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Optimization model of an energy community system with focus on the thermal sector electrification

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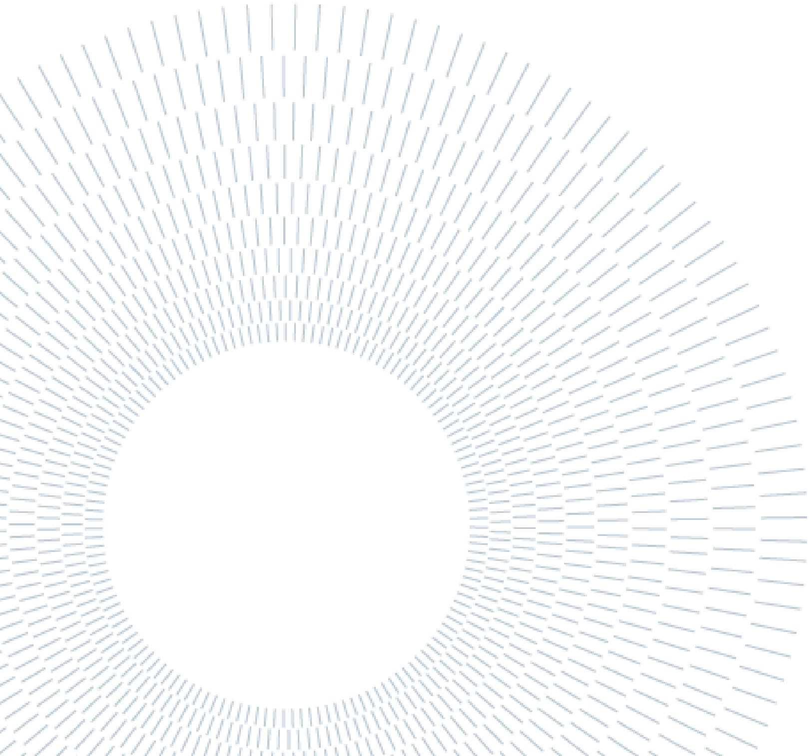


Abstract

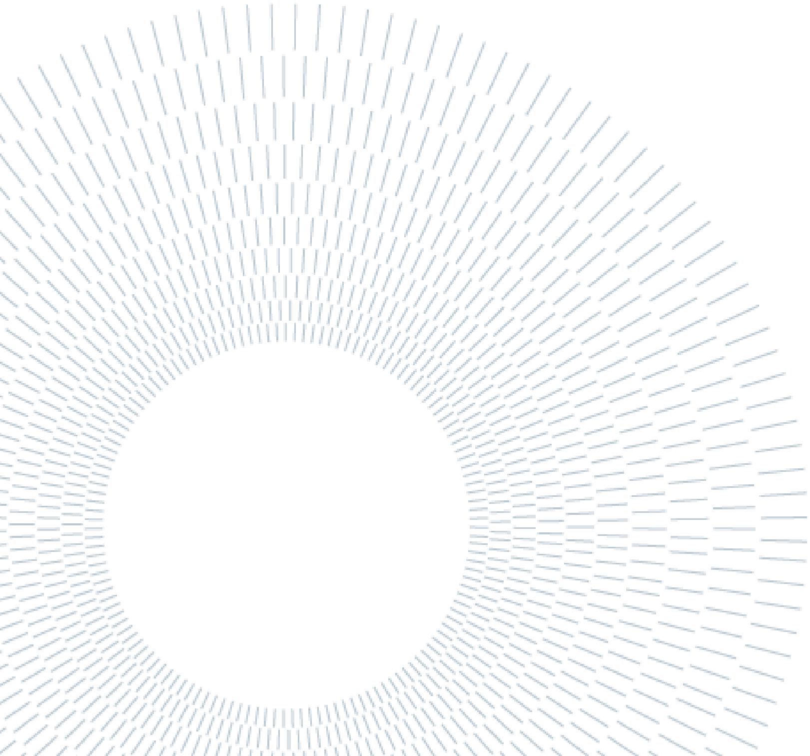
Energy communities are becoming a key element to enhance the renewable energy transition, as they can generate environmental, economic, and social benefits. Sector coupling contributes too, by being able to provide flexibility to the electrical grid. In this work, a bottom-up Single-Objective optimization model of an energy community is developed, by using the Oemof solph and the Oemof thermal Python packages. The focus is (i) on the thermal sector integration and electrification, (ii) on the detailed modelling of space heating, cooling and domestic hot water production devices, (iii) on the thermal storage modelling, and (iv) on the energy community characterization. Also, the demand side management is implemented for all the demand profiles. The model has been applied to two case studies, each one articulated in different configurations, to explore its potentialities as well as to investigate the impact of thermal sector electrification and integration in energy communities, together with the one of technical and flexible operation choices. Results show the impact of the technical settings, which lead to different coefficients of performance of heat pumps and so different electrical consumptions, different optimal capacities of the photovoltaic plant and the thermal energy storage, and differences in the electricity dispatch, which in some cases valorizes the sharing while in others the self-consumption. Investments on energy communities with thermal sector electrification resulted to be profitable, and relevant advantages were demonstrated, both in economic, emissions and energy dispatch terms. The electrification of the thermal sector emerges as the optimal solution too in case the photovoltaic plant is not activated. On the contrary, solar thermal collectors have not been evaluated as a profitable investment, and their contribution for DHW production was limited.

Key-words: Energy System Modelling, Renewable Energy Community, Sector Coupling, Thermal Sector Electrification, Oemof, Demand Side Management

Abstract in italiano

Le comunità energetiche rinnovabili stanno diventando elementi chiave della transizione energetica rinnovabile, dal momento che sono in grado di generare benefici economici, ambientali e sociali. Anche il sector coupling è emerso come elemento utile, essendo in grado di fornire flessibilità alla rete elettrica. In questo lavoro viene sviluppato un modello di ottimizzazione bottom-up e Single-Objective di una comunità energetica, utilizzando i pacchetti di Python Oemof solph e Oemof thermal. L'attenzione è (i) sull'integrazione e l'elettrificazione del settore termico, (ii) il modellamento dettagliato dei dispositivi per la produzione di riscaldamento, raffrescamento ed acqua calda, come (iii) sullo sviluppo dell'accumulo termico e (iv) sulla caratterizzazione dettagliata della comunità energetica. Il Demand Side Management viene inoltre integrato per tutti i profili di domanda. Il modello è stato applicato a due diversi casi studio, ognuno articolato in diverse configurazioni, in modo da esplorarne le potenzialità e investigare l'impatto dell'elettrificazione e integrazione del settore termico nelle comunità energetiche, nonché di quello delle scelte tecniche e di flessibilità operativa. I risultati dimostrano l'impatto delle impostazioni tecniche, che portano a diversi coefficienti di performance delle pompe di calore, e quindi a diversi consumi elettrici, capacità ottime installate di fotovoltaico e accumulo termico, e differenze nella distribuzione elettrica, che in alcuni casi valorizza la condivisione mentre in altri l'autoconsumo. Gli investimenti nelle comunità energetiche con l'integrazione del settore termico elettrificato sono risultati positivi, e diversi vantaggi sono stati dimostrati sia in ambito economico, che in termini di emissioni e distribuzione elettrica. L'elettrificazione del settore termico è emersa come l'opzione migliore anche nel caso in cui l'impianto fotovoltaico fosse disattivato. Al contrario, i collettori solari termici non sono stati valutati come un investimento redditizio, ed il loro contributo nella produzione di acqua calda è risultato limitato.

Parole chiave: Energy System Modelling, Comunità Energetiche Rinnovabili, Sector Coupling, Elettrificazione del settore termico, Oemof, Demand Side Management



Contents

1 Introduction

1.1. Motivation

These are challenging years for the Earth's future. Human influence has warmed the atmosphere, ocean and land at a rate that is unprecedented in the last 2000 years, and this is causing extreme events such as heatwaves, heavy precipitations, tropical cyclones. Increases in greenhouse gases concentration since 1750 are caused by human activities and climate change is affecting every inhabited region across the globe. [1] The actions that countries will take in the near future will determine the achievement of different scenarios, each one with peculiar scopes. [2] In the light of this awareness, the European Council endorses the objective of achieving climate-neutrality by 2050, in line with the Paris Agreement. [3] In particular, the 'Clean energy for all Europeans package', adopted in 2019, will help to decarbonize EU's energy system, in line with the European Green Deal objectives. The revised Renewable Energy Directive [4] promotes the development of a wide spreading of renewable energy sources, with the ambitious objective of the 32% of the energy share covered by renewables. Italy, as a state member of the European Union, integrates this objective, with many other related to climate action, within the 'National Energy and Climate Plan (PNIEC)' [5]. One of the key elements considered in the documents cited above is the definition of renewable self-consumers and energy communities [4]. Energy communities are in fact considered as an effective tool to increase public acceptance of new projects, mobilize private capital for the energy transition and increase the flexibility in the market. [6]. According to the European Commission [7], energy communities organize collective and citizen-driven energy actions that will help pave the way for a clean energy transition, while moving citizens to the fore. They contribute to increase public acceptance of renewable energy projects and make it easier to attract private investments in the clean energy transition. At the same time, they have the potential to provide direct benefits to citizens by advancing energy efficiency and lowering their electricity bills. By supporting citizen participation, energy communities can moreover help in providing flexibility to the electricity system through demand-response and storage.

Another element is emerging as useful to enhance the energy transition: the sector coupling. Coupling of sectors can in fact provide flexibility by converting electric power to heat, gas or liquid fuels, thereby providing flexible consumption, fuel substitution and storage. It also increases possibilities of transmission and flexible energy conversion if converting back to electricity. Sector coupling can thereby facilitate a green transition with integration of VRE sources at low cost [8]. For these reasons, this study is aimed at creating an optimization model for the electrification and the integration of the thermal sector in energy communities.

1.2. Background

1.2.1. Energy community

The Italian and European energy system is going through deep transformations, starting from the Clean Energy for all Europeans Package [9], which gives a new active role of citizens in the energy transition. Two directives at European level enhance the spreading and promotion of new initiatives, such as energy communities: the 'Renewable Energy Directive (2018/2001/EU) (RED II) [4] and the Directive (EU) 2019/944 (IEM) [10]. Italy integrates these directives through the combination of 'Legge 8/2020' [11], the regulation model identified by ARERA ('Delibera 318/2020' [12]) and the incentives system defined 'Ministero per lo Sviluppo Economico – MiSE' ('D.M. 16 settembre 2020' [13]). Within these, specific definitions concerning auto-consumptions schemes and energy communities are introduced.

In particular, the collective auto-consumption (AC) of renewable energy is defined as a group of at least two renewable energy self-consumers which act collectively and are in the same building. The renewable energy self-consumer is identified as a final customer which produces electrical energy from renewable energy sources (RES) for self-consumption, can store or sell this self-produced electricity provided that, if it is for a self-consumer different from families, the activity does not constitute the principal commercial or professional activity.

The renewable energy community (CER) is: a legal entity which is based on the open and voluntary participation; it is autonomous and effectively controlled by members or investors which are located near the renewable energy production plants of the EC, whose members or investors are physical persons, small or medium enterprises, territorial bodies or local authorities, provided that, for private companies, the participation to the EC is not the principal commercial or industrial activity; whose principal objective is to provide to its members or investors or to local areas in which it operates, environmental, economic, social benefits at community level.

ARERA [12] also identifies the necessary characteristics to activate the AC and CER schemes, the regulation model and the process to follow to be accredited to GSE (Gestore dei Servizi Energetici). The authority individuates two models for the EC constitution: the virtual one, which is considered the simplest and most effective one to operate the scheme, and the physical one. In the physical model (Figure 1 *left)* there is a direct and private connection between the electricity generation plant and the domestic/common users, with a unique point of delivery (POD) to the national electrical grid. The virtual model (Figure 1 *right)* provides for the use of the national electrical grid for the energy exchange between generation and consumption units. In this model the virtual scheme will be used.

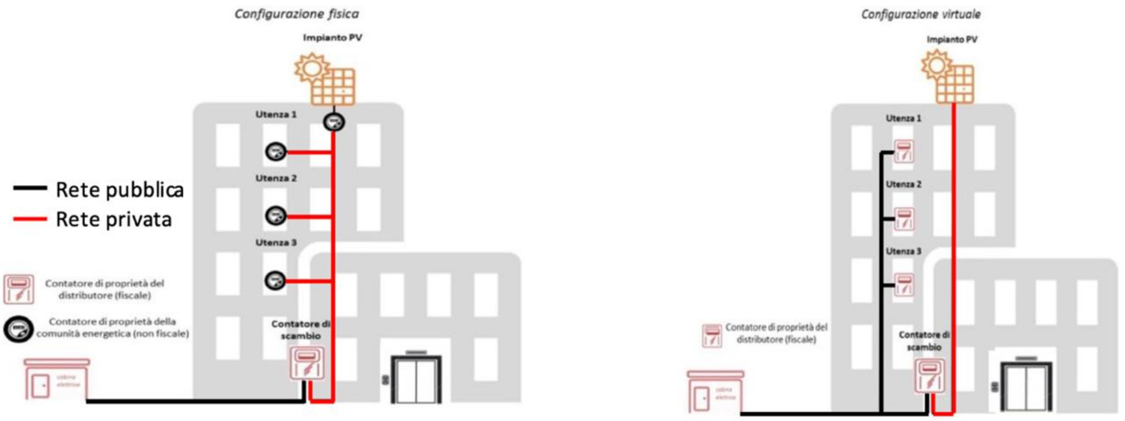


Figure 1: *Physical connection scheme (left) and virtual connection scheme (right) for the EC.* [14]

For what concerns limits on the EC scheme applications, these have been updated in Italy during the 'Consiglio dei Ministri' (CdM) on August the 5th, 2021. This lead to the approvement of the legislative decree for the transposition of the IEM and RED II directives and introduced two novelties about EC application limits. The first one sets the power limit of the renewable energy production plants of the EC to 1 MW for each plant and the second one the enlargement of the perimetral zone of the EC, which has now to be connected to the same primary cabin (AT/MT). This allows to overcome the difficulties in collecting information of DSO about the secondary cabin-connected users and also to install bigger plants which can effectively satisfy the needs of EC members.

