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Modeling technology retrofit scenarios for the conversion of condominium into an energy community: an Italian case study.

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Abstract

This work aims to investigate what kind of impact retrofit scenarios have on ”building energy communities” in view of the European Union climate targets on CO_2 emission reduction, energy efficiency, and the share of renewable energy.

Data-driven retrofit scenarios have been simulated considering a condominium constituted by eighty-seven units, located in the North-West of Italy. Different technology mixes (including roof-top photovoltaic, air-source heat pump, battery energy storage, and electric vehicles chargers) supplying for the electric and head demands have been simulated. The techno-economic feasibility of each retrofit scenario has been evaluated along with its compliance with the EU climate target by a multi-criteria analysis. The retrofit with roof-top photovoltaic systems always leads to positive environmental and economic indicators. Besides, it also reaches the highest internal rate of return of 18.2%. The air-water heat pump helps in reducing the total primary energy demand of -26% and the CO_2 emission of -30%. Nonetheless, it introduces electric load-volatility on the electric grid that appears to be even more challenging than the photovoltaic intermittency. This issue can be conditioned by installing a storage system smoothing the heat pump load-volatility. The charge of electric vehicles within the condominium also has a global positive effect as it increasing the self-consumption up to 9.5%.

The multi-criteria analysis shows that the diffusion of condominium energy communities by itself does not guarantee the pursue of the European Union decarbonization roadmap. In fact, if the purpose of condominium energy communities is not well channeled to the citizen, by giving them other forms of incentives besides the economic ones, they might still opt for the economic benefit over the environmental one jeopardizing the potential benefit related to energy communities initiatives.

Keywords: Energy community, building, data-driven, storage, heat pump, electric vehicle.

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Nomenclature

Acronyms

EC	Energy communities
EU	European Union
IEA	International Energy Agency
JRC	Joint research center
TMY	Typical meteorological year

Indicators

CAPEX	Capital Expenditure
CO_2	Carbon dioxide emission
COP	Coefficient of performance
EE	Energy efficiency
IRR	Internal return of investment
KPI	Key performance indicators
NPV	Net present value
OPEX	Operational Expenditure
PBT	Payback-time
RES	Renewable energy sources
S.C.	Self-consumption
S.S.	Self-sufficiency
VAT	Value Added Tax

Others

F1, F2, F3	Time of Use time slots
HDD	Heating degree day
PUN	National average price
ToU	Time of Use

Technologies

EV	Electrical Vehicle
HP	Heat Pump
PV	Photovoltaic

1. Introduction

The new 2018/2001 European Union directive (RED-II) (European Union, 2018b) and the 2019/944 directive (European Union, 2019) introduce two new stake-holders in the energy market, i.e., the ”joint self-consumer”, called here condominium energy community (condo-EC), and the *energy communities* (EC). Neglecting some slight differences in the definitions provided by the two directives, the new entities promise to engage citizens in a more aware final use and production of energy. As defined within the directives, energy communities should own distributed energy generation and storage assets while users consume energy collectively. The European Union counts on energy communities for delivering the 2030 target (European Council, 2014), as energy communities are considered a key driver for the diffusion of distributed renewable energy sources technologies in the private sector, the decarbonization of the building sector and the contrast to energy poverty (Bartz and Stockmar, 2018).

The relevance of the energy communities has already been proven by their implementation in some pioneer EU countries (Strasser et al., 2018; Berka and Creamer, 2018; Brummer, 2018; Ceglia et al., 2020; Braunholtz-Speight et al., 2020), even though up to now there was no common framework for energy community among Europe. To have a figure of the impact that energy communities can have on the EU energy system, an insight arise from the German citizen energy communities where the whole electricity sales in 2016 (79 TWh) was worth as the 14th European electricity retailers (Bartz and Stockmar, 2018). On the other side, by recent calculation of the JRC (Bódis et al., 2019), the whole EU rooftop photovoltaic electricity generation is 680 TWh, which is superior to the energy sold by the 1st European electricity retailer in 2016.

The European building stock is old and energy-inefficient so that it is responsible for about 40% of EU energy consumption and 36% of the CO_2 emissions. Campaigns of retrofit and a technological upgrade are encouraged by the EU as it is also pointed out in the 2018/844 Energy Performance of Buildings Directive (European Union, 2018a). Besides, most EU citizens live in condominium buildings. In 2018, about 42% of the European citizens (EU-28) lived in flat, 23.8% of which in flats with more of 10 dwellings (EU-SILC), i.e., large condominium. From these figures, the condominium buildings appear to be the most suitable place where the mass diffusion of the energy communities can occur. Condo-EC can drive the building sector to achieve the European Union climate targets of CO_2 emission reduction, energy efficiency, and renewable energy share. Nevertheless, it is unclear what building retrofit technology mix can assure the achievement of the EU targets and benefit the citizen, the electric grid, and the member state. In this perspective, this work aims to assess what benefits are associated with the diffusion of Condo-EC, considering its economic and environmental impact with a multi-perspective approach.

In the scientific literature, energy communities have been theorized by many authors (Zepter et al., 2019; Klein and Coffey, 2016; Hicks and Ison, 2018; Bauwens and Devine-Wright, 2018; DellaValle, 2019; Long et al., 2018). A recent work of Moroni et al. (2019) reviewed critically the scientific literature addressing the problem of what is an *energy communities* with a taxonomical approach. They showed how vast and diverse is the horizon at which researchers refer with the same terminology. In this regards, our work refers to ”energy communities” in agreement with the EU 2018/2011 directive that in the framework proposed by Moroni at al. are multi-purpose placed based energy-related communities.

The topic of ”energy communities” inherits many of the findings and issues related to the smart-grid and micro-grid (Yamashita et al., 2020), but has to take into account issues related to technological and social feasibility within a market-policy framework (Jank, 2017). Many authors investigated grid and micro-grid configurations with the focus on the technological device that can enable the sharing of distributed generated electricity (Shaukat et al., 2018); as well as what are the control and optimization strategies to optimize the grid (or micro-grid) power flow (Yamashita et al., 2020); or multi-objective approach to determine the optimal capacity and type of the generation resources for microgrids (Jafari et al., 2020). Other authors focused their investigation on how generation technologies can match with the energy demand improving the self-sufficiency and self-consumption (Sousa et al., 2019). Widén et al. (2009) studied a community of 200 households, single house and multi-family, located in Sweden, analyzing how to maximize the match of the electricity generation and demand by optimizing the configuration of distributed photovoltaic array (size and orientations), demand-side management tools and energy storage, without modeling the economics. Gupta et al. (2019) investigated an eighty-two dwelling socially-deprived community equipped with photovoltaic systems to analyze the effect of installing a battery storage system for each unit on the average self-consumption; without further analyze a community energy sharing scheme. Parra et al. (2015) investigates the optimum sizing of shared storage systems for an energy community of 100 single houses in UK, equipped with only PV systems accordingly with the Zero Carbon scenario of 57% PV penetration. This study highlights the importance of the size of the community in the optimization of economic parameters and the choice of the storage system size, particularly when not all the end-users are prosumer. Some authors focused their attention on the central role that the energy storage might have in an energy community. It can enable multiple strategies to maximize the self-consumption of the generated energy or the economic outcome (Parra et al., 2017), as well as generating new opportunities for the participation of citizens and helping in increasing awareness on energy consumption and its environmental impacts (Koirala et al., 2018). Barbour and González (2018) investigated the techno-economic feasibility of a community electrochemical storage evaluating the best size considering the power flow in the United Kingdom feed-in tariff scheme and market price, but no environmental impact was evaluated.

D. Campisi (2018) use a multi-criteria analysis to determine the best heating technology for a single-family building located in south Italy. They investigate different technology scenarios comparing boiler technologies (liquid petroleum gas condensing boiler, oil boiler, pellet boiler) and air-water heat pump configurations (heat pump only, heat pump and solar panels, heat pump and PV system). The economic evaluation implements the Italian support scheme, but the analysis uses annual aggregated data and nominal efficiencies rather than a time-step simulation to analyze energy system performance.

In this work we address which technology mix can turn a condominium into an energy community while maximizing the benefits in terms of economic feasibility, impact on the distribution grid, and reduction on primary energy consumption, CO_2 emission, use of fossil fuels for electricity generation. We created a simulation framework to calculate a set of key performance indicators of different building retrofit scenarios and use a multi-criteria approach to identify the best technology configuration and the sizing of technological components.

We created a simulation framework to calculate a set of key performance indicators of different building retrofit scenarios and use a multi-criteria approach to choose the best technology configuration and the sizing of technological components.

The proposed approach is based on the use of real data from an existing condominium to simulate, with 30 minutes resolution (17520 time-steps), the yearly energy demand and supply, of different technology mix scenarios under the Italian market framework. Both the electricity and the heat demand have been modeled, evaluating eight possible retrofit scenarios using trending technologies in Italy as photovoltaic system, air-to-water heat pump, charging station for electric vehicles, and battery storage. For each technology different sizes are evaluated.

The benefits that each retrofit scenario produces on the condominium energy system have been analyzed in detail and compared to the reference electricity supply system (i.e., the electric grid). Besides, an economic analysis has been performed calculating the cash flows by using the actual capital and operational costs of the technologies, the price of the energy vectors, the direct subsidies on the capital cost and the Italian net metering tariffs for the exchange of electricity on the grid; assuming the extension of the actual policies in favor to the self-consumer also to the condo-EC. Finally, in order to identify the most beneficial retrofit scenario, a multi criteria analysis on different economic and environmental KPIs has been performed.

The case study is an eighty-seven unit condominium located in north Italy. The location was chosen for its climate, as with 2850 heating degree days it is representative of the European climate, considering that 2938 heating degree days was the average for the European Union (EU-28) (Eurostat) in 2018. For this reason, the general results of this work can be sufficiently generalized for condominium located inside the European Union.

The article is structured as follows. Section 2 describes the architecture of the simulation framework, detailing the different simulation steps and calculation blocks; the case study of a balding energy community and boundary conditions are provided in this same section. In Section 3 are presented the main results which are discussed in Section 4. Finally, Section 5 offers conclusions.

2. Material and methods

2.1. Simulation framework

This section presents the simulation framework used to simulate the different scenarios of the selected the case study. The simulation framework, represented in Figure 1, is composed of three main steps: simulation of energy demand, simulation of energy supply, computation of economic and environmental key performance indicators (KPIs). Each step, described in details in the followings, is constituted of independent simulation modules interacting one another exchanging input and output data. The simulation framework executes each Step in sequence, not in run time, i.e. running the modules and exchanging their data from left to right along the arrows in Figure 1.

