	219.00	484.50
HPPV	0.12	0.94	1.23	0.33	20.28	271.34	270.00	541.34
HPR	0.12	0.81	1.20	0.27	18.20	212.52	295.00	507.52
HPH	0.26	0.94	2.66	0.10	22.59	740.56	460.00	1200.56
HPPVS	0.10	0.94	0.98	0.00	9.53	266.40	944.00	1210.40
HPRS	0.10	0.81	0.97	0.00	11.17	201.69	777.00	978.69
				Future context				
BAU	0.27	0.18	1.20	0.00	0.25	289.16	137.00	426.16
HPPV	0.06	1.25	1.12	0.48	23.23	218.54	265.00	483.54
HPR	0.06	1.13	1.09	0.44	16.53	171.79	284.00	455.79
HPH	0.10	1.25	1.82	0.28	27.22	530.94	295.00	825.94
HPPVS	0.04	1.25	0.68	0.00	13.10	180.22	8526.00	8706.22
HPRS	0.04	1.13	0.69	0.00	8.51	122.16	6558.00	6680.16

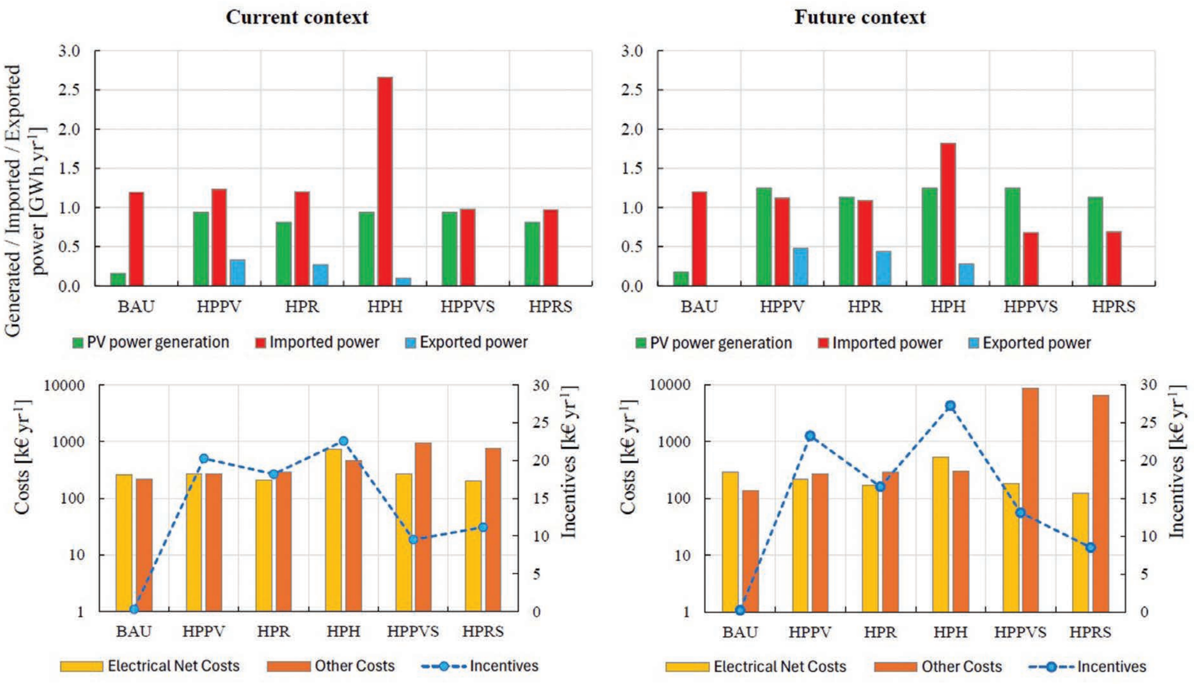

Figure 11: Generated, imported and exported power (top) and costs and incentives (bottom) for both current (left) and future contexts (right).

match electricity production with electricity demand. This mismatch can be seen analyzing export and import quantities, suggesting a potential benefit from electricity storage to harness surplus electricity (Figure 11).

HPPVS and *HPRS* scenarios in the current context can effectively leverage electricity storage to nullify district exports and subsequently minimize imports. This strategy inherently reduces CO_2 emissions (75% lower than the *BAU* scenario, as shown in Figure 10), given the renewable nature of stored energy compared to potentially emission-laden imports. However, it is imperative to note that even redistributing storage quantities among individual buildings does not wholly eliminate their district-level export, indicating the presence of complex storage dynamics. From an economic point of view, these electricity storage solutions largely amplify investment costs (Table 12 and Figure 11), although without proportionally reducing electricity costs, making them less economically convenient: indeed, total costs increase respectively by +150% and +102% with respect to the *BAU* scenario.