For the support of EC initiatives, ARERA [12] identifies benefits that CER and AC bring to the national electrical grid and so the tariff components that must not be applied (or remunerated to EC partecipants). At the same time, MiSE defines the incentivation scheme for CER and AC, which implies incentives on shared electricity flows within the community. In addition to that a remuneration of the energy injected into the national grid at the zonal price is planned.

To allocate these contributions, ARERA [12] specifies some definitions:

- *Electric energy effectively injected*: it is the electric energy injected into the national grid net of the loss coefficients.
- *Withdrawn electric energy*: it is the electric energy taken from the grid from each user which takes part to the scheme.
- *Shared electric energy for auto-consumption or shared electric energy*: it is the hourly minimum value between the sum of the electric energy effectively injected into the grid and the sum of the withdrawn electric energy, in points of the grid which identify groups of self-consumers of renewable energy with act collectively or a CER.

In Italy are now active 20 [15] principal energy communities, not considering the ones in project phase, but also over 7900 municipalities which are totally based on renewable energy sources [16]. 'Piano Nazionale di Ripresa e Resilienza' (PNRR, [17]), which allocates 2.2 Mld € to the developement of Energy Communities, aims at installing over 2.000 MW of new electric generation capacity in distributed configuration by EC and AC.

1.2.2. Energy system modelling

In energy system modelling there are two main approaches that can be followed: the Top-down and the Bottom-up models [18]. Top-down models are characterized by a simplified representation of the components and complexity of the energy system, and this is why they are usually adopted by economists and public administration, but they are not suitable for sector-specific policies. They are mainly used for the evaluation of economic and social impact of energy and climate policies. On the other side, Bottom-up models analyze in detail the components and interconnections between the different energy sectors. This aspect is useful to compare the impact of various technologies on the energy system and evaluate their implementation to reach determined objectives.

However, this approach does not consider the interconnections with the macro-economic sector. A third approach merges the advantages of both the cited approaches: the hybrid one. This is obtained combining the Top-down macro-economic model with the Bottom-up one for each considered sector. This is used, for example, in economic-engineering or Integrated Assessment models. In this work, the Bottom-up approach is chosen for the model, to give a clear and precise description of sector coupling and energy system components.

There are also differences related to the final use of the model, which can be aimed to simulate an energy system or to optimize it [19]. The first one simulates the physical behavior of a defined system, with its inputs and parameters, and can often be recursive to evaluate hypotheses and parameters which evolve in time. The second one is also based on the simulation of the physical energy system, but it has one or more criteria and parameters to be optimized. The model presented in this work is an optimization one, whose objective is the definition of optimal capacities of energy production systems and thermal and electrical devices, and the dispatch of electrical and thermal energy within them for each EC user (and between users), in a cost-minimization optic.

Another criteria to characterize tools and models is the spatiotemporal resolution [19]. In this case the optimization is made over one year and uses an hourly resolution for input and output data. This allows to set precise input data about temperatures, conversion coefficients, irradiance, demand profiles and so to have a realistic view on the modelled situation which leads to clear and precise energy dispatch outputs. The spatial resolution comprehends an energy community, made of a precise number of users, each one representing a node in the model.

1.3. Literature overview

Different studies treat the topic of the sector coupling.
Gea-Bermúdez et al. [8] analyzes the role of sector coupling towards 2050 in the energy system of northern-central Europe when pursuing the green transition. This study models the demand for electricity, heat, and transport sectors with a spatial resolution related to the bidding zones of different countries. This article is not focused on the methodology but on the combination of different factors that can be relevant in the determination of the role of sector coupling in the green energy transition. An hourly temporal resolution is used and the optimization is based on ten years-steps (towards 2050).

The model used is Balmorel and the objective is a capacity development optimization and a long-term operational decision optimization. In the model, electricity flow is allowed across regions and heat flow is allowed across areas, not between the single users. The sectors considered are industry and residential ones. In the residential sector users are only split in two categories, depending on the use or not of district heating, and so only two different types of demand profiles are present. The only technology allowed in space-heating areas is air-to-air heat pumps, while the ones for domestic hot water supply are solar heating, air-to- water and ground-to-water heat pumps, electric radiators, fuel boilers, and short-term hot-water tanks storage. The space cooling is not considered in this model.

Hrvoje Dorotić et al. [20] presents a novel approach to define the energy system of a carbon neutral island, only supplied with intermittent renewable energy sources. The sector coupling here is mainly focused on the vehicle-to-grid concept but also models the integration of power, heating, and cooling. The energy consumption of the base year is calculated by using the LEAP tool and comprehends the sectors of households, service and transportation. Hourly distributions of thermal loads are created by using heating and cooling degree-hour analysis, while electricity load is acquired from the measured data provided by the grid operator. The households' consumptions are defined considering an averaged reference household for the whole island. The heating and cooling demand is covered only with heat pumps and solar thermal collectors and the transport sector is 100% electric. The optimization of supply capacities is made by using EnergyPLAN and considering two constraints: only solar and wind capacities must be utilized, and the total electricity import and export must be balanced, which means that the island is 100% CO2 neutral.

Gils et al. [21] proposes an integrated optimization of all sector coupling options to reach a zero-emission power, heat and transport energy system in Germany in the year 2050. For this scope, a regionally and hourly resolved optimization model is applied, for an integrated evaluation of the capacities and operation of the required infrastructures for energy conversion, storage and transport of power, heat, hydrogen, and methane. [21] is mainly focused on the evaluation of the expansion of large-scale hydrogen infrastructures and on their interaction with the energy system. The modelling approach is derived from the Renewable Energy Mix (REMix) energy system modelling framework, which has been further extended to include a simplified representation of the gas sector (any type of gas, including hydrogen and chemically produced methane). REMix model is then implemented in the General Algebraic Modeling System (GAMS) and solved using CPLEX.

Rinaldi et al. [22] analyzes optimal electricity investments finalized to the decarbonization of the heat supply in residential buildings under different energy retrofitting scenarios, in the representation of the Swiss power and heating system. It extends the model GRIMSEL-A, obtaining GRIMSEL-AH, to also comprehend the heating sector with a focus on the residential one. This is done by adding 24 nodes to the national existing ones. GRIMSEL-AH is an open-source dispatch sector coupling model which objective function is to minimize energy system costs for heating and electricity supply in Switzerland with a daily time resolution for the first one and an hourly one for the second. The demand is based on archetypes referred to sub-national nodes and derived from the combination of urban setting and consumer type. Only heat pumps with fixed temperature levels are considered for the heating demand coverage, with the analysis of different HP deployment scenarios.

Calise et al. [23] thermodynamically analyses a novel hybrid Renewable Polygeneration System, powered by geothermal and solar energy, and connected to a district heating and cooling network situated in the Pantelleria island. The article is also focused on the desalinated water production and on a control strategy to avoid heat dissipation. The cooling and thermal demands are obtained by using building dynamic simulation models, while the electrical demand comes from measured data. In order to obtain building characterization data, ISTAT statistics on the building typologies present in the zone have been used. The scope of the study is not an optimization but a simulation which results are analyzed on daily, monthly and yearly basis. This means that the layout of the plant is already defined.

Maruf [24] outlines a method for analyzing the 100% renewable-based and sector-coupled energy system's feasibility in Germany. At this scope, an hourly optimization tool called 'OSeEM' based on 'oemof Tabular' (open energy modelling framework) is developed. The objective function here is the cost minimization, where the total costs comprehend both investment and operational ones. The country is only divided in two sub-national nodes (Southern and Northern Germany), for which the hourly electricity demand is based on ENTSO-e statistical database, and the heating on the When2Heat project, both obtained from OPSD project. The available electric energy sources are Onshore wind, Offshore wind, Solar PV, and Hydro Run-of-the-River (ROR) plants, while the ones for the heat supply are CHPs fed with biomass and heat pumps with fixed COP, accompanied by thermal energy storage based on water tanks.

Bernath et al. [25] examine the impact of an efficient sector coupling on the market of RES in a European energy system with ambitious decarbonization objectives.

At this scope different scenarios regarding RES utilization and sector coupling are analyzed through the Enertile hourly optimization model, based on cost minimization. In particular, the analysis concerning the sector coupling are about smart charging of electric vehicles, decentralized heat pumps in buildings, multivalent district heating grids and hydrogen economy. The objective function is the cost minimization, and it contains all the costs caused by the modeled technologies and infrastructures.

Jimenez-Navarro et al. [26] analyzes the European sector coupling focusing on the cogeneration plants connected with district heating as one of the main possible pathways to decarbonize the energy system. In order to evaluate this coupling pathway in term of costs, emissions of CO2 and efficiencies, Dispa-SET is used, which is a detailed and open-source power and heat dispatch model. The input demand data have an hourly resolution and the objective is to optimize the power dispatch at the minimum cost.

Østergaard et al. [27] investigates the optimal use of heat pumps in the domestic heating system focusing on the objective of electrification of heating sector with renewable energy sources. In particular two alternatives are analyzes, which are central heat pumps supplying domestic heat for space heating and domestic hot water and central heat pumps combined with small booster heat pumps using domestic hot water as heat source. This is done by implementing an hourly simulation that evaluates advantages and disadvantages related to energy efficiency and operational economic viability. The simulation model used is energyPRO, which is in this case applied to 900 Danish buildings. The Space Heating Demand is modelled as a linear function of the ambient air temperature and a specific factor which accounts for temperatures below a reference one, above which no heating is required. One of the main features of this study is that the analyses are conducted with hourly varying factors: heating demands, domestic heat grid losses, COP of heat pumps and spot market prices. No optimization is carried on.

The articles treating about energy communities are quite rare. In the next section the principal ones are analyzed.

Bernadette et al. [28] investigates the profitability and optimal installation capacities of PV systems in energy communities with respect to individual buildings. In particular four different typologies of buildings are analyzed and for them a mixed-integer linear optimization model is developed with the objective of maximizing the net present value over 20 years. A sensitivity analysis is done to consider the impact of the size of the customer (relative to the demand) on the profitability of the investment.

The toolbox used for the optimization is Yalmip and the solver is Gurobi. For what concerns the electrified heating sector, only heat pumps are implemented while the hot water storage is considered only in the sensitivity analysis. In order to satisfy the heating demand also district heat, pellet heating, gas and oil heating are considered. The analysis of the community is based on four settlement patterns, each one representing a building typology connected to the area in which it is located. In this study, the focus is on the building and not on the single user (household). The outputs of the optimization are the NPV, the energy flows and the energy technologies capacities.

Zatti et al. [29] proposes a novel methodology to design and manage energy communities by firstly solving a design and optimization problem to calculate the best size of the energy assets (energy conversion and storage units) and then by exploiting a Shapley value-based approach to distribute energy community's incomes to members. The case study involves a building in the north of Italy made of nine apartments, occupied by both residential and commercial users. The demand profiles have been collected from previous studies, and so they are not peculiar to each type of user, to the location and don't reflect the Italian's families composition nor the distribution of building energy classes and size. Demand profiles are implemented in the model by considering five representative days, each one representing a particular period of the year, in order to avoid an hourly simulation for all the year. This is an approximation, as five days are not punctually representing the real yearly situation. The optimization tools are not specified in this study, as it's mainly focused on proposing a novel methodology to approach energy communities, so no open-source model useful for the calculations is indicated. The heating sector is modelled by using heat pumps, boilers and thermal storage, which are implemented or not to simulate different scenarios. These configurations, called 'electrification cases', are pre-determined, so the model only optimizes the size of the selected components but doesn't help in the choice between different technologies. A big attention is given to the distribution of benefits through the Shapley value and to the economic analysis results, while no details are explained about the modelling of the single energy system's components (e.g. conversion factors, temperatures, treatments of water).

Martorana et al. [30] investigates the energy performances of different configurations of solar-assisted heat pumps equipped with PV and PVT panels and solar thermal collectors for domestic hot water production. Electricity storages are also considered to smooth the interactions with the grid. Evaluations are made for micro energy communities located in the South of Italy. Different variants of system layout can be chosen.

This study uses a simulation model (TRNSYS), and not an optimization one, to reproduce the operation of the plant. Each component is simulated by using a pre-defined TRNSYS type. The size and configuration of the plant are defined before the simulation takes place.

Di Lorenzo et al. [31] proposes an innovative power sharing model for aggregations of users able to share the power produced by common generators. The novel principle of the model is that energy produced by common generators is shared between end users in a unidirectional way, so there is only one active user which represents the balance node. The feasibility of the model is discussed by using a dynamic Matlab/Simulink model, applied to various case studies. The model is different if applied to existing or new buildings. In fact, for the existing ones, the installation of a heat pump is considered in addition to a gas fired heater for what concerns the heating system and the domestic hot water production. In this configuration, the main feature is the integration of the power-sharing mode for PV: the device is connected to several users and to the switchboard, to cover the heating and electrical demand. The system proposed for new buildings is based on the use of only electrical energy and so the heating system is totally made by heat pumps. In particular in the Matlab/Simulink model are present a PV system installed on the roof of the building, a dc/dc step up converter, a dc bus connecting all the users and voltage source converters. The focus is mainly on the identification of the optimal control strategies for the energy sharing, and not on the detailed modelling of the single components.

Moncecchi et al. [32] pursues two objectives: firstly to find the optimal portfolio for the considered energy community and then to allocate costs and profits of shared infrastructures among community members by integrating the Shapley value. The model of renewable energy community has been implemented in Python’s environment and applied to a real case study, which is the low voltage grid of Chiou, a fraction of the village of Porossan in Aosta. The optimization is solved by Gurobi. With respect to the generation side, two technologies have been investigated: photovoltaic and hydroelectric. The power profile of each user has been obtained from real measurements collected by the DSO and the consumption of each type of user identified by ISTAT is linearized according to the number of members of the family. In this study no attention is given to the thermal sector, nor to the electrified thermal one. The focus is on the implementation of the game theoretic approach aimed at the redistribution of the value coming from the energy community.