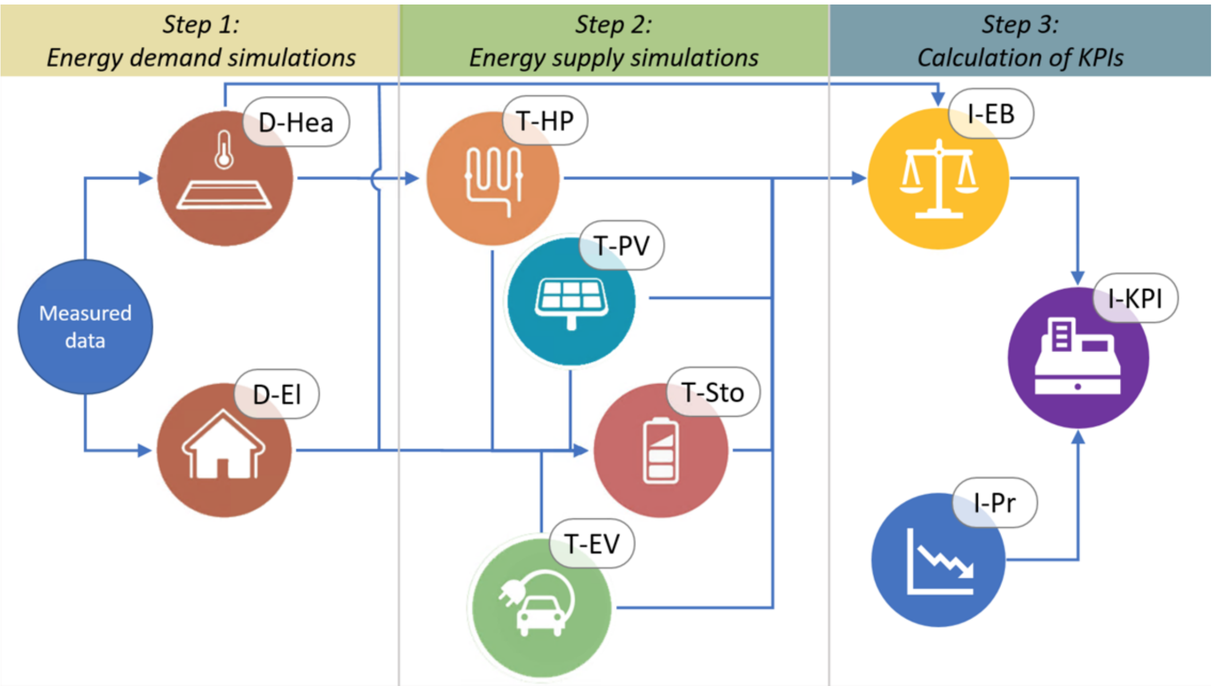


Figure 1: Scheme of the general simulation framework. The three main steps are: energy demand simulation, energy supply simulation, evaluation of the key performance indicators (KPIs). Each symbol represents a simulation module. The modules are executed in sequence from left to right, modules inter-linkage and data exchange direction is depicted by the arrows.

As this study want to assess the benefit associated to different technology mixes, the simulation framework activates only those modules that are necessary to simulate the chosen case study scenario.

The first Step of the simulation framework is constituted of two modules, D-Hea and D-Ele, which are capable of reconstructing the yearly demand curve of heat and electricity, respectively, by using the electric bills data and heat consumption measurements. Real measured data are the monthly electricity bills for each apartment and the building energy consumption for heat uses with day resolution, and with an hourly resolution for one desing month only.

The second step includes all the available technologies modules used to compose the different building retrofit scenario. T-HS is the module simulating the heating system constituted by an air-source heat pump (HP), T-PV represent the roof-top photovoltaic (PV) system, T-Sto the battery storage system and T-EV the electric vehicle (EV) charging station. For this study, the time resolution of the simulation used at Step A and Step B, is 30 minutes as a compromise between the possibility to evaluate transient effects or interactions between the different technologies and the availability of data (Salom et al., 2014).

The last step contains the I-Pr module that account for the costs of technologies, energy prices in the current market, as well as the support scheme framework in Italy; while, the I-EB module computes the energy balance for the condominium at each simulation time step; at last, the I-KPI module calculates the environmental and economic KPIs.

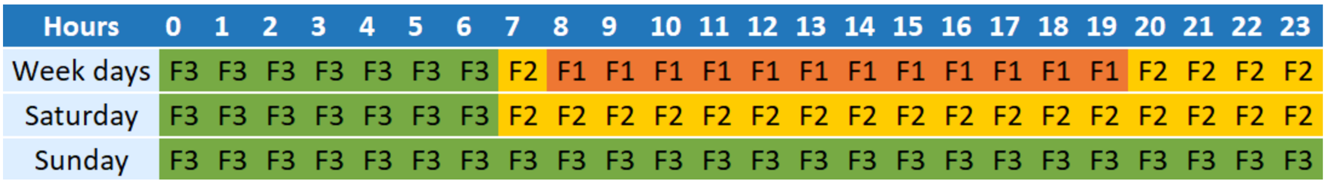
As the size of retrofit technologies is a simulation variable, for each retrofit scenario the results are obtained for different combination of technology sizes. Therefore is possible to determine thorough a multi-criteria analysis what is the size that optimize the economic and environmental KPIs.

2.1.1. Step 1: Simulation of energy demand

In this section, are presented the D-El and D-Hea modules, which are able to generate respectively the electric and heat demand curves by using real data from bills and measured data.

Module D-El: Electricity demand curve

The monthly electricity bills provide the detail on the consumption of each real user within the three Time of Use tariffs (ToU), namely F1, F2, F3, summarized in Figure 2. Therefore, it is possible to determine if the occupant has a consumption habit in using the electricity within the central hours of the weekdays (F1), rather than in the evenings and Saturdays (F2), or during Sundays and night hours (F3). The D-El module uses a database of simulated domestic electric loads (S-users), generated by the tools developed by Bottaccioli et al. (2019), to reconstruct the load curve of each occupant for the whole year with a resolution of 30 minutes, and thus the total condominium demand curve.



Hours	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Week days	F3	F3	F3	F3	F3	F3	F3	F2	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F2	F2	F2	F2
Saturday	F3	F3	F3	F3	F3	F3	F3	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2
Sunday	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3

Figure 2: Representation of the hour of the week according to the three time bands F1, F2 and F3 within the Italian ToU tariff.

The main idea of the D-El module is to compare the consumption habits of a real user (R-users) with those of a simulated user (S-users) and make the R-user inherit the S-user demand curve. The steps of this module methodology is represented in Figure 3. The assumption behind the D-El module algorithm is that if, for a specific month, two users (i.e. a real and a simulated ones) have the same electricity demand ratio F1/F2/F3, they exhibit the same demand curve.

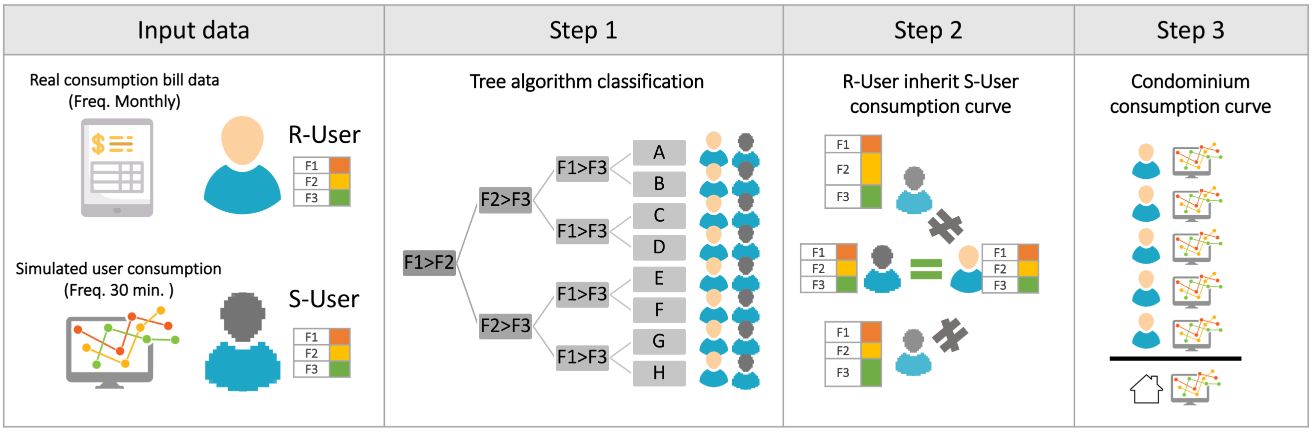


Figure 3: Scheme representing the steps of the D-El module.

In the first step, the monthly electricity consumption of both simulated and real users is classified within eight groups by using a tree algorithm. The user's ToU consumption is compared on three levels: (Level 1) F1>F2; (Level 2) F2>F3; (Level 3) F1>F3. The result is that each user, simulated or real, has a specific behavior classification for each month of the year. The high-resolution demand curve of the simulated user is aggregated on a monthly base accordingly to the ToU time slot prior to the classification.

In the second step, to each R-user is assigned the monthly demand curve of the S-user, belonging to the same ToU group, which exhibited the most similar F1/F2/F3 consumption ratio. Then, each R-user year demand curve is reconstructed month by month.

In the third step, the yearly condominium demand curve is generated by summing all the R-user's demand curve at each time step.

Module D-Hea: Heat demand curve

The D-Hea module calculates the condominium heat demand curve for a typical meteorological year. The correlation between the external temperature and the heat demand is found analyzing the available measurements of the thermal energy meter and the external temperature.

Two data sets of measurements have been considered: the hourly energy consumption for space heating and the daily one. The former has been used to identify 24 linear regressions, one for every hour of the day, for modeling the relationship between consumption and external temperature. The latter has been instead used to evaluate a segmented (or piece-wise) linear regression representing the correlation between the daily consumption and the average daily external temperature (Dotzauer, 2002). In this last case, the location of segments dividing the temperature domain is optimally found in order to minimize the least square error.

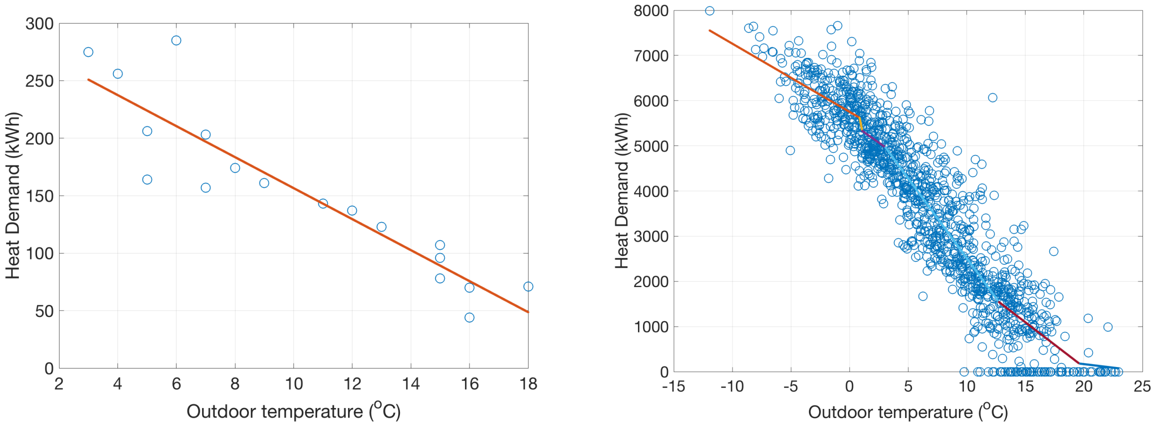
This approach allows, by using twenty-four linear regression, to reconstruct the hourly profile keeping the information concerning the time scheduling of the heating system, i.e., the on/off status. On the other hand, the segmented linear regression enables to identify the daily correction factor to re-adapt, for each day, the hourly profile of space heating according to the average daily external temperature.

In particular, $g(t)$ is a function that correlates the hourly building heating demand and the external temperature $T_{ext}(t)$ (see Figure 4-a), obtained from the hourly measurements of the thermal energy meter, as follows:

$$g(t) = \beta_0(t) + \beta_1(t) \cdot T_{ext}(t) \tag{1}$$

where $\beta_0(t)$ and $\beta_1(t)$ are the coefficients of the linear regression at a given hour t of the day. While the daily correction factor (k_d) is calculated through the function f correlating the daily heat demand and the outdoor mean daily temperature $\overline{T}_{ext,d}$ (see Figure 4b), obtained from the daily measurements of the thermal energy meter, as follows:

$$k_d = f(\overline{T}_{ext,d}) \tag{2}$$



(a)

(b)

Figure 4: Correlation between the heat demand measured data and external temperature at hourly resolution (a) and daily resolution (b). The solid lines indicate the fit function g(t).