Moreover, also the *HPH* scenario stands out as economically unfavorable due to two pivotal factors (Table 12 and Figure 11). First, the large expenses linked with hydrogen technologies, particularly to electrolyzers and hydrogen storage units. Second, low technology efficiency drives electricity demand to 3.5 GWh yr^{-1}, almost double those of other scenarios. This very large electricity demand, along with the escalated reliance on electricity imports and the consequent CO_2 emissions, make this scenario the second least desirable in terms of its environmental impact: in fact, it leads to only 35 % less CO_2 emissions than the *BAU* scenario (Figure 10), with a large increase in total cost.

4.2.2 Analysis of the scenarios in the future context

In the future context, the *BAU* scenario represents again the worst-case scenario for CO_2 emissions (Figure 10). Indeed, despite an increase in *PV* production, the annual output only covers small part of the electricity demand. Moreover, there is a negligible energy-sharing among district buildings, largely due to substantial self-consumption patterns (which also means low energy community incentives as depicted in Figure 11). Both CO_2 emissions and total cost improve significantly compared to the *BAU* scenario in the current context (i.e., –32.5% and -12%, respectively), thanks to a lower demand for space heating to be covered with (polluting and expensive) natural gas boilers.

HPPV and *HPR* scenarios in the future climate exhibit lower total cost compared to the *BAU* scenario in the current climate conditions (i.e., -0.5% and -6%, respectively), and at the same time a remarkable -85% in the CO_2 emissions. As in the current climate conditions, also in the future climate change context these configurations do not optimally match electricity production and demand.

HPPVS and *HPRS* scenarios behave in the future context in a similar way as in the current one, with an effective leverage on energy storage to nullify district exports and minimize imports. Although they significantly reduce the CO_2 emissions (i.e., 90% lower than the *BAU* scenario in the current climate conditions), very high total costs are shown (Figure 11).

Concerning the *HPH* scenario, even if it stands out as economically unfavorable, overall, it shows a significantly better economic and environmental performance than the corresponding *HPH* scenario in the current context (Figures 10 and 11), thanks to a substantial increase in the efficiency of hydrogen technologies and lower investment and operational costs linked to an expected mass economy.

5. Conclusions

Renovation of existing districts into renewable energy communities can represent an effective approach in order to achieve the decarbonization long-term goals set by the European Commission. However, to get a comprehensive insight of the effectiveness of different solutions and technologies, multiple tools have to be adopted and several scenarios explored, accounting also for the impact of different climatic conditions. In this framework, this study has combined urban building energy modelling and energy planning codes to analyze the potential of some decarbonization strategies in the context of climate change, focusing in particular on different *HVAC* systems (i.e., gas boilers, heat pumps, hydrogen-based solutions), renewable energy systems (e.g., *PV* and thermal solar panels), as well as storage solutions (i.e., battery systems).

The Santa Chiara district in Trento, Italy, has been selected as a case-study, discussing the different proposed strategies in terms of energy balance of the district, CO_2 emissions, total costs and impact of incentives for energy communities. To this end, an Urban Building Energy Model has been developed with the *umi* software for energy needs estimation (specifically, space heating, space cooling, domestic hot water, electricity demands), at both annual and hourly scales. *EnergyPLAN* has been then adopted to simulate six different decarbonization scenarios, each one in both current and extreme future climate contexts.

umi simulations have highlighted that in both climate conditions the total amount of energy demand is approximately the same. However, even if the energy demands for electricity and domestic hot water have not changed, the breakdown of the energy balance varies significantly in the simulated context of climate change, with a 30% reduction of needs for space heating and a 100% increase of needs for space cooling.

EnergyPLAN results have emphasized a convenient replacement of traditional heat generators (i.e., natural gas boilers) with renewables-based ones (i.e., solar thermal panels and heat pumps) to decarbonize the district. Since future climate conditions indicate a shift of energy demand towards cooling, a better integration with *PV*-produced electricity is also suggested.

Despite an excess of electrical energy production, scenarios involving electrical storage and hydrogen boilers to reach a 100% renewable energy source district are economically unfeasible. Indeed, for this case study, results support the adoption of heat pumps coupled with *PV* and solar thermal panels as the most suitable approach. Furthermore, implementing an energy community in the Santa Chiara district emerged as a viable solution for maximizing electricity utilization and valorizing the related incentives.

Finally, this work underscores the significance of integrating different tools and methodologies to support urban decarbonization strategies aligned with the carbon neutrality goals set by public authorities. Considering that point, future developments could involve introducing optimization techniques for a more comprehensive exploration of optimal energy system solutions, including also measures for the building envelope.

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