Liu et al. [33] develops a novel distributed energy system model combining solar energy utilization with hybrid energy storage technology, so heat and electricity storage.

Secondly, with multiple objectives like primary energy saving rate, carbon dioxide equivalent emission reduction rate, annual cost per unit supply area, an integration optimization method is adopted. The study is then applied to twelve nearly zero energy community scenarios with the adoption of electric vehicles. The model is implemented in Python environment and in particular the Non dominated sorting genetic algorithm-II (NSGA-II) is used to solve the multi-objective optimization problem and aims at finding the optimal equipment capacities. Different scenarios in the area of Beijing are analyzed, with different proportion and scale, in order to find the energy-efficient, environmentally benign, economic and reasonable type and scale of energy community. In this study, the focus is directly on buildings, not on the single user, and so the demand. The modelling of heating or cooling devices is not deepen because the main focus is on the differences in resulting configurations for the various typologies of community implemented.

Fouladvand et al.[34] explores various technical and institutional conditions that influence the thermal energy community formation process by using an agent-based modelling approach. In ABM, agents are heterogeneous, autonomous and individual decision-making entities, able to learn and interact with each other and with the environment. So, it’s useful to investigate the behavior of stakeholders of the community. In order to have reliable results, a case study located in Netherlands is considered. The model, set on the testing ground of the PAW, represents the participants to the hypothesized community, the idea phase, the feasibility phase, the building phase and the expansion one. For what concerns the collective heating technology, stakeholders choose one of the three options (Bio pellet boiler, ATES and TEA). So, the main analyzed results are focused on the formation process duration, neighbor support and participation and the share of community investment and average household investment. This is a totally different type of model with respect to the previously discussed ones, but useful to identify and overcome the barriers to the development of energy communities. The difficulties could be in fact firstly related to the disinformation of the citizens about the EC, then to the bureaucracy necessary to constitute it and also to the regulations about the sharing of costs and benefits.

Casalicchio et al. [35] develops an integrated method for the implementation of a linear bottom-up optimization model, in order to address different aspects of an energy community, which are the definition of the dispatch and the best technology mix, the assessment of the role of the Demand Side Management, the definition of an original and fair method to allocate the benefit among the participants and of a Fairness Index to compare different business models. The focus is on the electric sector and no sector coupling is implemented.

A summary of the reported articles can be found in Table 1.

Reference	Sector	Optimisation	Objective function/Simulation	Software/Solver	Temporal/Spatial resolution	Zone	Source	Implemented aspects
Gea-Bermúdez [8]	Electric, Thermal (space heating, dhw), Transport	capacity and operation	minimise discounted system costs/-	Balmorel	hourly/bidding zones	United Kingdom, Belgium, Netherlands, Germany, Poland, Finland, Sweden, Norway, and Denmark	wind & PV	• Factors impacting sector coupling
Hrvoje Dorotić [20]	Electric, Thermal (space heating and cooling, dhw), Transport	supply capacities with constraints	minimization of investment costs and total electricity import/ energy demand	LEAP and EnergyPLAN	hourly/ island	Croatian Island of Korčula	wind & PV	• Import/export balance • CO2 emissions
Gils [21]	Electric, Thermal (space heating, dhw), Transport	capacities and operation of the infrastructures for energy conversion, storage and transport of power, heat, hydrogen, and methane	cost minimisation /-	REMix	hourly/ region	Germany	wind, hydro, PV, hydrogen	• Hydrogen penetration
Rinaldi [22]	Electric, Thermal (space heating, dhw)	optimal capacity and schedule of power assets	cost minimisation /-	GRIMSEL-AH / CPLEX	hourly (electricity) and daily (heat)/country	Switzerland	PV	• Future energy mix scenarios
Calise [23]	Electric, Thermal (space heating and cooling, dhw)	-	_/polygeneration system	TRNSYS	daily, monthly, yearly/ island	Pantelleria	solar and geothermal	• Desalinated water production • Heat dissipation
Maruf [24]	Electric, Thermal (space heating, dhw)	energy mix and capacity investment	cost minimisation /-	OSeEM-DE from Oemof	hourly/country	Germany	wind, solar, hydro, biomass	-
Bernath [25]	Electric, Thermal (space heating, dhw), Transport	capacity expansion and hourly dispatch	cost minimisation /-	Enertile	hourly/continent	Europe	PV, CSP, wind	• EU energy market • Future energy mix scenarios
Jimenez-Navarro [26]	Electric, Thermal (space heating and cooling, dhw)	power dispatch	cost minimisation /-	Dispa-SET	hourly/continent	Europe	CHP	• CO2 emissions
Østergaard [27]	Thermal (space heating and cooling, dhw)	-	_/energy system	energyPRO	hourly/region	Denmark	CHP, Heat sources	• Energy efficiency • Hourly varying factors
Bernadette [28]	Electric, Thermal (space heating and cooling, dhw)	NPV, capacities, energy flows	maximize net present value/-	Yalmip / Gurobi	hourly /EC	fictitious	PV	• Building typology impact
Zatti [29]	Electric, Thermal (space heating and cooling, dhw)	capacities, energy flows	best cash flow for community/-	-	typical day/EC	Italy	PV	• Shapley value to distribute benefits
Martorana [30]	Thermal (space heating, dhw)	-	_/plant operation	TRNSYS	hourly/ micro EC	South of Italy	PV & PVT	-
Di Lorenzo [31]	Electric, Thermal (space heating, dhw)	-	_/energy sharing	Matlab/Simulink	hourly/building	Italy	PV	• Unidirectional electricity sharing • Optimal control strategies for energy sharing
Moncecchi [32]	Electric	capacity of generators and storage	maximize economical value of investment/-	Python / Gurobi	hourly /EC	Italy	PV & hydro	• Shapley value to allocate costs and benefits
Fouladvand [34]	Thermal (space heating, cooling, dhw)	-	_/community formation	PAW	daily /EC	Netherlands	renewable thermal energy sources	• Technical and institutional factors influence on EC formation • ABM approach
Casalicchio [35]	Electric	capacity and dispatch	cost minimisation /-	Oemof / Gurobi	hourly /EC	Italy	PV	• BM schemes • DSM strategy • TOU tariffs • Regulatory framework • Clustering • Composition analysis
Liu [33]	Electric, Thermal (space heating, cooling, dhw)	equipment capacity	multi-objective: emission reduction rate, annual cost minimisation, energy saving rate/-	Python / NSGA II	hourly /EC	Beijing	PV, ICE	• CO2 emissions
This Work	Electric, Thermal (space heating and cooling, dhw)	capacity and dispatch	cost minimisation/-	Oemof / Gurobi	hourly /EC	Italy	PV, solar	• DSM strategy • Hourly COP • Italian regulatory framework • Italian population composition • Flexible setting options • Economies of scale • Technical temperatures

Table 1: *Literature overview.*

1.4. Objectives and novelty

As it's possible to notice from the analyzed studies, there's a lack in the development of optimization models which integrates sector coupling in energy communities. The study presented in this work aims at proposing a detailed and versatile model of an energy community, which focuses on different aspects. First of all, it models the electrified thermal energy sector in the community, giving high relevance to each aspect of the space heating and cooling devices as well as devices for domestic hot water production. In fact, it considers different typologies of temperature regulation for space heating systems, domestic hot water treatments, temperature regulation of space cooling systems based on heat gains which lead to the itemized definition of performance coefficients, which also depend on the external ambient temperature. Also, the coupling of components with electrical and thermal energy storages is considered. These ones are modelled basing on Oemof Thermal package components, which allow to consider aspects related to temperatures and thermal losses. The traditional heat sources are then considered for sensitivity analyzes. Secondly, it focuses on the single user's needs and characteristics: peculiar electricity, heating and cooling demands are settled for each user, basing on a set of predefined categories. For what concerns demand, a novel contribution is also present: the implementation of demand side management in a very detailed manner derived by studies on the input parameters. In the model, each user is set as a single node with its own energy fluxes, sources, and devices, and shared fluxes between EC members are evaluated. Another important aspect is the versatile nature of the model, which can be customized by varying different parameters of the input file. In this way, the user is able to evaluate the impact of the implementation of different devices and operating settings, as well as the influence on the optimal capacities and dispatch of the climatic zone in which the EC is located, together with the related temperatures and meteorological data. What can also be noticed from the literature analysis is that only one of the studies cited above is implemented by using an open-source model, and none of them uses the Oemof Thermal package of the Python environment. This work crates an energy system relying on the Oemof Solph package, which is part of the Open energy modelling framework (Oemof) and integrates different components and functions of the Oemof Thermal package.

1.5. Thesis overview

This Thesis work is organized as follows. First, an introduction chapter is presented. This aims at explaining the motivation of the work, together with a description of energy communities and energy system modelling followed by a literature overview, made to analyze the state of the art of energy system modelling with thermal sector coupling and electrification, and to evidence the novelty of the presented model. Then the methodology chapter is detailed. In this section, a precise description of all the elements constituting the model is made, which means both the studies on available technologies and parameters to insert, and details on the components modelling in the code. Specifications on the EC model and input file structures are also added. In the following chapter, case studies are characterized, made with the aim of validating the model, evidencing all the possible settings and evaluating the thermal sector coupling and ECs. Then results are presented underlining the impact of thermal sector integration in ECs and electrification.

2 Methodology

A bottom-up Single-Objective optimization model of an EC with focus on thermal sector electrification was developed. Objective function and power balance are reported in Equation 1 and Equation 2, where i stands for input, o for output, n for node, vc are the flows variable costs, epc are the periodical costs, E stands for the electric or thermal energy, L for load, gen for generated, charge and disch for charged and discharged, sh for shortage, which can enter or exit the node.

Equation 1

$$Obj = \sum_{i,n} \sum_{o,n} \sum_{t} flow_{i,o,t} \cdot vc_{i,o,t} + \sum_{n} inv_n \cdot epc_n$$

Equation 2

$$L_{n,t} = \sum_{n} (E_{gen,n,t} - E_{charge,n,t} + E_{disch,n,t} - E_{excess,n,t} + E_{sh,in,n,t} - E_{sh,out,n,t})$$

In this chapter the methodology of the work is reported. The organization of the report is made as follows: firstly, the structure of the model is explained together with the used tool, followed by a detailed description of all the components of the model and the relative studies, then specifics on the adaptation of the code to the energy community (EC) are itemized, finding at the end the economic and environmental parameters used for the evaluation of results.

2.1. Structure of the model

The purpose of the work is to create an hourly optimization model of an energy community with a focus on the thermal sector electrification. It is implemented in oemof (open energy system modelling framework) [36], a Python toolbox for energy system modelling and optimization. For doing this, the single user, intended as a household unit which is part of the energy community, is detailed and modelled as a single node. In the second step the code is adapted to integrate different users in the community. The scheme of the single user's thermal model items is reported in Figure 2. The main components of the model are sources, buses (which represent a grid or network without losses), sinks (used to define demands), transformers (nodes with multiple input and output flows), generic storages, which are all components of the oemof.solph [37] package, functions of the stratified thermal storage component of the oemof.thermal package [38], the solar thermal collector, component of the oemof.thermal package. Flows are used to interconnect all the components. Four different demands have to be satisfied in the model: the one called ‘heat_removed’, referred to the space cooling (SC) demand, the ‘heat_output’, referred to space heating (SH) demand and ‘heat_DHW’, which represents the domestic hot water (DHW) needs and finally the electrical one (EL). Demands can be covered through electricity, which is converted into the needed heat/cold by means of different types of devices. All the represented transformers are the available ones, within which the optimization will choose. The transformers that can be seen in Figure 2 differ for type of device, heat source and domestic system implemented. The principal renewable source of electricity is the photovoltaic plant, which installation is evaluated for each user. In addition to this, in the model, there is the electrical national grid, which supports the PV electricity production, and it is added to evaluate the effective advantages of using the photovoltaic source. For each element composing the single user’s thermal model, peculiar characteristics are detailed, so that each component has different operating options, precise temperatures, and conversion factors. All the variable parameters, which are the one that can be customized basing on the case that is being analyzed, can be directly given as an input by the user of the model. In fact, a customized input file (an excel file) is predisposed, containing all the details about the described components. This attributes to the model a high versatility.