The yearly heating demand curve is finally calculated with a time step t resolution of 30 minutes, as follows:

$$D_{Hea}(t \cdot d) = k_d \cdot g(t) = f(\overline{T}_{ext,d}) \cdot g(t), \quad t = 1, \ldots, 24 \;\; \text{and} \;\; d = 1, \ldots, 365 \tag{3}$$

The typical external temperature is obtained from the typical meteorological year (TMY) dataset imported from third-party data sources such as the Joint Research Center (Hewitt et al., 2019). They provide a set of meteorological data such as dry bulb temperature, relative humidity, direct/global/diffuse irradiance, wind speed, air pressure with hour resolution for each location. Hourly data are interpolated linearly to downsample the timeseries at 30 minute frequency.

The annual heating demand calculated for a typical meteorological year is showed in Figure 5. The D-Hea module is validated by comparing the simulated and measured heat demand between 2014 and 2017. As reported in table 1, the error is less than 5%.

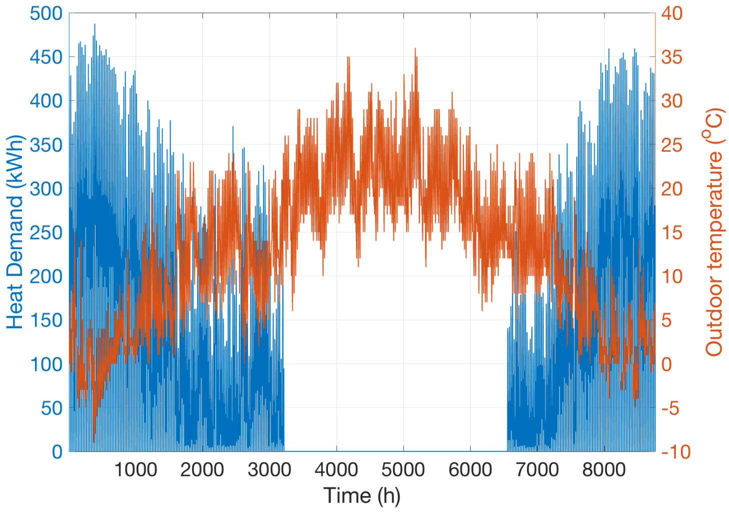


Figure 5: Simulated annual heat demand for the typical meteorological year (TMY).

Table 1: Validation of the annual heat demand simulated by the D-Hea module between 2014 and 2017.

Year	Measured consumption (MWh)	Simulated consumption (MWh)	Relative error (%)
2014	803	820	2.0
2015	848	846	0.3
2016	851	886	4.1
2017	878	865	1.5

2.1.2. Step 2: Simulation of energy supply

In this section, are presented the technologies model used in this study to investigate the condominium retrofit scenarios as a mix of the following technologies: roof-top photovoltaic (PV) system, charging station for electric vehicles, centralized heat pump (HP) and a centralized electric storage system.

Module T-PV: Photovoltaic system

The modeled PV system is a building integrated type, mounted directly on the rooftop pitch.

The size of the PV system (S) is a scenario optimization parameter that can assume values at step of 3 kW$_p$ up to cover all the available rooftop area. The total PV electricity generation (G) at the time step (t) is expressed by the equation:

$$G_{PV}(t, S) = \sum_{\alpha} G_{\alpha}(t, n_{\alpha}) \tag{4}$$

where G_{α} is the power generated by the roof pitch (α), written as:

$$G_{\alpha}(t, n_{\alpha}) = G_{1KWp}(\phi_{\alpha}, t) \times n_{\alpha} \tag{5}$$

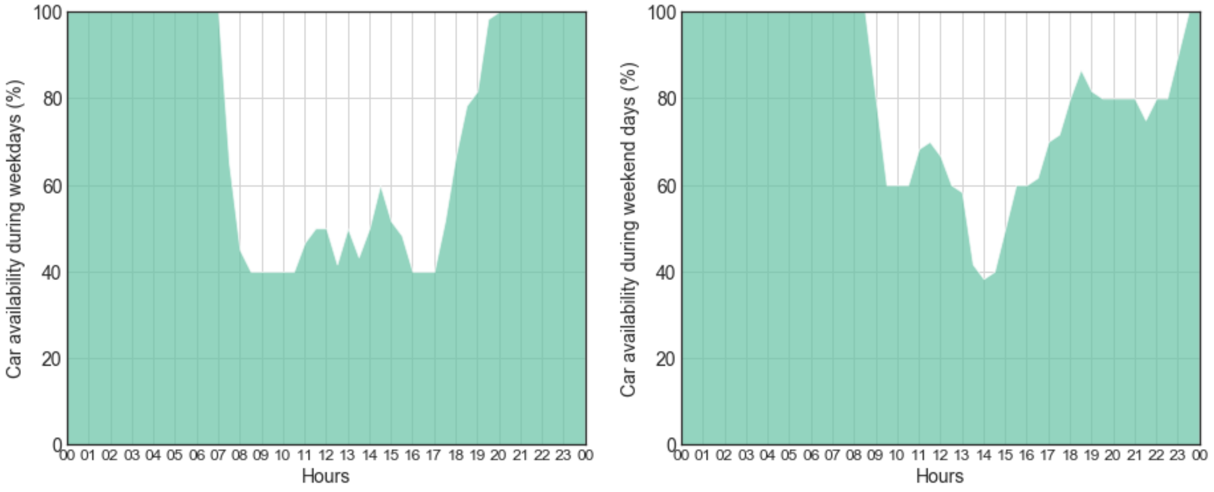
G_{1KWp} is the electricity generation of a 1 kW$_p$ module on the α roof pitch, with azimuth orientation ϕ_{α}, and n$_{\alpha}$ is the number of modules on the $_{\alpha}$ roof pitch allocated by an algorithm that distribute the total PV modules on the roof pitches by covering first the most productive ones.

The electricity generated G_{1KWp} is simulated for a TMY by using the PVGIS tool (Hewitt et al., 2019), a distributed open-source tool by the Joint Research Center. The data are gathered thorough APIs by setting the following input parameters: geographic coordinates, solar radiation database, PV technology, installed peak power, system loss, slope of the PV modules, azimuth orientation, horizon to account the terrain shadows. For more details on the simulation tool check its online documentation (EU Science Hub).

Module T-EV: Electric car charging station

The T-EV module calculates the electric profile of the electric vehicles (EVs) charge. The module uses the JRC database (Pasaoglu et al., 2012, 2014) as basis, where are reported the journeys traveled by different types of drivers living in EU countries (e.g. Italy, France, Germany, etc.), classified by the kind of trip (e.g. home-work-home or home-work-home-leisure-home) and by the type urban environment where it took place (e.g. large city, small town, rural area). Moreover, the traveling time and the distance traveled are classified for each trip as well. Through a statistical analysis presented in (Lazzeroni et al., 2019), the following information can be extracted for each EVs considered within this study: time of departure and return of the vehicle, duration of each trip, distance traveled in each journey, average vehicle speed.

By matching these information, it is possible to determine the discrete probability distribution representing the period in which each EVs is connected to the condominium charging station. Figure 6 shows the discrete probability distribution, assumed for this study, under the hypothesis that ten electric vehicles can be potentially used by the residents.



(a)

(b)

Figure 6: Discrete probability distributions of car presence during weekdays (a) and weekend days (b).

In Figure 6, a 100% of probability indicates that all electric vehicles are parked and connected to the charging stations; instead, a lower percentage represents situation where part of the EVs are travelling. The energy consumption of EV for traveling is calculated, for each trip, by using calculated average distance and other assumptions presented in Table 2.

Table 2: Average distance travelled and average consumption assumed for EVs.

Average distance weekday (km/day)	**Average Consumption (kWh/km)**	**Average distance weekend (km/day)**	**Average speed (km/h)**
30.3	0.225	62.7	40.3

The energy consumption for travelling was then used to evaluate the residual energy of the EVs battery, i.e. its State of Charge (SOC), once the vehicle come back and it is connected to the charging station. The evaluation assumes that each EV belongs to the market segment B (i.e. small cars not exceeding 4m in length), with a battery capacity of 40kWh (Thiel et al., 2014).

The electric load profile for charging each EV was finally identified assuming that each weekdays (or weekend days) has the same pathway and considering the following data:

- the period in which each EV remains connected to the charging station
- the electricity required to restore the SOC of EV batteries to 100%
- the rated electric power of the condominium charging station

In particular, since a "slow" charging process for EV has been considered in this study, the rated electrical power required during the EV charge has been set constant on the 3kW. The aggregated profile has been finally obtained summing up the charging profiles of each vehicles as shown in Figure 7. The T-EV module does not implement vehicle to grid logic; therefore, cars represent just an electric load with a specific demand profile.

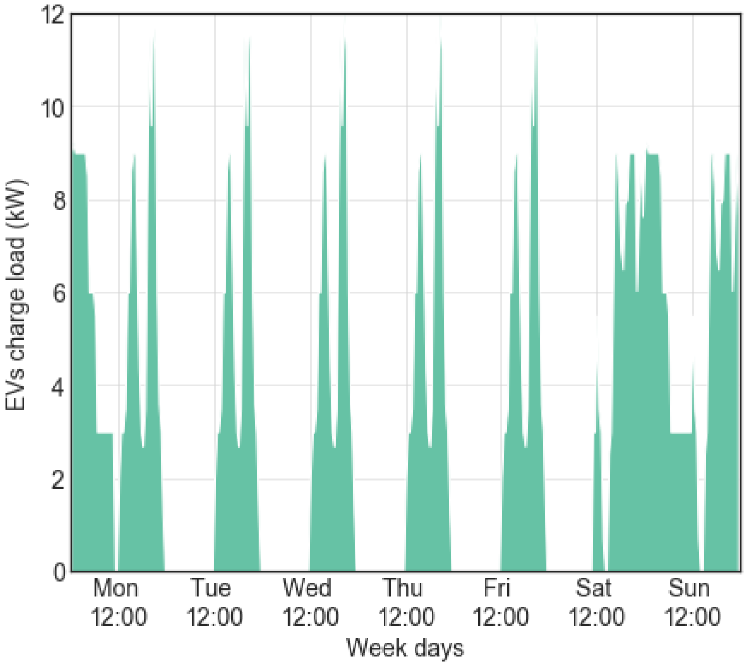


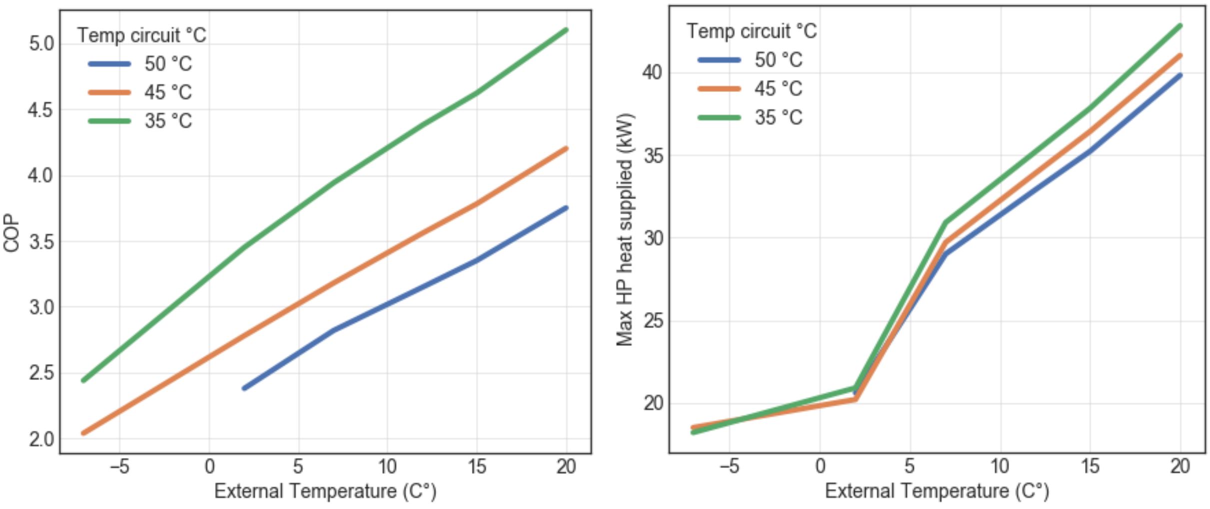
Figure 7: Weekly electric load profile of EVs charge.

Module T-HP: Centralized heat pump

The T-HP module simulates the heating system of the condominium where an air-water heat pump (HP) is installed in integration with the preexisting centralized gas boiler. The two system are mounted in parallel to switch from one another or, eventually, to be used in combination. The air-source HP was selected because of the impossibility to install a ground-source HP in the chosen case study. The HP is equipped with a R410A refrigerant and an hermetic scroll compressor.

The simulation algorithm, at each time step, matches the condominium heating demand with the heat technologies supply, giving priority to the heat pump. The gas boiler is used to complement the HP, whenever the latter is not able supply enough heat to meet the demand.

The heating system model uses the following parameters to determine the amount of heat supplied by HP: external temperature, heating circuit temperature, HP coefficient of performance (COP) curves (see Figure 8), cost of electricity, cost of methane gas.



(a) (b)

Figure 8: (a) Dependence of COP from the external temperature, for different feed stream temperature (35 °C, 45 °C, 50 °C); (b) Dependence of the maximum HP power output from the external temperature, for different feed stream temperatures (35 °C, 45 °C, 50 °C).

The heat pump COP is very sensitive to the external temperature, heating circuit temperature and load power. Therefore, at each time step, the algorithm decides whether it is more economical to run the HP rather than the gas boiler, by having a COP threshold equal to:

$$COP_{thr.} = \frac{\eta_{Boiler} \times Price_{gas}}{\eta_{HP} \times Price_{elec.}} \tag{6}$$

The size of the heat pump, nominal power, is a scenario optimization parameter, selecting the range by a preliminary analysis.

Module T-Sto: Battery storage

The T-Sto module has been used to identify the energy exchanged to the battery storage unit. An algorithm has been implemented to manage the energy fluxes according to the operational limits of the battery. The logic implemented for the battery usage establishes only one charge/discharge cycle per day to increase battery lifetime. So the following scheduling has been imposed:

- Battery is charged in case of a surplus of electricity generated by the PV system. The charge of battery using electricity withdrawn from the grid is not admitted.
- Battery discharge occurs when the PV production is zero (i.e. during nighttime), therefore, the discharge during PV production is not allowed.

The charging phase continues until the battery rated capacity is reached; similarly, the battery is discharged until energy content reaches its lower limit. The algorithm for managing the battery also verifies the energy balance at each time interval, ensuring that the State of Charge (SOC) does not exceed its rated capacity SOC_{max}, the SOC is kept within an opportune operational interval to prevent capacity loss due to depth of discharge. Then, the charge/discharge efficiencies (i.e. η_c and η_d) are taken into account, as follows (P. Lazzeroni, 2019):

$$SOC(t+1) = SOC(t) + \left[\eta_c P_{sto,c}(t) - \frac{P_{sto,d}(t)}{\eta_d}\right]\Delta t \tag{7}$$

with:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{8}$$

Additionally, the power exchanged with the battery during the charging and the discharging has been limited according to the full charge/discharge time of the battery T_c and T_d, as follows:

$$0 \leq P_{sto,c}(t) \leq \frac{SOC_{max}}{T_c} \tag{9}$$

$$0 \leq P_{sto,d}(t) \leq \frac{SOC_{max}}{T_d} \tag{10}$$

It is well known that the minimum SOC in eq. 8 (i.e. SOC_{min}) is related to the level of Depth of Discharge (DOD) assumed by the storage system (Letcher, 2016). Table 3 summarizes the value of this technical characteristics of the battery as well as the other operational characteristics assumed for this study.

Table 3: Main characteristics of the storage system considered in the study

Technology	**DOD (%)**	**Charge/Discharge efficiency (%)**	**Full charge/discharge time (h)**
Lithium-Ion	80	0.9	2

Once the battery management mode is established, the algorithm determines the optimal size of the storage system for each retrofit scenario configuration.

The battery sizing is carried out on an economic basis. For each size of the storage system, are compared the battery system cost with the savings arising from the reduction of electricity withdrawn. In Figure 9 is reported an example of the annual cash flow of a battery retrofit scenario for each size of the storage. The cost of the battery system per year is evaluated as the CAPEX (considering subsidies), divided by the number of cycles declared by the manufacturer (10K in this case) and multiplied by the number of cycles per day expected (cycles/day in this case). On the other hand, it is computed the savings associated with the electricity accumulated and self-consumed, valorized at the price of electricity withdrawn from the grid. The net cash flow maximum indicates the most profitable size for the storage system for the selected retrofit scenario.

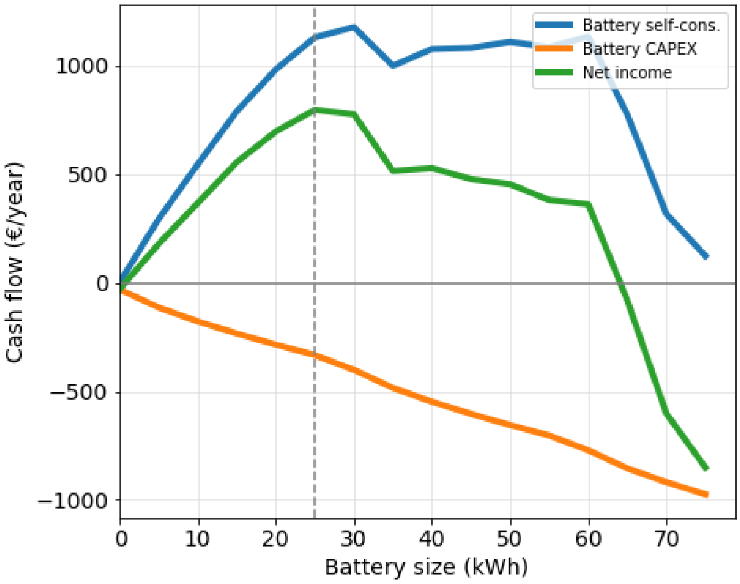


Figure 9: Example of the identification of the optimum size of the storage unit on economic basis.

Figure 9 shows how the cost of the storage system (i.e., the orange curve) increases as the size increases (i.e. according to the battery capacity). The marginal gain deriving from the use of storage (i.e. the blue curve) initially grows and subsequently decreases. This effect is due to the fact that initially the increase in size leads to an increase in marginal gain: if the size increases compared to the previous one, the marginal gain improves because it improves the battery utilization factor (i.e. the battery energy content is exploited in a ”better” way). For large sizes instead the marginal gain decreases because utilization factor worsens. Moreover, after a certain battery size the net income become negative, i.e. is not profitable.

2.1.3. Step 3: Economic and environmental KPIs

In this section, are presented the I-EB, I-Pr and I-KPI modules. The I-EB module simulates the energy flows, evaluating how the retrofit scenario changes the energy balance of the condominium. The I-Pr module computes the economics associated with the energy flows for the different retrofit configuration by using the real market price of technologies, energy vectors and supporting schemes. The I-KPI module performs a benchmark to evaluate the retrofit configuration that brings the most benefit to the environment and the investors.

Module I-EB: Simulation of the condominium energy balance

The I-EB module computes the balances of electricity and heat within the condominium, ensuring the matching between energy demand and supply at each simulation time step. In particular, at each time step, are computed the electricity self-consumed, the electricity fed into the grid, the electricity withdrawn from the grid, the electricity exchanged with the storage system (in charge or discharge), the electricity consumed by the HP to generate the heat, the gas methane used by the old boiler. Therefore the annual KPI self-consumption (S.C.) is calculated as the ratio between self-consumed and self-produced electricity, as weel as, the self-sufficiency (S.S.) is calculated as the ratio between self-consumed and total electricity demand.

In Figure 10 it is shown an example of how much of the condominium heat demand is supplied by the HP, for different sizes, and how much is the compensation of the old gas boiler. In the graph are visible situations (especially in the morning) where the HP COP is lower than its economic threshold (see 6), thus, the HP is switched off, and heating demand is covered only by the gas boiler. In other moments of the day, the heat pump is capable of supply the majority of the demand.

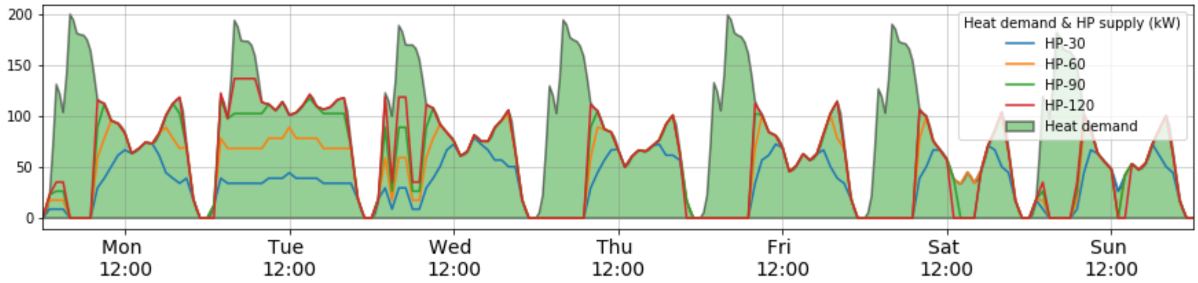


Figure 10: Heat condominium demand (green area) and heat generated by the HPs of different sizes.

On the other side, on the electric vector point of view, the generation of the PV system and electricity delivered by the batteries (during the discharge phase) is matched with the electricity demand of condominium, the EV charging station, the centralized HP and electricity absorbed by the battery during charge mode.

When either PV generation or storage energy content is not enough to satisfy the electric load demand, electricity is withdrawn from the grid. Viceversa, when a high PV production occurs and the battery storage is full, the electricity surplus is fed into the grid.

Figure 11 and 12 show two examples of the electric balance for the condominium during winter and summer seasons, respectively. During the period with minimum solar irradiance (Figure 11), the corresponding electricity demand is typically at its maximum because of heat pump that contributes to cover the heating demand. In this case, the PV production is often entirely self-consumed, and the battery is scarcely used to store the PV surplus. Therefore, most of the electricity is withdrawn from the grid.