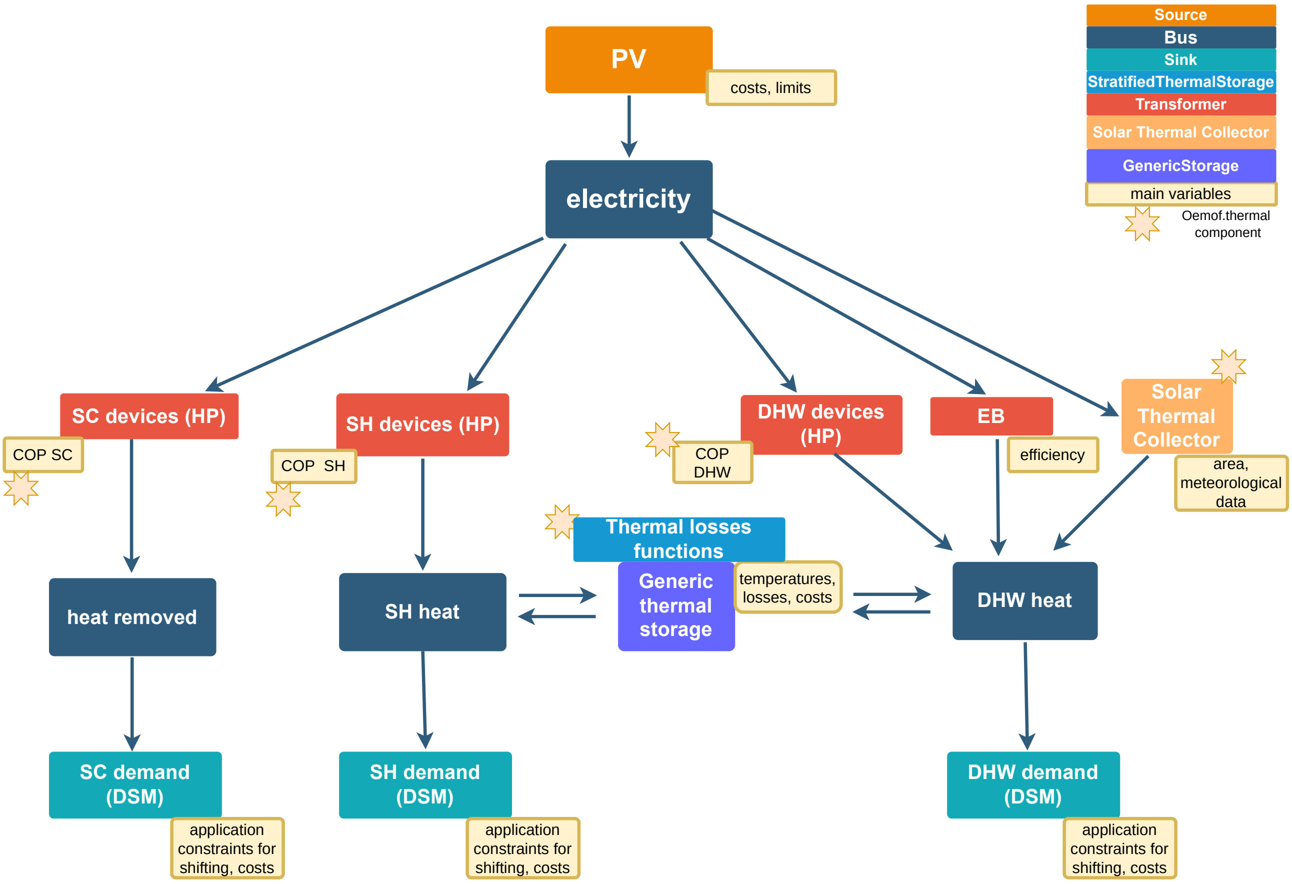


Figure 2: *Scheme of the single user's items.*

2.2. Open Energy Modelling Framework

Oemof [36] stands for "Open Energy System Modelling Framework" and provides a free, open source and clearly documented toolbox to analyze energy supply systems. It is developed in Python environment based on the optimization package pyomo and designed as a framework with a modular structure, containing several packages which communicate through well-defined interfaces. In this work two packages of oemof are used: oemof solph and oemof thermal.

Oemof solph [37] is a model generator for energy systems modelling and optimization. Its structure allows to create models on different levels of detail by means of predefined components and an optional formulation of additional expressions and constraints [39]. With its open and documented code base, extensive collection of examples and an active community it is useful across many levels, from simple applications to advanced modelling.

Oemof thermal [38] is an oemof library with a focus on thermal energy technologies (heating/cooling). In its original intention it is an extension to the components of the optimization framework oemof solph. However, some of its functions may be useful for their own. For each technology that is covere, oemof thermal provides a module which holds a collection of useful functions, which can be applied to perform pre-calculations of an optimization model or postprocess optimization results. They can also be used stand-alone for different types of optimizations. The implementation of oemof thermal components is based on the used of facades (based on the oemof tabular facades module), which are classes that offer a simpler interface to more complex classes. In particular, in this application, facades inherit from oemof solph generic classes to serve more concrete and energy specific interface. So, the user will be able to instantiate a façade using a keyword argument, which is then used to construct an oemof solph component and to set it up in an energy system. In this model the used elements from oemof thermal package are evidenced with a star in Figure 2.

2.3. Demand Side Management

In order to manage in an optimal manner energy consumptions, the demand side management in implemented in the model.

2.3.1. Demand Side Management definition

With the increase of the penetration of non-programmable renewable energy sources, the demand side management is gaining importance in the last years.

The Demand Side Managements is the energy management technique that is used to modify the load pattern of the consumer and it refers to a series of actions aimed to the optimal managing of energy consumptions [40]. Its objective is to modify the consumption profile to save money and energy and to better match the renewable energy sources production with the energy needs of the consumers, providing in this way additional flexibility to the system. Dranka et al. [41] evidences how DSM has emerged as a valuable resource option for balancing electricity supply and demand, leading to a delay in investments, integration of RES, a reduced need for thermal capacity, a decrease in the level of CO2 emissions, and the possibility of enhancing the synergies between power subsystems. For these reasons, demand side management is implemented in the model, both for electricity and thermal sectors, which represents one of the novelties of this work.

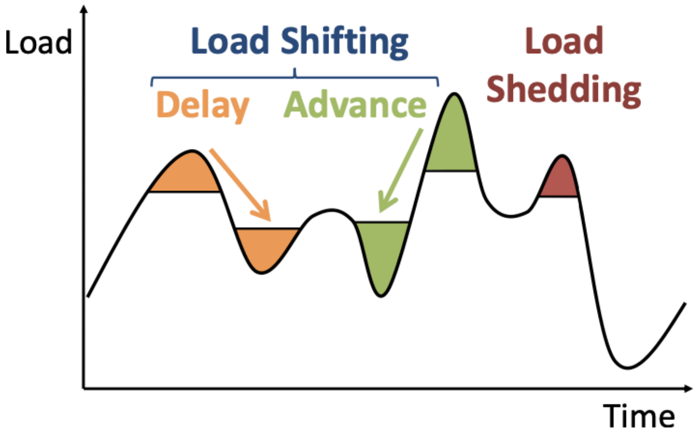


Figure 3: *Load shifting and load shedding.*

Energy efficiency and Demand Response (DR) are two different categories of DSM implementation. The first one includes the replacement of inefficient equipment with efficient ones, while the implementation of DR involves different techniques such as peak clipping, valley filling, load shifting, load shedding, load growth, strategic conservation and flexible load curve [40]. It is possible to notice that DR is focused on load flexibility and short-term customer action, in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. In this work, according to the aspects considered in the oemof tool, the focus is on the DR and in particular on the load shifting and on the load shedding. These techniques make use of consumer demand elasticity, which is typically provided by thermal inertia, demand flexibility or physical storage. The peak shifting is the shifting of the load from peak periods to off-peak periods while the peak shedding consists in cutting the load during peak demand periods, and results in a minor energy consumption.

2.3.2. Implementation of DSM in oemof

In the oemof model, Demand Side Management can be implemented by using the SinkDSM component of the oemof.solph package [37], which represents flexibility in a demand time series. This component can consider both load shifting and load shedding and the DSM model can be chosen between three possibilities. Until now, three principal approaches for DSM are implemented: 'DIW', 'DLR' and 'oemof'. Other two approaches are under development: 'IER' and 'TUD'.

The 'DIW' approach is developed following the model presented by Zerrahn et al. [42]. In this paper, the model developed from Goransson [43] is improved for what concerns two aspects:

- the undue recovery problem, which means that demand served is instantaneously compensated by new demand delayed within the same DSM process.
- the specific temporal structure imposed on load shifts, which brings to situations like the one represented in Figure 4.

The first problem is solved by introducing an additional constraint on hourly maximum load shift. So the new equation states that the same DSM capacity can't shift demand up and down at full capacity at the same time. The second problem is solved by including a set of parameters and equations that start with positive demand shifts. In particular, DSM up and down are related by two indexes, and so downward load shifts are directly tagged to the respective upward shifts. These solutions lead to a more realistic temporal structure of load shift, represented in Figure 5. Details about the DIW approach are reported in Equation 3 and Equation 4.

Equation 3

$$\dot{E}_t = demand_t + DSM_t^{up} - \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \quad \forall t \in T$$

Equation 4

$$DSM_t^{up} + \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \leq max\{E_{tt}^{up}, E_{tt}^{do}\} \quad \forall tt \in T$$

Where DSM_t^{up} represents the energy involved in the up-shift in instant t, $DSM_{t,tt}^{do}$ the energy involved in the down-shift in the instant tt, $\dot{E}_t$ is the resulting energy demand in instant t, E_{tt}^{up} *and* E_{tt}^{do} represent the capacity of shift up and down.

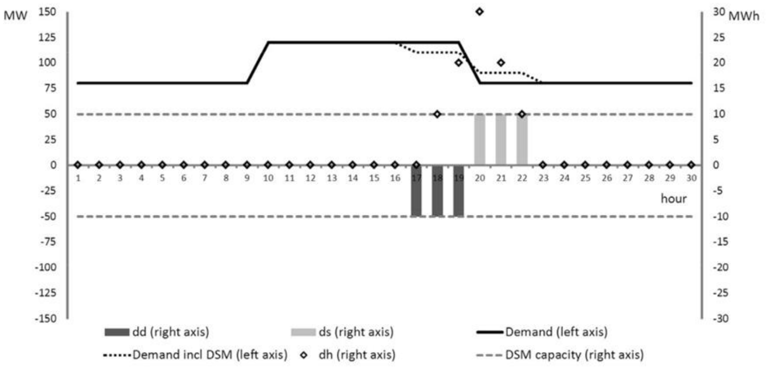


Figure 4: *Specific temporal structure of load shifts according to Goransson et al.* [43]

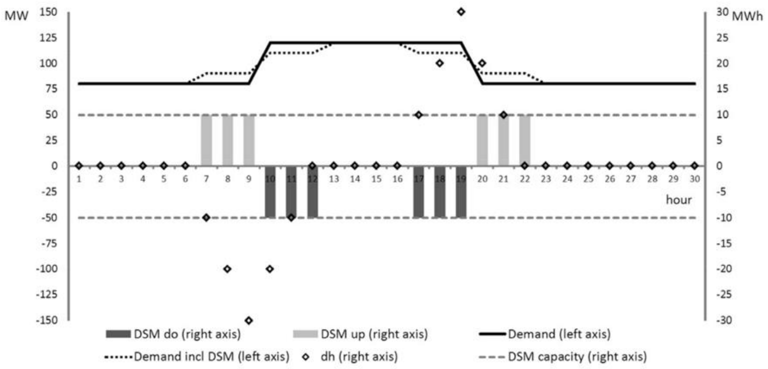


Figure 5: *A more realistic temporal structure of load shifts.* [42]

The 'DLR' approach is developed following the DSM modelling approach of Gils [44], which analysis focuses on the identification of different types of constraints, regarding the theoretical, technical, economic and practical potential of DR application.

The ‘oamof’ “approach is a fairly simple one. In this case, within a defined windows of time steps, demand can be shifted within the defined bounds of elasticity and the window sequentially moves forwards.

In the report of the session on Demand Side Management and Demand Response between oemof developers and users, by Kochems et al. [45], the approaches described above have been analyzed and compared after being applied to some case studies in the oemof framework.

In particular, they are implemented in a simplified toy energy system model which considers wind infeed and coal plant as backup and a 48 hourly timestep. Different cases are also analyzed, such as flat demand and constant generation or variation in both generation and demand. Criteria for comparison are formulation, performance, objective value, amount and structure of DR activations. The ‘DIW’ approach delivers the best results in terms of demand curve representation, number of activations, optimal objective and doesn’t show relevant differences in time of execution, so it will be used in the model

2.3.3. DSM parameters

For the definition of the SinkDSM component for electric, heating, domestic hot water and cooling demands, different parameters have to be defined. In order to make the model as versatile as possible, a study on these parameters have been made which results are reported above.

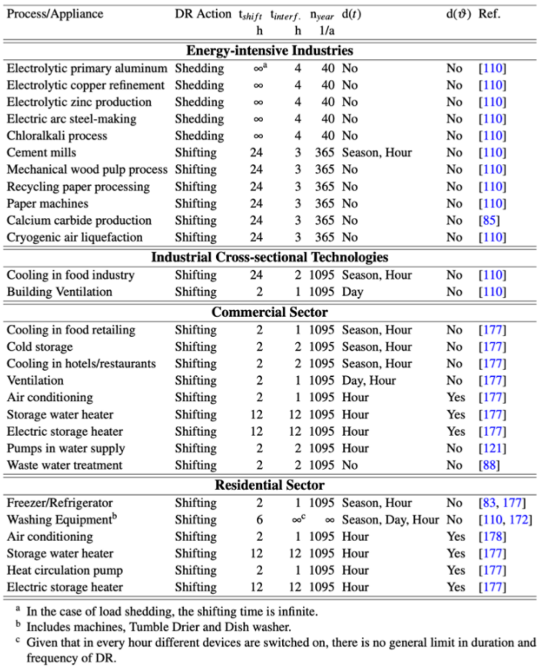
First of all, the activation of load shifting and load shedding has to be evaluated. Gils [44] weighs the adoption of load shifting and load shedding both for residential and industrial sectors. What emerges is that even if in residential and commercial sector typically both load shifting and shedding can be realized, due to higher costs and losses of comfort caused by load shedding, the study adopts it only for energy-intensive industrial processes. So, in the model, the Boolean parameter ‘shed_eligibility’ is set to ‘False’.

The second value that has to be considered is the delay time, which represents the duration of time until the amount of energy must be completely balanced (between the up and down shift of DSM). Gils [44] considers different types of limits for the DR application which are the theoretical potential and the technical potential, composed by the practical, social and economic ones, as shown in Figure 6. Basing on these aspects, the characteristic DR parameters are evaluated.

Figure 6: *Theoretical and Technical Potentials.*

In [44], a total of 30 different processes and appliances are taken into consideration. Shiftable loads typically rely on thermal storage, demand flexibility or physical storage. Results concerning values about load shifting and shedding based on consumer participation in DR are reported in Table 2.Data about interference time, defined as *down*/up Interference time of the load shifting in one direction, are also reported in Table 2.For what concerns shift capacity up and down, from Gils [44] it emerges that due to the high impact on comfort and working routines caused by changes in the consumption pattern, the theoretical potential of DR application is reduced to an approximated social potential. Therefore, the parameters s-reduction and s-increase, which represents the capacity potential of down and up shift, are partly adjusted to values below 100% according to Table 3.