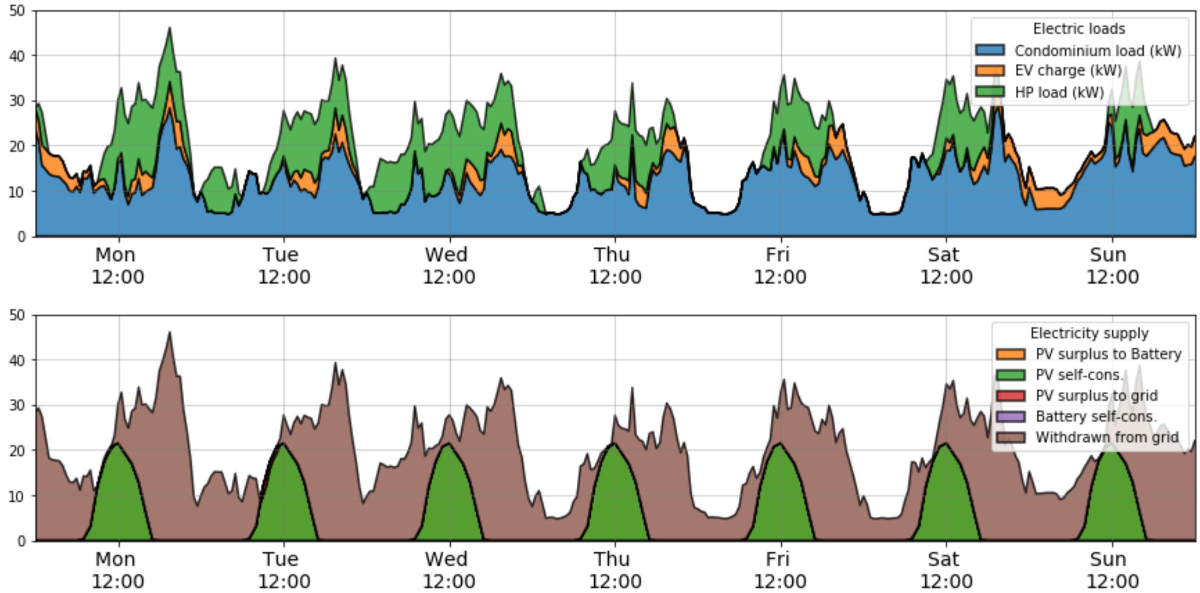


Figure 11: Electricity demand and supply during a winter week; (top) electric demand decomposed by loads; (bottom) electric supply decomposition. The PV electric generation that overcome the total demand (surplus) is firstly stored in the battery and once the battery is full it is sold to the grid.

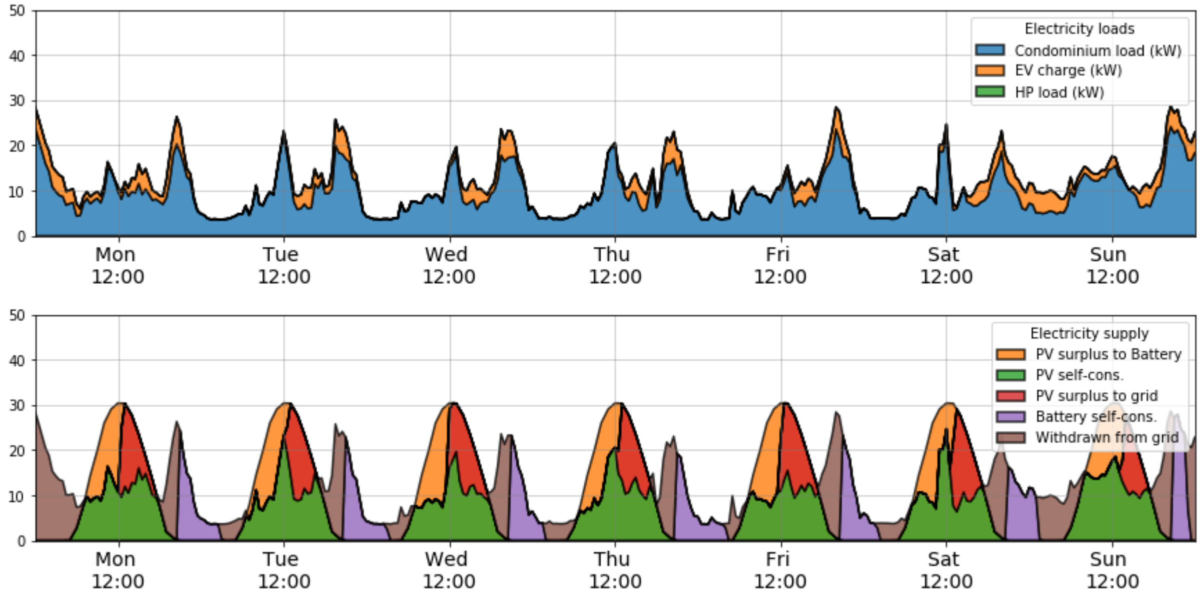


Figure 12: Electricity demand and supply during a summer week; (top) electric demand decomposed by loads; (bottom) electric supply decomposition. The PV electric generation that overcome the total demand (surplus) is firstly stored in the battery and once the battery is full it is sold to the grid.

On the contrary, in the summer season (Figure 12), the battery usage increases significantly and it is often at its maximum capacity. In this case, the PV surplus generation is fed to the grid. The stored electricity is then discharged and self-consumed during night-time.

Module I-Pr: Technology and market costs

The I-Pr module evaluates the different components of the annual cash flow associated with each retrofit scenario configuration. The cash flow components are summarized in Table 4. In the first column, the inflows components are listed. The savings from self-consumption of the PV generated electricity, calculated as avoided cost of electricity withdraw (including system charges and taxes). The saving from net-metering, calculated just on the quote of electricity that benefits of the support scheme. The revenues of the electricity sold to the grid, calculated only on the quote of electricity excluded by the net-metering scheme. The savings on the spared methane gas used by the boiler because of the usage of the heat pump. The supporting scheme on the capital expenditure (CAPEX) for the new installation associated with the specific retrofit scenario. In the second column are the outflow components. The CAPEX investment, accounted on the first year only and for the whole amount when it is paid without a loan; otherwise, it is equal to the mortgage payment. The operational expenditure (OPEX), i.e. the cost of the yearly maintenance. The insurance on the new installed equipment only. The cost of the electricity used by the heat pump to supply the heat.

Table 4: Components of the annual cash flow calculated for each retrofit scenario configuration

Inflows	**Outflows**
Saving from self-consumption	CAPEX
Saving from ”net metering”	OPEX
Revenues from electricity sold to the grid	Insurance
Saving from methane used by HP	Cost of electricity used by HP
Incentives on CAPEX	

The costs of CAPEX and OPEX associated with each technology are summarized in Table 5. On the CAPEX price, a 10% VAT is considered in the calculations. Some technologies price diminish at the increasing of the size; the price is then evaluated according to the cost-to-capacity method and using the associated cost exponent. The battery storage system has a size limit of 30 kWh for each storage module; as an example, the 50 kWh storage system is composed of two modules of 30 kWh and 20 kWh, respectively.

Table 5: Costs used in the outflow calculation, for each considered technology.

	PV system	**Battery Storage**	**EV charging station**	**HP**
Reference size	20 kW$_p$	30 kWh	1 unit	18 kWe
CAPEX	1.5 k€/kW$_p$	0.6 k€/kWh	2.8 k€/unit	1 k€/kWe
OPEX	2%	2%	-	2%
Cost exponent	-8%	-27%	0%	0%
Insurance	1.5 %/year	1.5 %/year	-	-

The implemented Italian incentives scheme (*Bonus Casa*) grants the investment on the proposed retrofit scenarios with a discount on the taxes equal to the 5% of the CAPEX for ten years.

Table 6: Mean price of the electricity and the methane gas (source ARERA) over the period 2018-2019.

	Price
Methane gas	0.555 €/Smc
Electricity	0.205 €/kWh

The I-Pr module calculates also the economic value of the electricity exchanged with the grid under the net metering scheme (known as *Scambio sul posto*). The electricity fed into the grid has an economic value equal to the hourly zonal price on the day-ahead market, while to the one taken from the grid, a value equal to the hourly national average price (PUN). The hourly zonal price and PUN used in this calculation are the average hourly price in the period 2018-2019. The value associated with the electricity and methane gas is equal to the mean price reported by the Italian regulatory authority (ARERA) over the period 2018-2019 (see table 6). No system and network charges are applied to the self-consumed generated electricity. Moreover, for a PV system below 30 kW the generated electricity is tax-free.

Module I-KPI: economic and environmental KPI

The I-KPI module is used to generate a comparison between all the simulated configuration for each scenario retrofit. The comparison is conducted trying to address the two dimensions affecting the users in choosing the desired scenario configuration: the investment profit and the environmental sustainability of the investment, seen as the intention to engage personally in solving the climate change issues.

A multicriteria analysis of environmental and economic indicator is performed. Each KPI is composed by the sum of three variables multiplied by their specific weight. The economic indicator is calculated combining the following variables: the long-term economic profit, by calculating the net present value at the 20th year (NPV); the time of return on the investment namely the payback-time (PBT); the interest on the investment by calculating the internal return of investment (IRR). On the other side, the environmental indicator takes into account the following variables: reduction of CO_2 emission (CO_2) in the residential sector; amount of electricity generated by renewable energy sources (RES); reduction of the energy consumption by increasing the energy efficiency (EE). The calculation of each variable composing the economic KPIs is well known (Matulaitis et al., 2016; Viti et al., 2020). While the methodology used to evaluate the variables composing the environmental KPI requires to be described more in detail. The CO_2 variable evaluates the savings of CO_2 emission considering the emissions associated to the electricity withdrawn from the grid (434 gCO_2/kWh for the thermoelectric production) and the emission associated to the gas methane boiler (210 gCO_2/kWh) (Istituto Superiore per la Protezione e la Ricerca Ambientale, 2020). The RES variable accounts for the amount of electricity generated by renewable energy sources (PV system) and self-consumed. The EE variable measures the reduction in primary energy supply for the building sector only. Each of these variables is expressed as a percentage reduction over the BAU scenario and are normalized to the EU targets 2030 of 32% RES penetration, 32.5% energy efficiency, and 40% reduction of greenhouse gas emissions. On the other side, the variables composing the economic KPI are normalized to the highest score registered within all the retrofit scenario configurations.

Table 7: Priority matrix and eigenvector representative of the KPIs economic (a) and environmental (b) weight.

(a)	NPV	PBT	IRR		Weight
NPV	1	1/3	5		0.38
PBT	3	1	9	→	0.39
IRR	1/5	1/9	1		0.22

(b)	RES	CO_2	EE		Weight
RES	1	1/3	3		0.28
CO_2	3	1	3	→	0.58
EE	1/3	1/3	1		0.14

To determine the variable weight, a preference matrix has been produced for each indicator (Table 7. That is a triangular matrix expressing the relative coefficient among each pair of variables. The coefficients are defined on the base of the modeler experience and perception – in this case, the authors. On the matrix diagonal are found the identities, e.g., RES= 1 x RES, elsewhere a coefficient ranging from 1/9 to 9. Afterward, the variables weight is determined by finding the eigenvectors relative to the highest matrix eigenvalue. At last, the weights are normalized to one (see ”weight” column in Table 7). Therefore the final KPIs are defined as:

$$KPI_{eco} = 0.38 \times NPV + 0.39 \times PBT + 0.22 \times IRR \tag{11}$$

$$KPI_{env} = 0.28 \times RES + 0.58 \times CO_2 + 0.14 \times EE \tag{12}$$

2.2. Case Study

The case study investigated in this work is a condominium located in Italy, in the Aosta region, at 580 m on the sea level in a submontane territory. The territory is characterized by a continental/alpine climate with 2850 heating degree day (HDD), corresponing to ”Zona E” according to the Italian classification. The yearly average temperature lies between 15.3 °C and 6.6 °C, with a thermal excursion up to 26.7°C in July and -3.2°C in January.

The condominium was built in the 60s and 70s; it is comprises of five interconnected buildings of a maximum of six floors, with about three apartments per floor, and a shared internal yard; has eighty-seven units, mainly residential apartment, 13 of which are office/shop.

The overall yearly electricity demand is about 220 MWh/year. Each unit has an independent contract with an energy retailer. On the other side, the condominium is equipped with a centralized heating system

Table 8: Selected rooftop area for the installation of the photovoltaic system on the condominium.