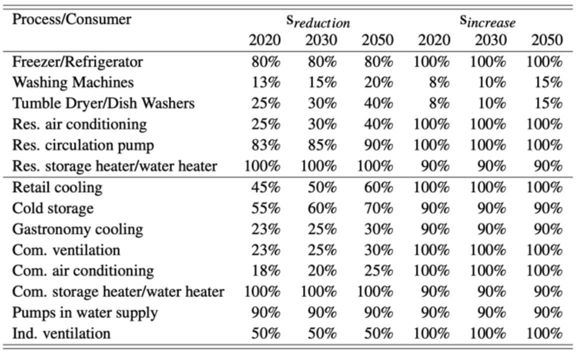
The estimates reflect the load shifting impact a particular device has on user convenience.
For the model values of the year 2030 are considered.



Process/Appliance	DR Action	t_{shift} h	$t_{interf.}$ h	n_{year} 1/a	d(t)	d(ϑ)	Ref.
Energy-intensive Industries							
Electrolytic primary aluminum	Shedding	∞^{a}	4	40	No	No	[110]
Electrolytic copper refinement	Shedding	∞	4	40	No	No	[110]
Electrolytic zinc production	Shedding	∞	4	40	No	No	[110]
Electric arc steel-making	Shedding	∞	4	40	No	No	[110]
Chloralkali process	Shedding	∞	4	40	No	No	[110]
Cement mills	Shifting	24	3	365	Season, Hour	No	[110]
Mechanical wood pulp process	Shifting	24	3	365	No	No	[110]
Recycling paper processing	Shifting	24	3	365	No	No	[110]
Paper machines	Shifting	24	3	365	No	No	[110]
Calcium carbide production	Shifting	24	3	365	No	No	[85]
Cryogenic air liquefaction	Shifting	24	3	365	No	No	[110]
Industrial Cross-sectional Technologies							
Cooling in food industry	Shifting	24	2	1095	Season, Hour	No	[110]
Building Ventilation	Shifting	2	1	1095	Day	No	[110]
Commercial Sector							
Cooling in food retailing	Shifting	2	1	1095	Season, Hour	No	[177]
Cold storage	Shifting	2	2	1095	Season, Hour	No	[177]
Cooling in hotels/restaurants	Shifting	2	2	1095	Season, Hour	No	[177]
Ventilation	Shifting	2	1	1095	Day, Hour	No	[177]
Air conditioning	Shifting	2	1	1095	Hour	Yes	[177]
Storage water heater	Shifting	12	12	1095	Hour	Yes	[177]
Electric storage heater	Shifting	12	12	1095	Hour	Yes	[177]
Pumps in water supply	Shifting	2	2	1095	Hour	No	[121]
Waste water treatment	Shifting	2	2	1095	No	No	[88]
Residential Sector							
Freezer/Refrigerator	Shifting	2	1	1095	Season, Hour	No	[83, 177]
Washing Equipment[b]	Shifting	6	∞^{c}	∞	Season, Day, Hour	No	[110, 172]
Air conditioning	Shifting	2	1	1095	Hour	Yes	[178]
Storage water heater	Shifting	12	12	1095	Hour	Yes	[177]
Heat circulation pump	Shifting	2	1	1095	Hour	Yes	[177]
Electric storage heater	Shifting	12	12	1095	Hour	Yes	[177]

[a] In the case of load shedding, the shifting time is infinite.
[b] Includes machines, Tumble Drier and Dish washer.
[c] Given that in every hour different devices are switched on, there is no general limit in duration and frequency of DR.

Table 2: *Electricity consumers suited for DR participation* [44].



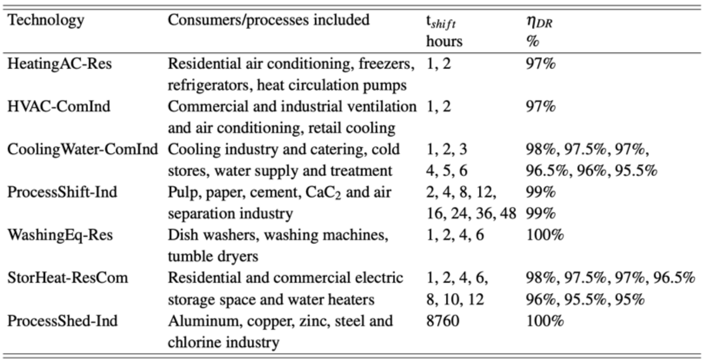
Process/Consumer	$s_{reduction}$			$s_{increase}$		
	2020	2030	2050	2020	2030	2050
Freezer/Refrigerator	80%	80%	80%	100%	100%	100%
Washing Machines	13%	15%	20%	8%	10%	15%
Tumble Dryer/Dish Washers	25%	30%	40%	8%	10%	15%
Res. air conditioning	25%	30%	40%	100%	100%	100%
Res. circulation pump	83%	85%	90%	100%	100%	100%
Res. storage heater/water heater	100%	100%	100%	90%	90%	90%
Retail cooling	45%	50%	60%	100%	100%	100%
Cold storage	55%	60%	70%	90%	90%	90%
Gastronomy cooling	23%	25%	30%	90%	90%	90%
Com. ventilation	23%	25%	30%	100%	100%	100%
Com. air conditioning	18%	20%	25%	100%	100%	100%
Com. storage heater/water heater	100%	100%	100%	90%	90%	90%
Pumps in water supply	90%	90%	90%	90%	90%	90%
Ind. ventilation	50%	50%	50%	100%	100%	100%

Table 3: *Assumed customer participation in DR measures* [44].

It is also necessary to attribute costs to the DSM application. For doing this, two different approaches are presented.

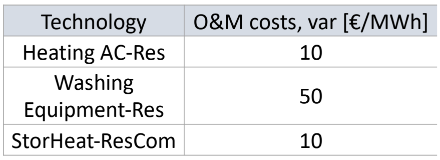
Gils [44] takes into account 30 consumers. All consumers of one technology are assumed to have the same techno-economic DR characteristics, including costs, limits in frequency, efficiency, as well as shifting and intervention time. Then the 30 consumers are resumed in 7 technologies, reported in Table 4.

For each category costs are estimated and reported in Table 5. The two categories of particular interest in this study are the evidenced ones (referred to thermal sector both for space heating and DHW production, which is a novelty). For the electricity demand, the shift of 'WashingEq-Res' is considered.



Technology	Consumers/processes included	t_{shift} hours	η_{DR} %
HeatingAC-Res	Residential air conditioning, freezers, refrigerators, heat circulation pumps	1, 2	97%
HVAC-ComInd	Commercial and industrial ventilation and air conditioning, retail cooling	1, 2	97%
CoolingWater-ComInd	Cooling industry and catering, cold stores, water supply and treatment	1, 2, 3 4, 5, 6	98%, 97.5%, 97%, 96.5%, 96%, 95.5%
ProcessShift-Ind	Pulp, paper, cement, CaC_2 and air separation industry	2, 4, 8, 12, 16, 24, 36, 48	99% 99%
WashingEq-Res	Dish washers, washing machines, tumble dryers	1, 2, 4, 6	100%
StorHeat-ResCom	Residential and commercial electric storage space and water heaters	1, 2, 4, 6, 8, 10, 12	98%, 97.5%, 97%, 96.5% 96%, 95.5%, 95%
ProcessShed-Ind	Aluminum, copper, zinc, steel and chlorine industry	8760	100%

Table 4: *Grouping of DR loads and techno-economic parameter of DR shift classes* [44].

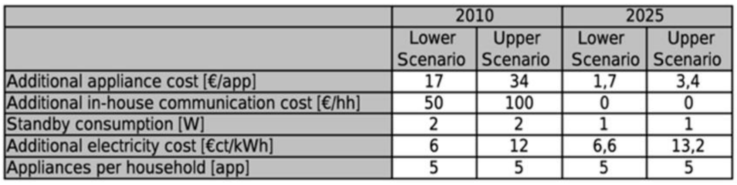


Technology	O&M costs, var [€/MWh]
Heating AC-Res	10
Washing Equipment-Res	50
StorHeat-ResCom	10

Table 5: *Techno-economic parameter of DR technologies*

In the estimation of investment costs, a unit cost value of 25€ per residential appliance and 50€ per commercial and industrial cross-sectional technologies are considered. To all technologies, an interest rate of 6% and an amortization time of 20 years is applied. The operational DR costs reflect the expenditures arising from the maintenance and utilization of the required ICT (information and communication technologies) infrastructure, as well as compensation for losses in production output and comfort. So, in the SinkDSM component of oemof, variable O&M costs will be considered (in €/KWh to be coherent with the unit of measure of the model), while investment costs will be taken into account in the final economic analysis. O&M cost could be considered constant if we are operating an up or down shift.

The second approach considered is the one proposed by Seebach et al. [46]. In this case there's no distinction between the applications of DSM in different sectors but the cost is attributed to the implementation of smart appliances, and it is expressed per unit of smart appliance. So, in order to allocate the activity on the up and down operation, this cost is split between the two with a proportion of 50/50. The values are reported in Table 6.



	2010		2025	
	Lower Scenario	Upper Scenario	Lower Scenario	Upper Scenario
Additional appliance cost [€/app]	17	34	1,7	3,4
Additional in-house communication cost [€/hh]	50	100	0	0
Standby consumption [W]	2	2	1	1
Additional electricity cost [€ct/kWh]	6	12	6,6	13,2
Appliances per household [app]	5	5	5	5

Table 6: *Costs assessment for smart appliances in different scenarios* [46].

For the model presented in this work, the approach of Gils [44] is chosen as more accurate.

2.4. Heat pumps and electric devices

To satisfy space heating and cooling and domestic hot water demands, different devices are considered. One of these is the heat pump, detailed and configured basing on different sources, domestic system typology, device functioning and operational options. The user will set these choices in the input file, together with the availability of the devices, then the model will implement these settings and finally, through the optimization, the suggested final configuration will be given in output together with the dispatch optimization.

2.4.1. Overview on heat pumps

Heat pumps are becoming a key technology to enhance the renewable energy transition and to promote sector coupling. In fact, almost 180 million heat pumps were used for heating in 2020, and the global stock increased nearly 10% per year over the past 5 years, as can be seen in Figure 7 [47]. According to IEA projections, in the Net Zero Emissions by 2050 Scenario, the installed heat pump stock will reach 600 million by 2030.

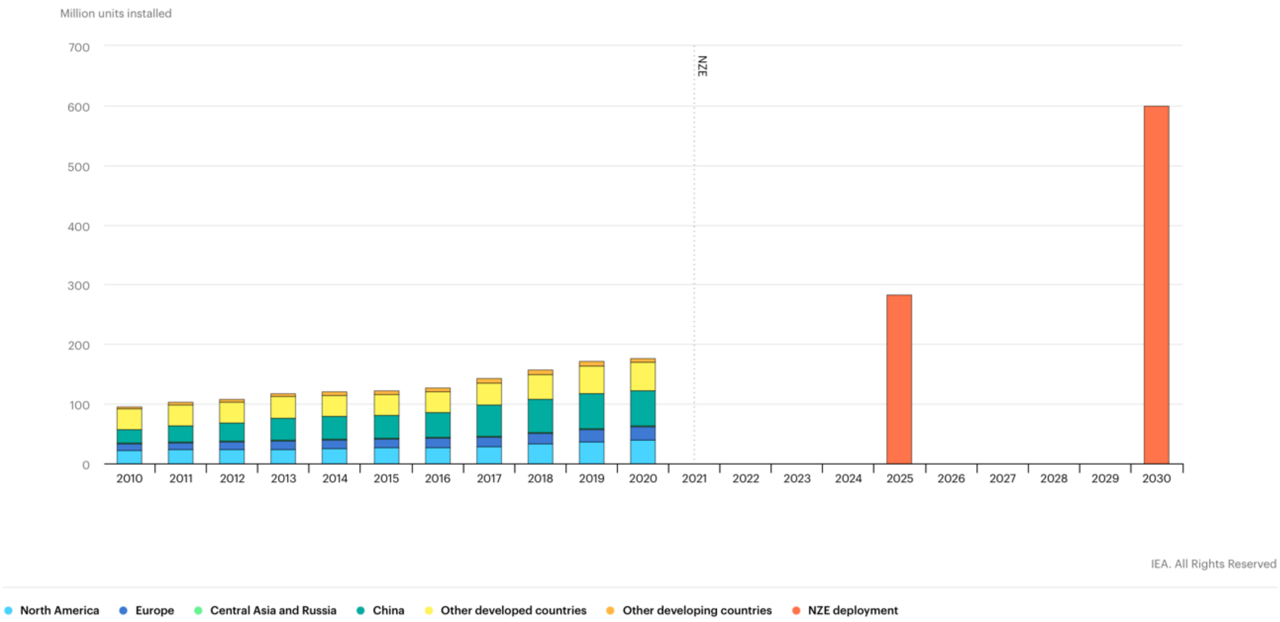


Figure 7: *Installed heat pump stock by region and global Net Zero Scenario deployment, 2010-2030* [47].

Most heat pumps are installed in new buildings. In fact, in many countries, heat pumps register the highest market share of all heating technologies in newly built houses. The EU market is expanding quickly, with around 1.8 million households purchasing a heat pump in 2020 (12% annual average growth since 2015, and 7.5% growth relative to 2019, despite the pandemic). Italy, together with Germany and France, was responsible for nearly half of all sales in the European Union. It is interesting to notice that all heat pumping technology subtypes are becoming more popular. Air-to-air heat pumps have been rapidly becoming more widespread in recent years and now dominate global heat pump sales for new buildings; several factors have raised the popularity of air-to-air heat pump technologies, including policy development, upgraded construction standards that make heat pumps in new buildings more competitive, and growing air-conditioning demand. Also sales of heat pump water heaters (for sanitary hot water production and space heating) have more than tripled since 2010, while ground-source heat pumps are less common globally, with annual sales of around 400 000. The spread of heat pump technology is also due to the fact that the typical seasonal performance factor – an indicator of average annual energy performance – has increased steadily since 2010 to nearly 4 today for most space heating applications. It is common to reach factors of 4.5 and up to 7, especially in relatively mild climates such as the Mediterranean region [47].

For what concerns space cooling the situation is similar. 2 billion AC units are now in operation around the world, making space cooling one of the leading drivers of rising electricity demand in buildings and of generation capacity additions to meet peak power demand. Residential units in operation account for nearly 70% of the total.

Demand for space cooling has risen at an average pace of 4% per year since 2000, twice as quickly as for lighting or water heating. Higher energy consumption for space cooling particularly impacts peak electricity demand, especially during hot days when equipment is used at full capacity. Although space cooling equipment performance is improving continuously and so high-performance AC units available on the market today could cut cooling energy demand in half if widely diffused, reducing energy bills for consumers as well as electricity system constraints [48].

For these reasons, in this work, heat pump technology are investigated and then integrated in the model as one of the key aspects to implement the electrification of the thermal sector in the energy community modelling.

2.4.2. Heat pump technologies

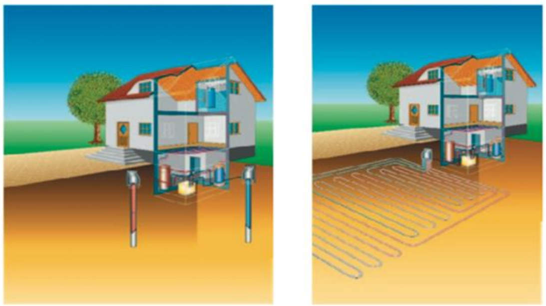


Figure 8: *Ground source which uses ground water as source vs ground source with heat exchangers.*

The first aspect that has to be considered in heat pumps modelling is the heat/cool source the device relies on. In this work three types of sources are considered: air, ground source with ground heat exchanger and ground source which uses groundwater as source. The distinction between the two ground sources typologies is explained in Figure 8. So, depending on the selected source, different correction factors for the coefficients of performance are associated to each type of heat pump.

Secondly, it is necessary to identify the principal heat pumps configurations, which means the typology of heat pump and the domestic system for space heating and cooling or domestic hot water production at which they are connected to.

For what concerns the typology of heat pump, in this work two main categories are represented, which are the air heat pump and the water heat pump, then detailed for each type of source described above (so A/W, W/W, A/A, W/A). This distinction depends on the ultimate heat/cool release method, which can be direct hot air injecting into the ambient from the heat pump or the heating/cooling of water then sent to heating/cooling devices. In case a water system is implemented, a further distinction can be made for space heating/cooling heat pumps, basing on the presence of radiators or floor heating/cooling. In the case of domestic hot water production, the type of heat pump implemented is the water heat pump, which directly heats up the domestic feed water. For this application, a particular attention on temperatures it is necessary to avoid Legionella risk. In Figure 9 the categories described above are schematized.

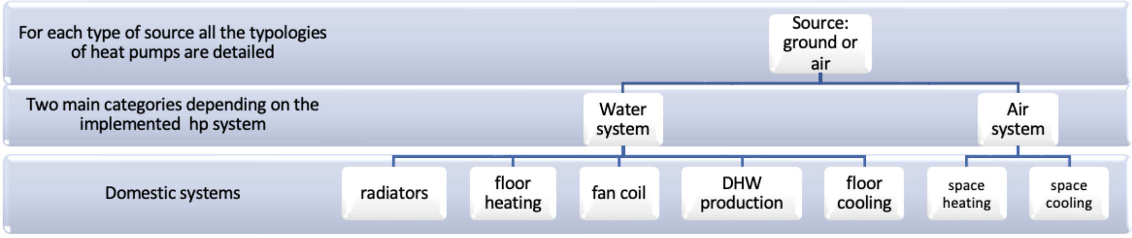


Figure 9: *scheme of heat pump typologies.*

2.4.3. Electric boiler

Another technology is considered for the domestic hot water production: the electric boiler. According to Caleffi [49], one of the most common devices used for domestic hot water production is the tank-type electric water heater. In the report [49] its efficiency is considered equal to 94%, due to losses through the storage tank. In fact, it is possible to say that the efficiency of heat transfer between resistances and water is 100%, which means that one kWh of electrical energy supplied to the heating element will yield exactly one kWh of water heating.

2.4.4. Oemof useful components

The SH/SC/DHW production devices are modelled in oemof through the 'Transformer' component of the oemof solph package. This class can in fact represent a node with multiple input and output flows such as a transforming device (like heat pumps). The component takes in input the electricity flow and gives in output the heat flow (which can be both the one for space heating and domestic hot water), considering a conversion coefficient, which is in this case the coefficient of performance (COP) of the heat pump. It is possible to define a conversion coefficient for every time step, making the analysis accurate and precise.

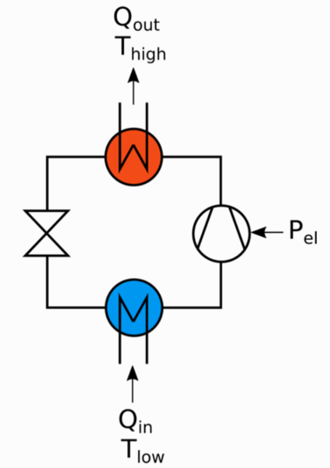


Figure 10: *The heat pump cycle and its two temperature levels.*

The user will activate (by putting 1 in the 'active' column of the input file) the available heat pumps/electric boiler between the ones listed in the file. Then a transformer for each activated device will be generated for each household of the community. The optimization process will then indicate the implementation in the system of one of them, according to the objective function, which in this model is the cost minimization.

In order to differentiate among the different typologies of implemented systems and so to furnish a precise representation of the actual situation, a function of the oemof.thermal package is used to calculate the COP of each heat pump: the 'calc_cops' function. The COP evaluated through the function is based on the 'compression heat pump and chiller' model, explained in the oemof documentation [36]. It increases the temperature of a flow using a compressor that consumes electric power. The inlet heat flux comes from a low temperature source (T_low) and the outlet has the temperature level of the high temperature sink (T_high). The same cycle can be used for heating (heat pump) or cooling (chiller).

The formulation of the COP is the same reported by Bloess et al. [50]: it considers the Carnot COP (the maximum achievable one, referred to ideal conditions), and then considers a correction factor, called the ' quality grade', which accounts for real performances, and varies depending on the heat/cool source. Details are reported in Equation 5, Equation 6, Equation 7 and Equation 8.

Equation 5

$$COP^{real} = \varphi \cdot COP^{Carnot} = \varphi \cdot \frac{T_{sink}}{T_{sink} - T_{source}}$$

Equation 6

$$COP_{Carnot,HP} = \frac{T_{high}}{T_{high} - T_{low}}$$

Equation 7

$$COP_{Carnot,chiller} = \frac{T_{low}}{T_{high} - T_{low}}$$

Where the quality grade is defined as:

Equation 8

$$\varphi = \frac{COP_{real}}{COP_{Carnot}}$$

As cited before, the quality grades are different basing on the type of source of heat/cool for the heat pump. Their values are:

- 0.4 for air source heat pumps
- 0.55 for ground source heat pumps using a ground heat exchanger
- 0.5 for heat pumps using groundwater as source.
- 0.4 to 0.6 for high temperatures heat pumps

These data are reported by oemof documentation [36] and verified through Patteeuw et al. [51].

However, as explained in the study of Bloess et al. [50], the COP is strongly influenced by the source temperature, so considering an average seasonal or even daily temperature would be unprecise. In this model, the adopted solution imports an hourly ambient temperature set [52], corresponding to the location in which the energy community is defined, and in the period considered for the optimization.

The hourly ambient temperature will then be given in input to the 'calc_cop' function for each heat pump typology, leading to an hourly-defined COP. This will result in a highly detailed modelling of heat pumps which considers hourly conversion coefficients that depend on the ambient temperature.

2.4.5. Temperatures

To define conversion coefficients for the different heat pumps configurations, a study on temperatures has been done.

Air systems for heating/cooling

For what concerns air systems for heating/cooling, comfort temperatures for domestic ambient have been investigated, which correspond to the cold/hot temperature sink explained in the COP calculations. Comfort temperatures for summer and winter season are reported in 'UNI EN ISO 7730:2006' [53] and the emerged values are reported in Table 7. In this model, intermediate values between the ones reported are considered, and so 21°C for winter and 25°C for summer.

However, for summer season it is necessary to keep in consideration the contribution of radiation, which represents an additive heat gain inside the building (through the transparent envelope). For this reason, a delta temperature of 3°C is considered corresponding to the contribution of radiation, leading to an internal temperature (which in this case is the hot temperature sink) of 22°C.

Season	Air Temperature [°C]	Relative Humidity [%]	Air Speed [m/s]
Winter	19-22	40-50	0.01-0.1
Summer	24-26	50-60	0.1-0.02

Table 7: *Comfort temperatures for winter and summer, UNI EN ISO 7730:2006.*

Water systems for space cooling

In the case of water systems for space cooling, which means floor cooling systems, the considerations of Karakoyun et al. [54] have been applied in the model. As stated in 'UNI EN ISO 7730'[53], the minimum floor temperature in houses has to be 19°C, in order to avoid discomfort and condensation of humidity on the floor. Karakoyun et al. [54] studies the impact of different configurations of heat gains (Figure 11 (left)) on the internal ambient temperature and consequently defines the supply cold

water temperature (Figure 11 (right)) in the floor system to keep the floor temperature in the normative range.

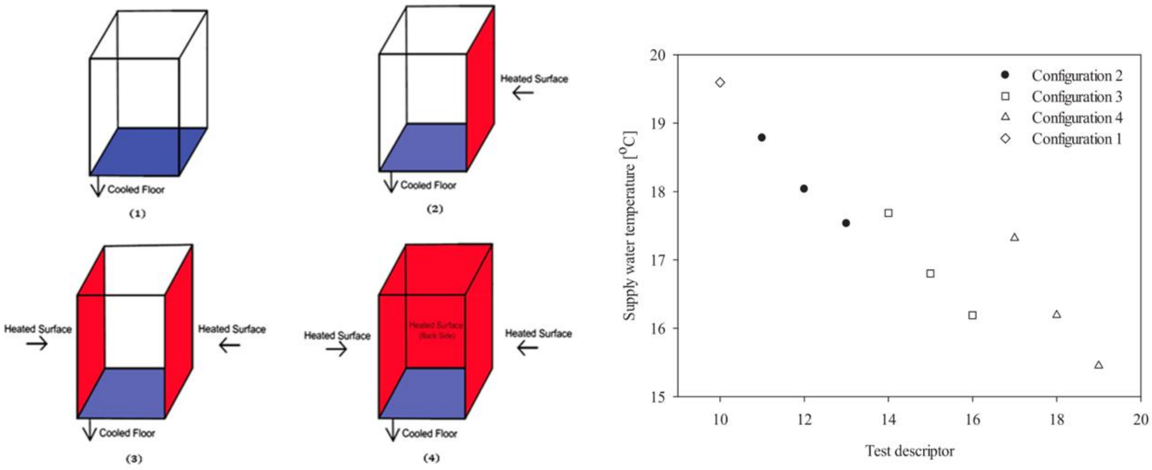


Figure 11: *Heat gains configurations (left), supply water temperature of cold water for different configurations (right).*

Water systems for space heating

For water systems for space heating, supply hot water temperatures are different if the system implemented is with radiators, with floor heating or with fan coils.
Also, there are two possible typologies of regulation of the supply temperatures which can be applied: the fixed-point regulation and the thermoregulation. In fixed-point regulation, the supply temperature of hot water in heating systems (radiators, floor, fan coils) is constant. In thermoregulation, the supply temperature is adapted basing on the external ambient temperature. For doing this, a curve is built starting from minimum and maximum flow temperatures of water and the minimum and maximum external ambient temperatures in the considered period.

Following the ‘Heat pump association’ data [55] and Caleffi report on heat pumps [56], the typical hot water delivery temperature range for each water system has been identified. This is 30-45°C for underfloor heating systems, 35-55°C for fan coils systems, 45-60°C for radiators systems. Also, the usual delta temperatures which occur during the transfer of heat to the internal ambient have been individuated by Maivel et al. [57] and are 10°C for fan coils systems, 15°C for radiators systems, 5°C for underfloor heating systems. In the case fixed-point regulation is chosen, the highest temperature in the interval for each system will be set, in order to account for the worst situation and be able to furnish an adequate heating to the house. All these data will be precisely applied in the model (details in the following section).

Domestic hot water production systems

For domestic hot water production systems (which are water systems), a particular attention has to be given to the Legionella risk [58]. Legionella is a very dangerous bacteria which causes pneumonia and that can be found in lakes, rivers, wells which feed aqueducts and it's able to overcome all the normal purification treatments. In order to avoid the Legionella formation risk, two types of thermal disinfection treatments can be applied: the continuous treatment or the periodic treatment. The first one consists in maintaining the water temperature above 50°C for all the hours of the day. The second one consists in keeping the water temperature at a lower temperature for all day but then to raise it to 65°C for at least 30 minutes per day. The temperature at which the water is kept when the periodic treatment is not applied depends on the type of user (commercial, industrial, residential…), and for the case considered in the model, which is the residential one, it's equal to 40°C [58].

2.4.6. Oemof model details

In the input file of the model, in the section 'q_grades' it is possible to activate the source of heat/cool considered for the moelled energy community. It is assumed to be the same for all the users.