Index	Building Pitch	Pitch Area (m^2)	Azimuth (Degree)	Orientation
1	BC_FcS	83	0	South
2	BB_FcS	36	-16	South
3	BE_FcS	160	-16	South
4	BC_FcS2	36	-16	South
5	BB_FcW	171	72	West
6	BB_FcE	131	-109	East

powered by natural gas, with a radiant floor as a distribution terminal in each apartment/office. The total heat demand is about 850 MWh/year.

The building rooftop area available to install a PV solar system is about 620 m^2, considering just the pitches with a good orientation to the sun. In Figure 13 are visible the position, orientation and space of the different pitches, summarized in table 8.

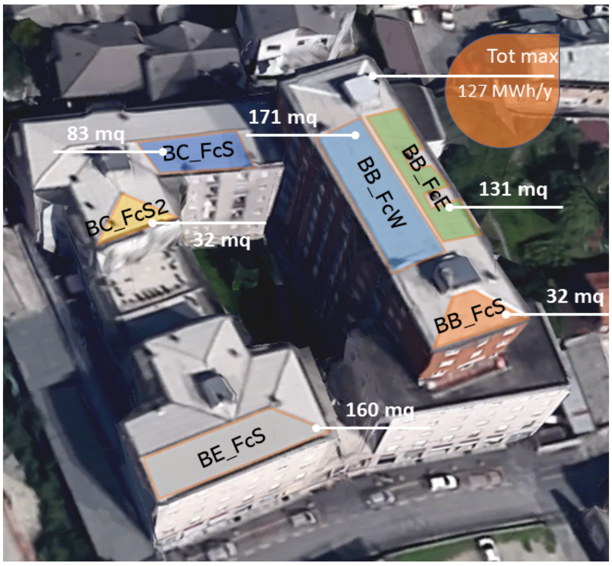


Figure 13: Aerial photo of the condominium subject matter of the case study; colored areas indicate the rooftop selected area described in Table 8

In order to evaluate the PV electricity generation with an hourly resolution, the PV-GIS application programming interface was set with the following parameters. *PVGIS-CMSAF* as solar radiation database, covering Europe and Africa 1.5 arc/min spatial resolution and an hour resolution; the PV technology is a mono-crystalline silicon module of 300 Wp nominal power and 180 W/m^2 power density; the estimated system loss is 14%; a building integrating installation with PV modules slope equal to the roof pitch, which is 30°; shadowing using the horizon height calculated by the tool itself.

The presented case study has been investigated simulating eight different retrofit scenarios, reported in table 9, in order to study the benefit arising from different technology mix.

Table 9: The investigated eight retrofit scenario. The black dot indicate the presence of a proposed technology.

Technology	S1	S2	S3	S4	S5	S6	S7	S8
PV	●	●	●	●	●	●	●	●
EV station		●	●			●	●	
HP			●	●			●	●
Storage					●	●	●	●

3. Results

This paragraph analyzes first the energy dimension of each retrofit scenario simulation, understanding how each technological configuration affects the condominium energy performance. Then, the retrofit scenarios, reported in table 9, are compared based on the economic and environmental indicators.

In Figure 14 is showed the yearly energy demand for the business as usual scenario (BAU) in comparison to those retrofit configurations that install the heat pump. The S4 retrofit scenario displays different sizes of HP. The maximum PV electricity production is indicated in the figure by a green line as a reference for the comparison. It is noticeable that more than 80% of the energy demand in the BAU scenario is supplied by the natural gas used exclusively for heating purposes.

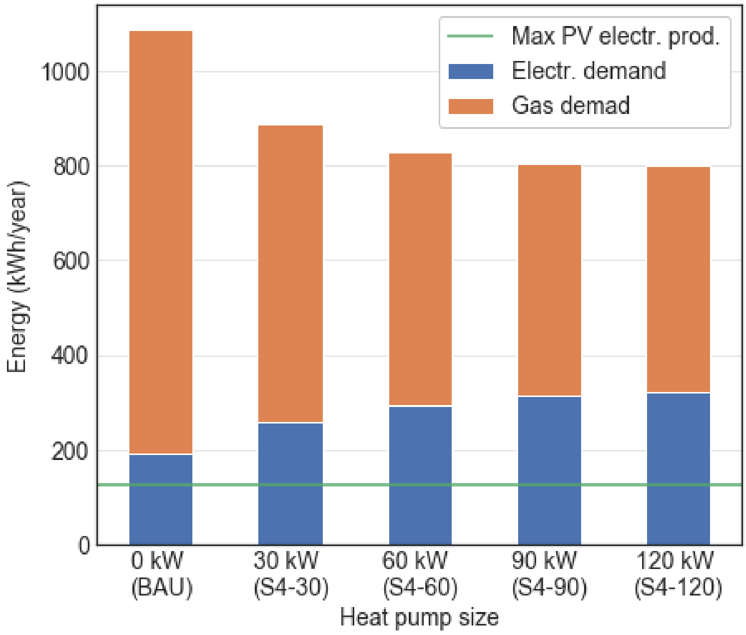
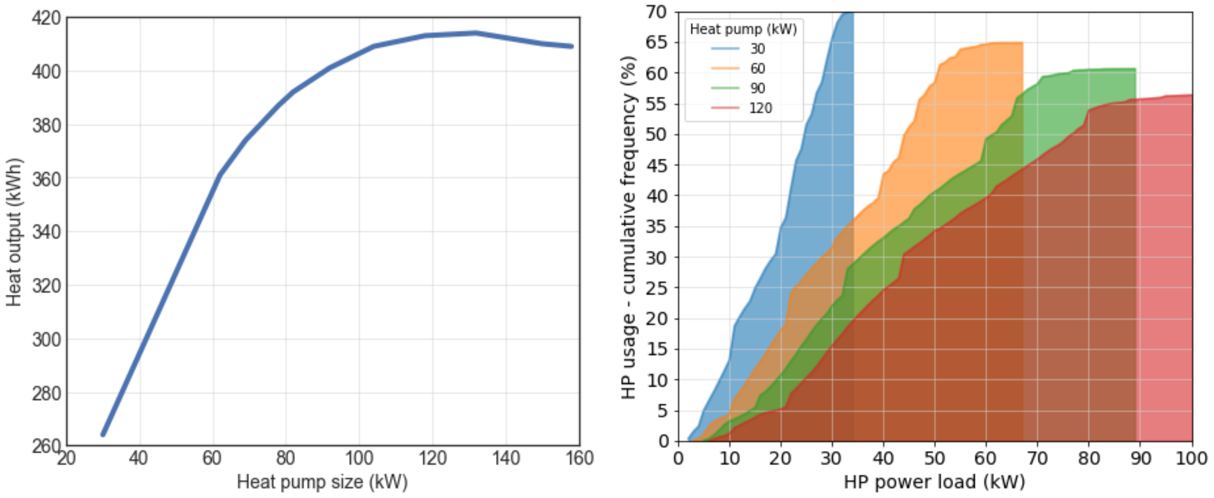


Figure 14: Condominium yearly energy demand by final use for different heat pump size; in parenthesis the corresponding retrofit scenario configuration; in green the maximum PV generated electricity ($111 kW_p$).

The overall reduction of natural gas is possible by electrification of the building's heat demand, adopting a hybrid heat pump - boiler heating system. Nevertheless, the reduction of energy demand does not vary linearly with HP capacity, as Figure 15-a presents a maximum value at 130 kW. For this value, 50% of the total heat demand is supplied by the HP, decreasing the total energy demand up to 26%. Besides, by analyzing the frequency of usage of the HP at different power loads (Figure 15-b), it



(a)

(b)

Figure 15: (a) Heat that can be delivered to the condominium by heat pump for a TMY for different size of HP; (b) HP usage cumulative frequency curve at different power loads.

is noticeable that the frequency of usage decreases from 70%, for a 30 kW_e HP, down to 56% for a 120 kW_e HP. For these reasons, it was not consider a heat pump with capacity larger than 120 kW_e in this analysis.

Air-sources heat pump might introduce unexpected and rapid variations of the electricity load. To quantify the load volatility introduced by the HP, was evaluated the displacement of the instantaneous electricity load from its average over a 3-hour time window, for each time-step. The higher the occurrence of large load-displacement value, the higher the load volatility. In Figure 16 is presented the cumulative frequency of volatility events, over the considered year, at different displacement values for the BAU, S1, S4 and S8 scenarios; in the inset, the equivalent power displacement, calculated as the sum of the load-displacement over the year.

From the inset, it is visible that the PV system alone (S1) does not change the load volatility significantly respect to the BAU scenario. On the other side, the S4-30 scenario increases the load volatility of 60% and the S4-120 one of about three times the S1 value. By analyzing the cumulative frequency, the BAU scenario shows a load-displacement of less than 5kW for 75% of the time, reaching a maximum value of 35kW. The S1 retrofit scenario also exhibits a similar trend to the BAU scenario. The S4-120 scenario shows a load-displacement within 5kW for only 50% of the time, while in the other 50% it fluctuates up to 95kW; the S4-30 instead, show 5kW load-displacement 60% of the time, and maximum displacement up to 42 kW. Therefore, the presence of the battery (S8-120) does not change the occurrence of load-displacement lower than 5kW (55%) but reduces the maximum load fluctuation down to 48kW, mitigating the load volatility.

A comparison among the different retrofit scenario is possible by analyzing their grade of energy self-sufficiency and self-consumption. Figure 17 shows the S.S. and S.C. achieved by each retrofit scenario when supplied with the maximum available PV system (111 kW_p). The S1 retrofit scenario, installing a

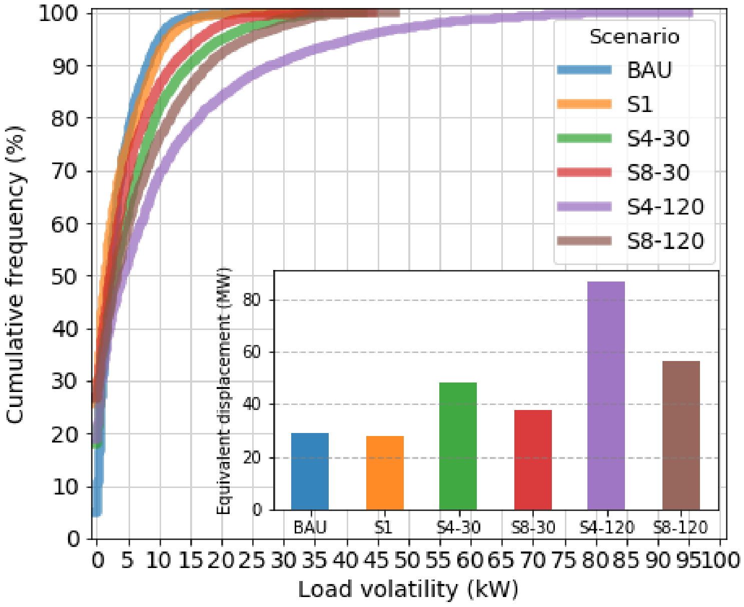


Figure 16: Cumulative frequency curve of the load volatility, expressed as displacement of the instant electric load from its average on a 3hours time windows; (inset) equivalent load displacement (sum of the load-displacement over the year) for different retrofit configurations: BAU, S1 (111 kW$_p$ PV), S4-30 (111 kW$_p$ PV and 30 kW$_e$ HP), S8-30 (111 kW$_p$ PV, 30 kW$_e$ HP and 175 kWh storage), S4-1200 (111 kW$_p$ PV and 120 kW$_e$ HP), S8-120 (111 kW$_p$ PV, 120 kW$_e$ HP and 180 kWh storage).

PV system only, reaches values of 38% self-sufficiency and 59% self-consumption. The effect of the heat pump adoption, investigated in the S3 and S4 scenarios, is a reduction of the self-sufficiency rate of about -28% (S3) and -26% (S4) respect to the S1 scenario, while the self-consumption changes by +22% (S3) and +14% (S4). A further insight is given by the color map in Figure 18 that shows how the size of the PV system and the HP influence self-sufficiency (Figure 18-a) and self-consumption rates (Figure 18-b). The cases with HP equal to zero correspond to the S1 scenario, while the HP from 30 to 120 kW$_e$ are possible configurations of the S4 scenario. The self-sufficiency increases (darker green) at the expansion of the PV size, while the self-consumption decreases (lighter blue).

The presence of electric cars, supplied thorough a shared condominium charger, has the overall effect of improving self-sufficiency and self-consumption rates. In particular, Figure 17 shows an increase of +5.5% in S.S. and +9.5% in S.C. for the scenario S2 respect to the S1, and a +2% in S.S. and +6.5% in S.C. for the scenario S3 respect to the S4. Because of the negligible electricity withdraw of cars (33 MWh/y), compared to the HP one, the self-sufficiency percent increment in the scenario S3 is understandably lower than the one without heat pump (S2).

The highest self-sufficiency value of 52.8% (+14.5 % respect to S1) is achieved in the S5 scenario by installing a storage system of 130 kWh, while the highest self-consumption value of 90% (+20% respect to S4) is achieved in the S8 scenario with a 60 kW$_e$ HP and storage of 170 kWh. The correct sizing of storage system, for each scenario, is guaranteed by the T-Sto optimization module that also simulates the interaction of the storage with the other installed technologies. In Figure 19 is showed the dependence

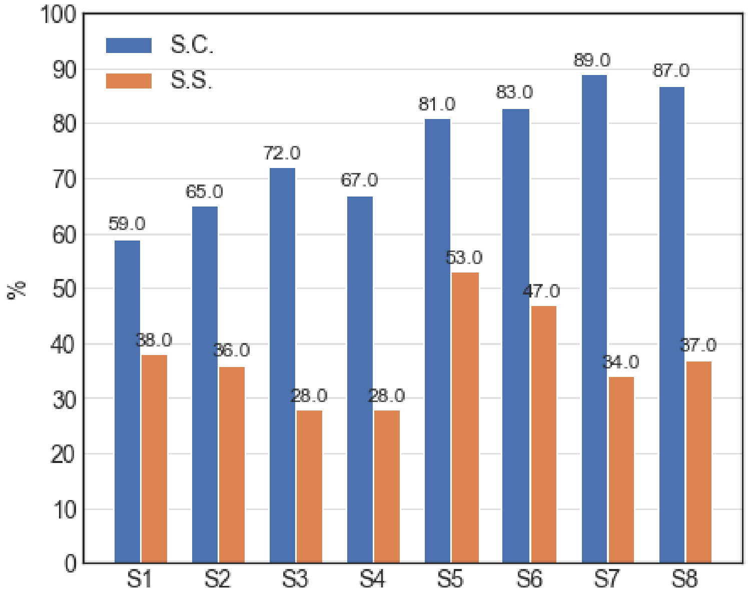
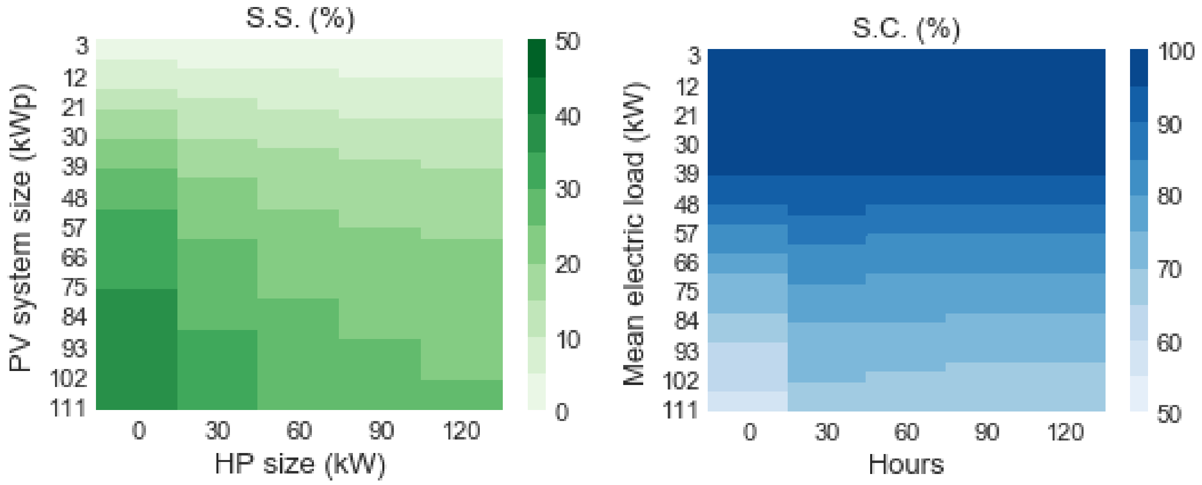


Figure 17: Self-consumption (S.C.) and self-sufficiency (S.S.) for the different retrofit scenarios (at maximum PV size) reported in Table 9.



(a)

(b)

Figure 18: (a) Self-sufficiency dependence from PV size and heat pump size; (b) Self-consumption dependence from PV size and heat pump size.

of the storage size on the PV size for the scenarios from S5 to S8.

In what follows, are examined which retrofit configurations appear more attractive by analyzing the economic and environmental KPI indicators. The components of the economic indicator are the net present value (NPV) after 20 years from the investment, the payback time (PBT) and the internal rate of return (IRR); while the environmental KPIs are the electricity demand supplied by renewable energy sources (RES), reduction of carbon dioxide emission (CO_2) and energy efficiency (EE).

Figure 20 shows the score of each retrofit scenarios by each KPI indicator. The colored circles represent for each scenario the configuration with the best score in both economic and environmental KPI (see Table 10), while the circles in grey are all the other configurations simulated by varying the

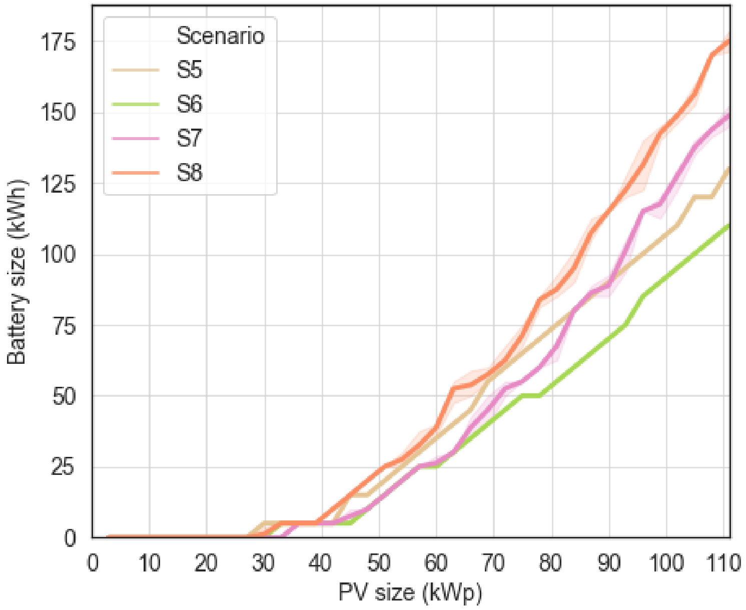


Figure 19: Sizing of the storage system for each retrofit scenario at the increasing of the PV size.

sizes of each considered technology. By looking at the graph, no retrofit scenario seems to excel in both economic and environmental KPI.

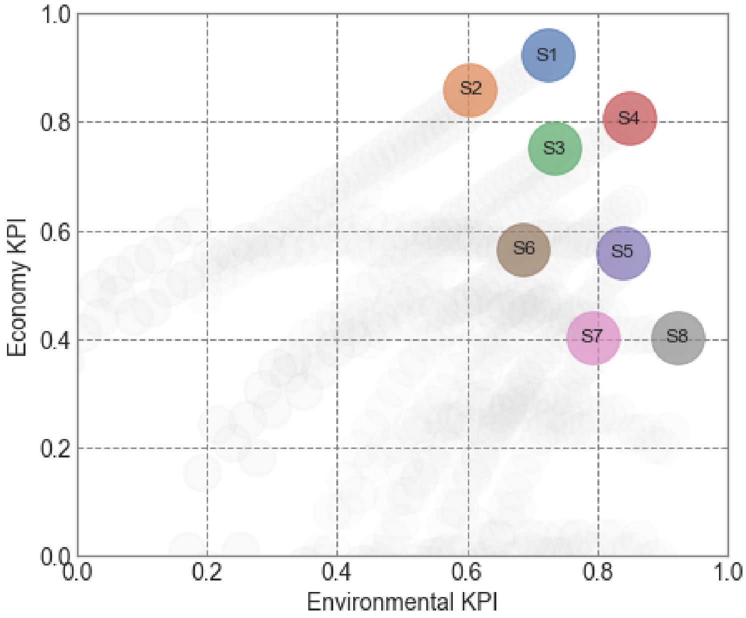


Figure 20: Comparison of the retrofit scenario scores on economic and environmental KPIs in the building sector only. In color the most performing configurations, in light grey all the other simulated configurations.

It is noticeable that the retrofit scenarios without storage (from S1 to S4) are located in the top-right corner of the plot, while those with storage (from S5 to S8) cover the middle-right part of it. The S1 scenario achieves the best scores on the economic KPI; on the contrary, the S8 scenario achieves the best score on the environmental KPI, while the S4 scenario is the one with the best trade-off among the two KPIs.

Table 11 reports the best KPIs variables scores for each scenario. The economics, NPV, PBT and

Table 10: Setup of the retrofit scenario configuration achieving the best KPI score.

Technology	S1	S2	S3	S4	S5	S6	S7	S8
PV	111 kWp	111 kWp	111 kWp	111 kWp	111 kWp	111 kWp	111 kWp	111 kWp
EV station		10 cars	10 cars			10 cars	10 cars	
HP			30 kW	30 kW			30 kW	30 kW
Storage					130 kWh	110 kWh	155 kWh	175 kWh

Table 11: The best performance of retrofit scenarios with regard to the economic (NPV, PBT, IRR) and environmental (RES, CO_2, EE) KPIs variables.

	NPV (k€)	PBT (years)	IRR (%)	RES (%)	CO_2 (%)	EE (%)
S1	354	4	18.2	38	23	12
S2	334	5	16.3	36	17	9
S3	289	6	12.9	31	24	27
S4	308	5	14.3	33	30	30
S5	197	8	8.5	53	23	11
S6	201	8	8.6	47	17	8
S7	124	10	5.2	39	24	27
S8	124	10	5.2	42	30	30

IRR, related to the S1 scenario are the highest recorded. An insight on this result is given bt the annual cash flow in Figure 21. For each retrofit the most relevant inflow components are the savings of the electricity cost thanks to the self-consumption, followed by the incentives on the CAPEX and the electricity savings thanks to the net metering tariff. Besides, in those scenarios with HP, the savings on methane gas bill are compensated by the increase of electricity bill used by the HP. Therefore, having a limitation on the electricity generated by the PV, the net cash flow results similar to the scenario without HP and cause longer payback-time due to a higher initial CAPEX.

By looking at the environmental KPIs, the S4 and S8 scenarios results to be the more compliant with the EU 2030 targets of 32% electricity generated from RES, 32.5% of energy efficiency and 40% of carbon emission reduction. They fulfill the RES target with the 33% and 42% for the S4 and S8 respectively, both achieve 30% of energy efficiency thanks to a 30 kW HP and the reduction of CO_2 emission is 30%.