Then the q-grade, which is the correction factor used to account for real performances in the COP definition, will be automatically set for each device.
In the model, all the typologies of heat pumps and electric devices described above, and the relative data, are imported from the input excel file. Then they are implemented through the oemof useful components described in section 2.4.4 and optimized through the optimization tool (the solver used is Gurobi [59]). The user can choose which device is available by putting '1' in the 'active' column of the 'mode' sheet, in which all the other information about input and output flows and temperatures are considered. In the sheet 'settings' the user can also activate the desired treatment for domestic hot water (periodic or continuous treatment) and the type of regulation to apply in water systems for space heating (fixed-point or thermoregulation). Also, in this case it is assumed that the energy community has a common operation line, and so the settings are the same for all the members of the community.
Once the activated options are defined, these must be implemented in the code.
For air systems, input parameters are easily imported by the activated options (Table 8) and assigned to the components.

type	conversion	input	output	active	thigh_hp	tlow_chiller
AW/A_hp_winter	cop_hp	electricity	heat_output	1	21	0
AW/A_hp_summer	cop_chiller	electricity	heat_removed	1	0	22

Table 8: *input parameters for air systems.*

For the implementation of the cold water flow temperature regulation in the cooling water systems which takes into account the heat gain distribution, detailed as in section 2.4.5, the user selects the number corresponding to the configuration (Table 9 in Figure 11 (left) which best fits the real house disposition. If no configuration is selected, the default one is configuration number 2, as common for multi-apartment buildings and multi-family houses. Basing on this choice, in the model flow temperatures will be automatically set on the values reported in Figure 11 (right).

type	conversion	input	output	active	cooling_config
AW/W_chiller_floor	cop_chiller	electricity	heat_removed	1	2

Table 9: *input parameters for floor cooling.*

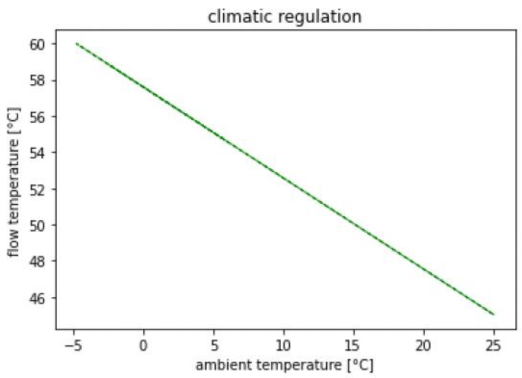
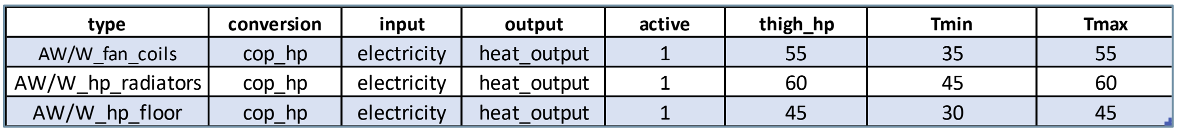


Figure 12: *example of climatic curve of space heating water system with radiators.*

To represent the space heating thermoregulation, a function has been created, called **'climatic_regulation'**. This function takes as input (i) the hourly ambient temperature according to the location of the energy community and the period considered, (ii) the minimum and (iii) maximum flow temperatures of hot water, which are automatically imported from the input file basing on the component that is being implemented and on the (iv) climatic zone in which the community is located. The function firstly creates an 'on_list' which is a list containing the value 1 when the space heating is supposed to be switched on, basing on the Italian legislation ('Decreto del Presidente della Repubblica n.74 del 16 aprile 2013, art. 4' [60]) and 0 when it is supposed to be switched off. Then, the minimum and maximum ambient temperatures are extrapolated from the ambient temperature array but considering only the ones corresponding to the 'on' period. Finally, a curve which relates the ambient temperature (between minimum and maximum values) and the flow temperature (between minimum and maximum values) is created. The function returns a list containing the hourly supply temperatures of hot water corresponding to the hourly ambient temperatures.

In Figure 12 an example of climatic curve is reported. In Table 10 the details about the water space heating systems implemented in the model is reported.

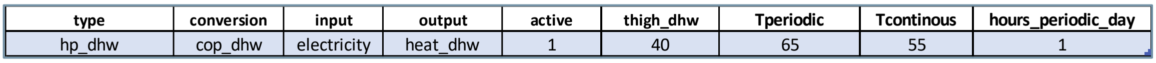


type	conversion	input	output	active	thigh_hp	Tmin	Tmax
AW/W_fan_coils	cop_hp	electricity	heat_output	1	55	35	55
AW/W_hp_radiators	cop_hp	electricity	heat_output	1	60	45	60
AW/W_hp_floor	cop_hp	electricity	heat_output	1	45	30	45

Table 10: *input detais of water space heating components.*

For the implementation of the domestic hot water treatments explained in section 2.4.5, a function to represent the periodic treatment has been created, while for the continuous treatment only the importation of one value is necessary. The function is called **'periodic_treatment'** and takes in input (Table 11) the list of hourly ambient temperatures corresponding to the selected period and location, the temperature at which hot water is supplied for the time of the periodic treatment, the temperature at which it is supplied for the remaining hours of the day, the hours per day at which the treatment will be done and a list containing the 'on' profile for domestic hot water demand.

In detail, the function creates a list containing the hourly 'usual' supply temperature of water for each hour of the period considered and then substitutes each 24 hours the value of the high temperature for the treatment. However, a further check is made. Considering that the system will operate when the demand is higher than zero, the function checks that at the supposed moment of the treatment the demand is not zero. If the check is not verified, the function goes back with a step of one hour, until a demand different from zero is found. That will be the hour of the periodic treatment implementation. This because the treatment, following the instructions cited in section 2.4.5, has to be made for at least 30 minutes per day, which means that no more that 24 hours can pass between one treatment and the next one. The function returns a list containing the hourly hot water supply temperature in case of periodic treatment implementation.



type	conversion	input	output	active	thigh_dhw	Tperiodic	Tcontinous	hours_periodic_day
hp_dhw	cop_dhw	electricity	heat_dhw	1	40	65	55	1

Table 11: *input parameters for domestic hot water systems.*

Once the temperatures are defined for each type of device, they are given as input to the 'calc_cops' function of the oemof.thermal package, which calculates the COP for each type of heat pump described. Heat pumps for space heating and domestic hot water production are separated, in order to precisely define temperatures and so related electricity consumptions. In the case of the electric boiler, the efficiency is set to 1.

Then the ‘transformer’ component is created for each heat pump typology and for each user of the EC, considering as input the COP previously calculated. Oemof optimization will then effectively implement the transformers which contribute to give the minimum cost and best dispatch. Further details on the structure of the implemented elements in the energy community model will be explained in the section ‘Energy community model details’.

2.5. Photovoltaic system

The main renewable source of electricity considered in this work is the photovoltaic one. However, in the ‘sources’ sheet of the input file also other ones could be implemented, such as wind turbines.

2.5.1. Overview on PV technology

The choice of relying principally on PV source is due to various considerations. According to Iea [61], PV is becoming the cheapest source of power in many economies, since its capital cost from 2010 (updated to 2020) has reduced by nearly the 80% (Figure 13).

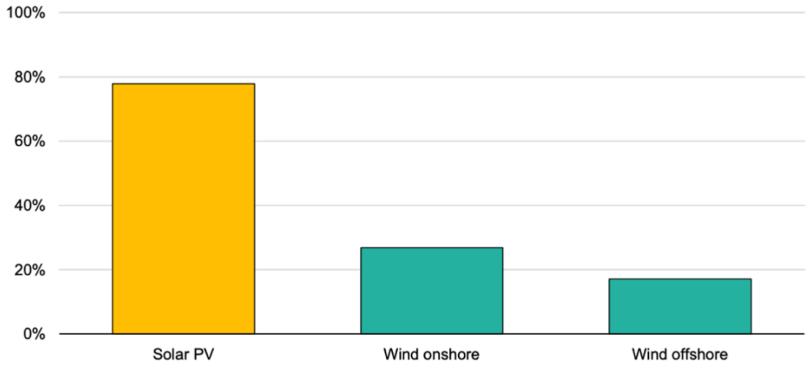


Figure 13: *Reduction in capital cost since 2010 for PV and wind power generation technologies* [61].

More recently wind and solar PV have seen rapid expansion, led by policy support in Europe, accounting today for the 2.5% of global power supply. The expansion foreseen for this technology in the ‘Sustainable Development Scenario’ is impressive and includes around 3 600 GW of distributed rooftop solar PV is integrated into the fabric of buildings (on the roof and walls, or in windows) in 2070 (Figure 14).
Also, in most of the cases analyzed in the literature overview section, PV are present and often identified as the principal electricity source.

Bernadette et al. [28] evidences, after the analysis of different case studies, that the profitability of implementing optimally-sized PV systems increases when forming ECs compared to the situation of considering buildings individually.

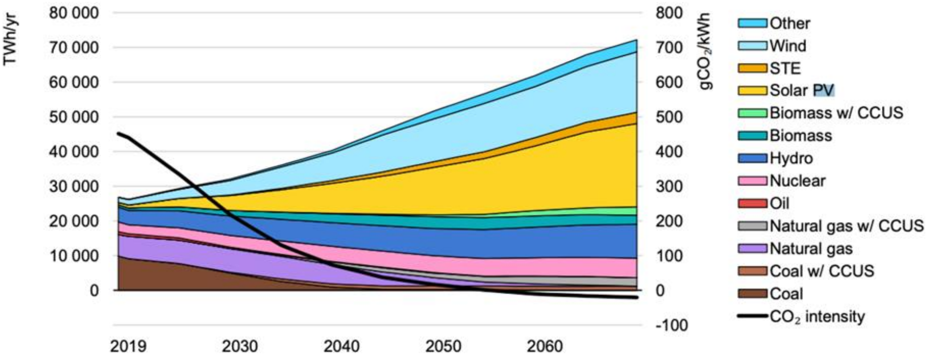


Figure 14: *Global power generation by fuel/technology in the DSD, 2019-70* [61].

The more different the load profiles, the more synergy effects, and the higher the cost saving potential. Another advantage of PV modules is that it's easy to install and it's modulable to adapt to the available space.

2.5.2. Oemof model details

The user can directly activate the source available/that he wants to implement by putting '1' in the 'active' column of the 'source' sheet of the input excel file. In the same location, the user can insert the parameters related to the selected source of electricity. However, to make the model as versatile as possible, default values which can be used for simulations have been studied. These values are relative to the costs, maximum capacity and normalized production profile of PV modules.
The normalized PV electricity production profile is reported in the 'time_series_so' sheet of the input file and corresponds to a general profile evaluated for a location sited in North Italy, simulated through the PVGIS [62] software. It can be substituted in the input file in order to have a precise normalized profile referred to the selected location.
The maximum capacity of PV that can be installed for each user is constrained by the available surface. This is considered peculiar to two cases: in the first one the user activates the 'AC' option ('autoconsumo collettivo', details in the following sections) in the input file, which means that the collective roof available surface is known and it's directly imported; in the second one the user activates the 'CER' option ('comunità energetica rinnovabile', details in the following sections), which means that the available surface is relative to each user.

In particular, it is assumed that the available surface for each user for PV installation in equal to the 50% of the house surface, considering unavailable the north side and taking into account eventual shaping objects. Details on the assignment of different house surfaces to the user will be explained in the demand profiles definition section. The surface occupied by 1 kWp of installed PV capacity is calculated considering the model 'LG385N1C-EG' of LG [63], and it's equal to 5.4 m^2/kWp. The limit capacity is equal to the ratio between the available surface and the one occupied by one kWp of installed PV.

Costs needed for the implementation are the one corresponding to 'ep_costs' and 'offset' voices of the Investment option with the activation of 'NonConvex' component. This mode is set because it allows to obtain a combined dispatch and investment optimization. With the NonConvex option, also, the solver can decide whether install or not the component. The objective function is reported in Equation 9. The ep_costs represent the portion of the overall costs which varies with the installed capacity, while the offset costs represent the fixed ones, which are the same for each installed size. This option allows to account for economies of scale, which have a great impact on the optimization. To find these two components of costs an interpolation curve was created considering the real turn-key costs obtained from EnelX store [64].
The curve is reported in Figure 15. These values are then actualized in the model through the economics.annuity function of the oemof.tools package, which considers a lifetime of 20 years and a Weighted Average Cost of Capital (WACC) of 0,04 [65]. The formula on which the function relies on is detailed in Equation 10.

Equation 9

$$Obj = E_{invest} \cdot c_{invest,var} + b_{invest} \cdot c_{invest,fix}$$

Equation 10

$$epc = capex \cdot (wacc \cdot (1 + wacc) \cdot lifetime/((1 + wacc) \cdot lifetime - 1)$$

Where:

$$epc = periodical\ costs$$
$$capex = investment\ costs$$
$$lifetime = life\ expectancy$$
$$wacc = weighted\ average\ of\ capital\ costs$$

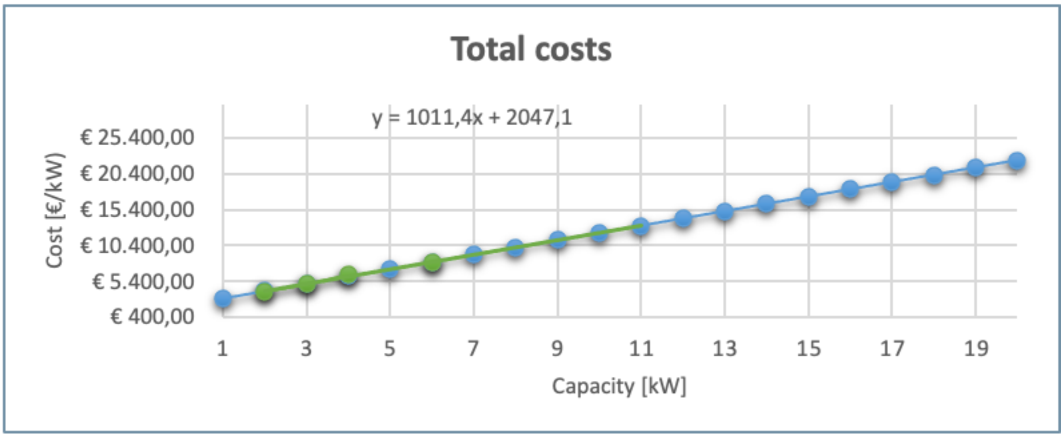


Figure 15: *Total cost curves for PV.*

Once all the necessary values have been found, these are implemented in the oemof.solph class ‘Source’. In the case a ‘REC’ is implemented, one PV source is created for each user, otherwise, if an ‘AC’ is chosen, only one PV source is generated for all the users, positioned on the roof of the multi-apartment building considered.