About the decarbonization target, it is worthy to remind that the reduction of CO_2 is calculated only for the building sector. Therefore, considering the contribution of the transport sector in the S3 and S7 scenarios (which assume the electrification of 10 cars), an additional reduction of 5500 kg of CO_2 per year needs to be accounted. This value, compared to the emission of the whole building (290 kg/year), gives the picture of how highly recommended it is to promote the diffusion of electric vehicles by installing charging stations within the condominium.

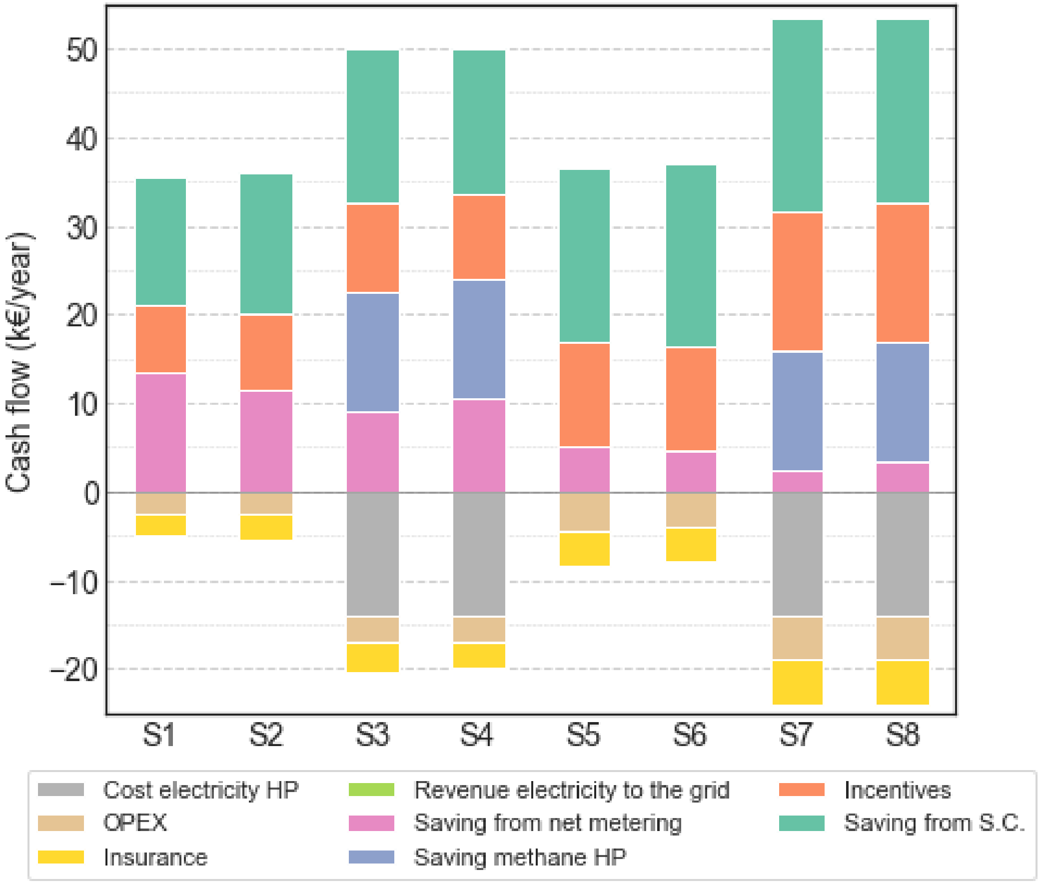


Figure 21: Annual cash flow for each retrofit scenario (best configuration).

4. Discussion

This analysis does not have the aim to determine what is the best retrofit scenario, one fit for all, for a condominium energy community. Rather, we analyze under different perspectives what are the pros and cons of each technology mix.

The self-sufficiency indicator measures how much of the consumed energy is generated by renewable energy sources (rooftop PV system in our simulations). Therefore, it represents, on one side, the rate of RES penetration in the building energy system and, on the other side, the impact of the CO_2 abatement potential.

The condominium's available rooftop area mostly limits the maximum amount of on-site electricity generation. At the maximum PV size (111 kW_p) for the considered case-study, the annual generation is 125 MWh/year that is about two-thirds of the electricity demand of the BAU scenario. With these numbers, the theoretical value of electrical self-sufficiency is 56.8%. Nevertheless, the real amount of self-consumed electricity, and in turn the S.S., reported by the simulations (see Figure 17) is reduced by the mismatch between building electric load and the PV generation. As shown for the simulation of the S1 retrofit scenario with a PV of 111 kWp, the maximum self-sufficiency achieved by installing a PV system is only 38%. Only a storage system (from S5 to S8 scenarios) can bring the S.S. closer to the theoretical one, i.e. 53% for the S5 retrofit scenario.

The mismatch between instantaneous PV generation and electricity demand is captured by the self-consumption indicator. Among the retrofit scenarios without energy storage, the highest value (72%) is achieved when the heat pump and the electric car charging station are installed (S3). The presence of supplementary electric loads increases the probability of contemporaneity; in turn, this affects the self-sufficiency that records the lowest score (28%). Storage systems can theoretically achieve self-consumption of 100% if no limitation of space and CAPEX is imposed. The retrofit scenarios from S5 to S8 achieve self-sufficiency above 80% thanks to the T-STO module that optimize the storage size base on a cost-opportunity algorithm. Also in this case, the S7 scenario equipped with HP and e-car charging stations is the one that scores better.

Besides Figure 18 shows the self-sufficiency decreases for larger HP capacity because of the rise of the total electricity demand induced by the HP, while the self-consumption increases thanks to a higher temporal coherence between the PV electricity generation and the electricity demand.

By comparing the retrofit simulations, there is no doubt that scenarios with HP can be beneficial for the energy system as they lower the primary energy consumption. Nonetheless, air-source HPs, depending on the user heat demand and their COP, might introduce unexpected and rapid variations of the building electric load. The HPs with larger capacity cover a higher range of the supplied power but their capacity factor over the whole year decreases. Therefore, the total amount of supplied energy does not increase with the size of the HP. This effect is due principally to higher occurrence of low COP working conditions for larger HP capacity. These results indicate that even an intermittent renewable energy source, like a PV system, does not increase the instability on the grid when it supplies a relevant number of users, like a condominium (S1 scenario). Besides, retrofit with heat pumps might introduce significant stresses to the grid, especially when the HP size increases and the fluctuation of the COP due to the temperature variation become substantial. In these cases, the installation of a storage system is highly recommended to balance and smooth the load volatility. Therefore, an air-source HP following the heat demand, regardless of the actual RES generation, might appear more problematic for the grid rather than an intermittent RES itself.

The multi-criteria analysis results provide an evaluation tool to rank the energy and economical retrofit scenario performances that are often not easy to compare with each other. The economic KPI is normalized with respect to the best results measured in this analysis, allowing us to identify which combinations of technologies are currently the most promising from an economic point of view. The robustness of the results depends on the input about the market prices and supporting mechanism. The evolution of these variables in the future can reverse the cost-effectiveness of the best solution in the future. For this study, we implemented the latest measures active in Italy. However, once the member state implements the European directives on energy communities, different support mechanisms could be in place.

On the other hand, the environmental KPI is normalized on European targets. Therefore, this indicator measures the grade of compliance with these goals in an absolute way. Nonetheless, the weights of the variables (RES, CO_2, EE) composing the KPI are defined by the authors, introducing a certain grade of discretion.

As mentioned before, none of the retrofit scenarios excels under both economic and environmental point of view. This means that the choice of the best retrofit scenario depends on the EC-condo citizen's priorities. In this perspective, one of the main findings in this work is to question that a condominium energy community automatically implies the commitment to follow the decarbonization path, according to the EU targets. In fact, depending on the sensibility of the stakeholder and final users, they could pursue economic goals at the expense of the environmental one. On the other side, the investigated scenarios are not mutually exclusive, because starting from the S1 scenario it is possible to implement the S7 scenario at any time.

5. Conclusion

This work investigates the benefit arising from the set up of a condominium energy community recently introduced by the new European Directives. The study aims to investigate what technology used in combination in different retrofit scenarios can help achieve the European Union climate target and benefit the energy system, the electric grid, and the citizen who will invest in the retrofit.

The implementation of different retrofit scenarios of a residential building, such as a condominium, has been explored within the Italian policy-market framework. Roof-top photovoltaics, air-to-water heat pump, charging stations for electric vehicles, and battery energy storage are the trending technologies considered to identify possible retrofit scenarios.

Data-driven retrofit simulations fed the multi-criteria analysis. A simulation framework modeled the technology performance, the electricity and the heat demand of a residential building. The case study is an eighty-seven unit condominium located in the North of Italy. The climate of the considered region (2850 heating degree days) represents a common condition in Europe, for which reason the work outcomes can be sufficiently generalized.

The adoption of a roof-top PV supplying the building is the main retrofit necessary to turn a consumer group into a condominium energy community. Nevertheless, since condominiums are made to maximize the population density by limiting the use of ground, it generally occurs that the available roof-top area is limited, as was represented by our case study. In particular, by using the maximum available roof-top area, the electric self-sufficiency results to be 50%. This value was reduced to 25% in the scenario with the electrification of the final use of heat in combination with the charge of electric vehicles. On the other side, the heat pump and the electric vehicles increase the self-consumption of about +20% and +10%, respectively. Besides, installing a proper battery storage system, sized to maximize the economic benefit, it was possible to achieve self-consumption up to 90%. Technology mixes equipped with HP showed undoubtedly benefit for the energy system as they lower the primary energy consumption. Nevertheless, the load volatility introduced by the air-water HPs it resulted in being more harmful to the electric grid than the intermittence of the PV system. In this case, we found out that a storage system is key to smooth down such undesired effects.

The multi-criteria analysis revealed that for all the investigated retrofit scenarios, we could find an economically profitable technology configuration, under the hypothesis of applying the actual incentive mechanism also to the condominium energy community. Nevertheless, the scenarios with the heat pump exhibited some economic mechanisms hindering their exploitation. In particular, the electricity bill results almost equivalent to the cost of the methane gas used to generate the same quantity of heat by the replaced gas boiler. Due to the heat pump working fed by electricity from the grid in the absence of PV generation. Therefore, the economics of the scenarios with HP result less attractive than the others.

Besides, none of the retrofit scenarios excelled in both economic and environmental key performance indicators. In general, scenarios without energy storage achieve better economic KPI, while the battery storage presence reduces the economic benefit increasing the environmental KPI. The best trade-off among the two KPIs is the S4 scenario that installs both PV and HP. In fact, this scenario is compliant with the EU 2030 target, achieving 33% of RES, 30% of energy efficiency and 30% of CO_2 emission reduction.

Moreover, the multi-criteria analysis showed that the set up of the condominium energy community does guarantee the pursuing of the EU 2030 decarbonization road-map, since the final user decision might be more focused on achieving better economic benefits rather than environmental benefits. On the other side, the investigated scenario are not mutually exclusive. Therefore, starting from the most profitable S1 scenario it is possible to implement the S7 scenario at any time by investing in supplementary technologies.

The limit of these results is that the techno-economic analysis has a strong hypothesis on policy framework. In fact, the support mechanisms will be defined only ones the member state will implement the European Directive. On the other side, this explorative study allows designing the future supporting mechanism finding other forms of incentives to promote condominium energy communities besides the economic ones.

Future works on this topic are strongly hoped. In particular, it is interesting to investigate what support mechanism and business model can boost the diffusion of Condo-EC and what factors affect the citizen's decision to engage in this kind of initiative.

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