2.6. Thermal Storage

The thermal storage is considered in the model for both the storage of space heating and domestic hot water. One thermal storage is created in the model for each EC user.

2.6.1. Thermal Storage options

The thermal storage can be applied in different manners. Hedegaard et al. [66] identifies four principal storage options:
1) intelligent passive heat storage in the building structure via radiator heating (or floor heating),
2) intelligent active heat storage in concrete floors via floor heating,
3) heat accumulation tanks for space heating,
4) storage tanks for hot water (for showering, dish washing etc.).
The first two options can be considered in the activation of load shifting and load shedding through the SinkDSM component.
Options 3 and 4, which implies the implementation of accumulation tanks for hot water, are deepened and applied through oemof.solph and oemof.thermal components.

2.6.2. Thermal Storage in the oemof model

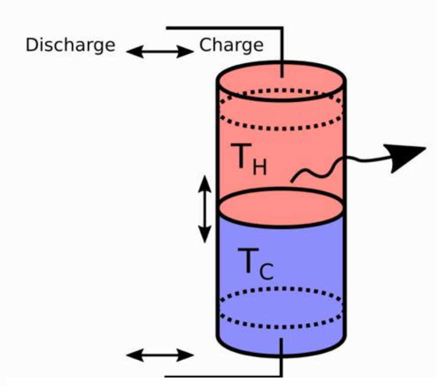


Figure 16: *stratified thermal storage component, oemof* [38].

In the oemof.thermal package [38], the thermal storage is represented though the 'StratifiedThermalStorage' component (Figure 16).

This is a stratified thermal storage with two perfectly separated bodies of water with temperatures Th and Tc. When charging/discharging the storage, the thermocline moves down or up, respectively. Losses to the environment through the surface of the storage depend on the size of the hot and cold zone.
A detailed mathematical model of an equivalent storage is made by Raccanello et al. [67]. Advantages related to the use of stratified storage technologies are described by [68].
The component takes as input the bus considered for the storage, the diameter of the tank, the high and low temperatures which characterize the thermocline, the ambient temperature, the u-value (which can be previously calculated through a function), the minimum and maximum storage levels, the efficiency, the marginal cost, the capacity and storage capacity costs. Also, if the investment mode is implemented to optimize the nominal storage capacity (kWh) with a fixed ratio with respect to the charging/discharging capacity (kW), a relation between the two has to be defined, which is equal to one over the hours of autonomy the storage should ensure.
In this work this option is chosen and 6 hours of autonomy are set, accordingly to the validation data proposed by oemof documentation [36]. It is possible to define a storage capacity potential which delimitates the maximum installable size of the component. Here this is defined through the 'calculate_capacities' function. The output with the investment mode will be the optimal storage capacity (and so the height of the tank will be also optimized) and the optimal dispatch, together with losses values, if the specific function 'calculate_losses' of the oemof.thermal package is implemented.
Two stratified thermal storages are considered for each user: one for the space heating storage and one for the domestic hot water storage, to obtain precise results.
In this model:

- The **bus** which enters and goes out from the thermal storage is the 'heat_dhw' for the domestic hot water storage and 'heat_output' for the space heating storage. The two storages are formally separated in order to be able to set specific temperatures and so evaluate losses in a detailed and precise way.

- The parameters for the calculation of the **u-value** depend on the characteristics of water, of the insulation material of the tank and on the convective heat transfer coefficients of water (inside the tank) and air (outside the tank). Raccanello et al. [67] proposes in its dynamic modelling of a single-tank thermal energy storage systems a set of useful values (Table 12), which will be used in this model (being its mathematical modelling coherent with the one implemented here).

Parameter	Fluid/material	Value
Working fluid specific heat capacity	Water	4186 J / kg·K
Working fluid thermal conductivity	Water	0.6 W/m·K
Working fluid density	Water	1000 kg/m^3
Insulation thermal conductivity	Fiberglass	0.05 W/m·K

Table 12: *Thermophysical properties of fluids and materials.*

- The **high temperature** for one single user is considered as the average of the high temperature list, obtained by applying one of the treatments described in section 2.4.6. This because it is not possible to integrate a list of temperatures in the component.
- The **cold temperature** for one single user is considered as the return temperature for space heating hot water and 20°C for DHW temperature. As explained in section 2.4.5 the usual delta temperatures which occur during the transfer of heat to the internal ambient (so for space heating water) have been individuated by Maivel et al. [57] and are 10°C for fan coils systems, 15°C for radiators systems, 5°C for underfloor heating systems. So, a list of return temperatures for space heating water is created starting from these information and then the average value is used for thermal energy storage calculations. For what concerns the temperature at which domestic water is supplied to households, a set of values is reported by Agudelo-Vera et al. [69] and for Italy it's 6°C for winter and 15°C for summer. However, following the schemes proposed by Cordivari [70], and the limits to Legionella survival [58], supply cold water is assumed to be mixed with hot water before entering the tank, reaching in this way a temperature of 20°C.
- In order to have reliable data about the **size of the component**, necessary for the calculation of the nominal storage capacity and the losses, a set of existing thermal storage models have been inserted in the input excel file. In particular, the models 'volano termico grezzo GC VT' of Cordivari [71] has

been chosen for space heating, while 'vaso inerziale accumulatore polywarm di A.C.S' of Cordivari [72] has been selected for domestic hot water. Different sizes of these components have been detailed in the input excel file, and for each one the 'active' option can be set to 1 (if it's available) or to 0 (if it's not available) by the user. These models have been picked out because they are coherent with the model proposed by the oemof.thermal package described above.

The contribution of this component is principally the evaluation of the thermal losses and the nominal storage capacity, precisely calculated for the thermal storage.

However, some difficulties emerged in the implementation of the 'StratifiedThermalStorage' in the model.
In fact, the component lacks in the possibility of using the 'NonConvex' option, which, as cited before, is useful to consider economies of scale, fundamental aspect in the choice of the size. So, the only way to evaluate this aspect by using this component would be to evaluate all the sizes of the two storage models of Cordivari described above for each user, and this will certainly slow down the optimization process, but it also limits the implemented size to the available ones.

The solution proposed in this work is to implement the thermal storage by using the **'GenericStorage'** component of the oemof.solph package, and integrate it with the 'calculate_losses' function of the 'StratifiedThermalStorage' component of the oemof.thermal package. In particular, in order to avoid oemof to calculate losses for each size of each thermal storage for each user, the model of the 'SingleUser' is used. As the settings are coherent for all the energy community, domestic hot water systems temperatures will be the same and implemented in the single user's code.
For what concerns space heating, it will be necessary to firstly run the code of the energy community (with an arbitrary loss value) and discover the output size of the optimized chosen component, to finally set the correspondent temperature. The relative information will be then used for the single user's model optimization, which will give in output the precise losses. The procedure of 'losses adjustment' will stop if the size of the optimized components of the energy community model remains in the range of one available existing model size (of the input excel file).

The losses implemented in the 'GenericStorage' component are composed by three different voices:

- Loss_rate: The relative loss of the storage capacity between two consecutive timesteps [-]

- Fixed_losses_relative: Losses independent of state of charge between two consecutive timesteps relative to nominal storage capacity [-]
- Fixed_losses_absolute: Losses independent of state of charge and independent of nominal storage capacity between two consecutive timesteps [kWh]

The economies of scale have been evaluated as detailed in section 2.5.2 for PV. In this case, costs of the thermal storage existing models of Cordivari have been used for the computation. Data and curves are reported in Table 13 , Figure 17 and Figure 18. The emerged value for variable costs is 23 €/kWh, the one for fixed costs is 305 €.

Model name	Size [L]	Size [kWh]	Diameter [m]	Price [€]
Cordivari_xxs	200	6.01	0.55	448.7
Cordivari_xs	300	8.39	0.65	559.7
Cordivari_s	500	13.86	0.75	655.26
Cordivari_m	800	23.62	0.9	796.18
Cordivari_L	1000	30.40	1	863.89
Cordivari_XL	1500	39.93	1.1	1317.99
Cordivari_XXL	2000	57.62	1.3	1588.73
Cordivari_xs_dhw	200	12.21	0.55	620
Cordivari_s_dhw	300	17.06	0.65	700
Cordivari_m_dhw	500	28.19	0.75	870
Cordivari_L_dhw	800	48.03	0.9	1280
Cordivari_XL_dhw	1000	61.81	1	1480

Table 13: *Data about considered thermal storage models.*

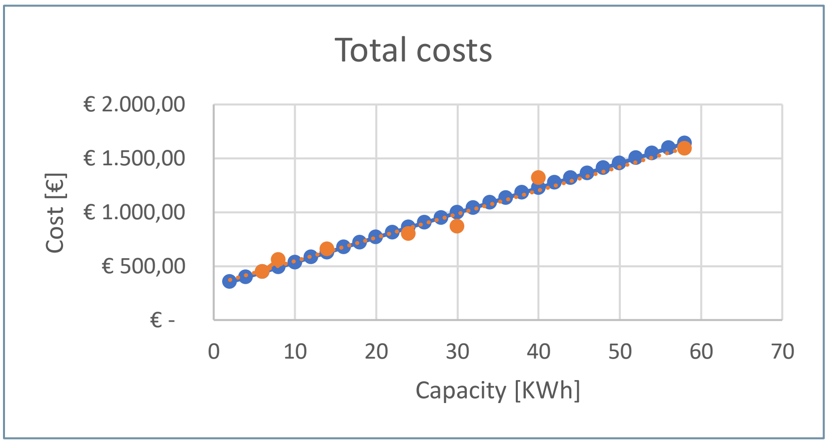


Figure 17: *Total cost curves for thermal storage.*

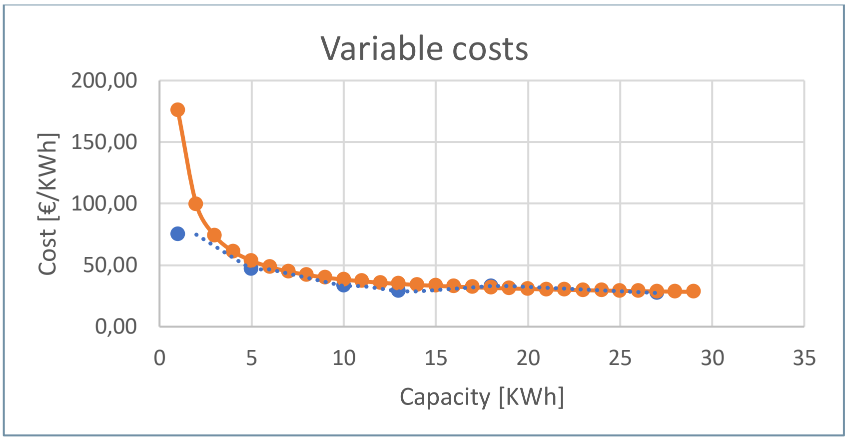


Figure 18: *Variable costs curve for thermal storage.*

2.7. Electric Storage

An electric storage is added in the model to allow a realistic optimization which also considers the aspects relative to the electric sector, besides the electrified thermal one.

To model it the 'GenericStorage' component of the oemof-solph package is used. One electric storage for each user is created and then, through the optimization, the effectively installed one with the relative capacity will be given in output.

The input parameters are referred to the battery 'LG CHEM RESU SERIE' [73], which is characterized by a round trip efficiency of 94.5% and an end-of-life efficiency of 80%.

Also for this component economies of scale are implemented by using the 'NonConvex' option in the 'Investment' mode. Costs are calculated as explained in the previous sections for PV and for the thermal storage. In Figure 19 and Figure 20 resulting curves are represented. The emerged value for fixed costs is 2140 €, while the one for variable costs is 620.83 €/kWh.

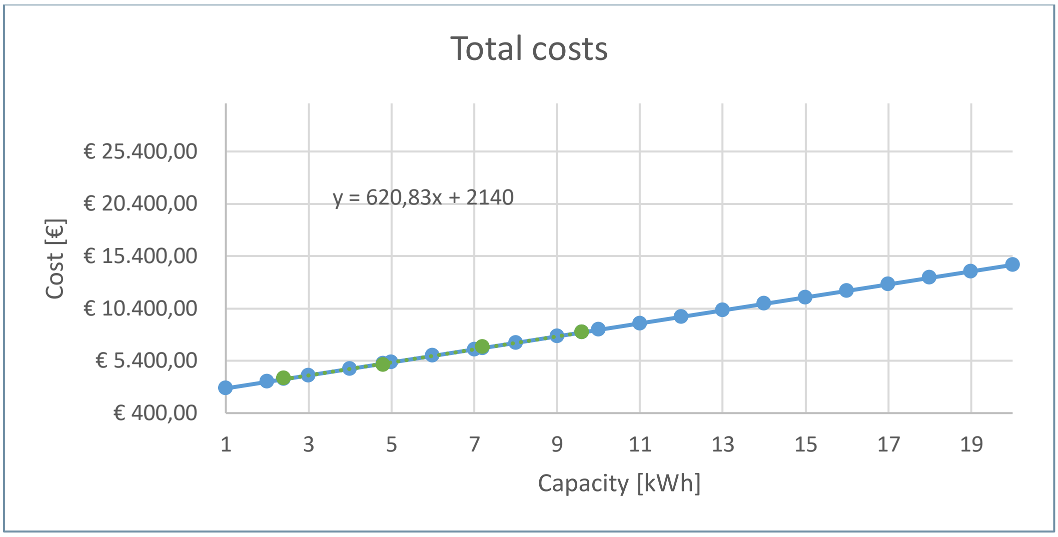


Figure 19: *Total costs for electric storage.*

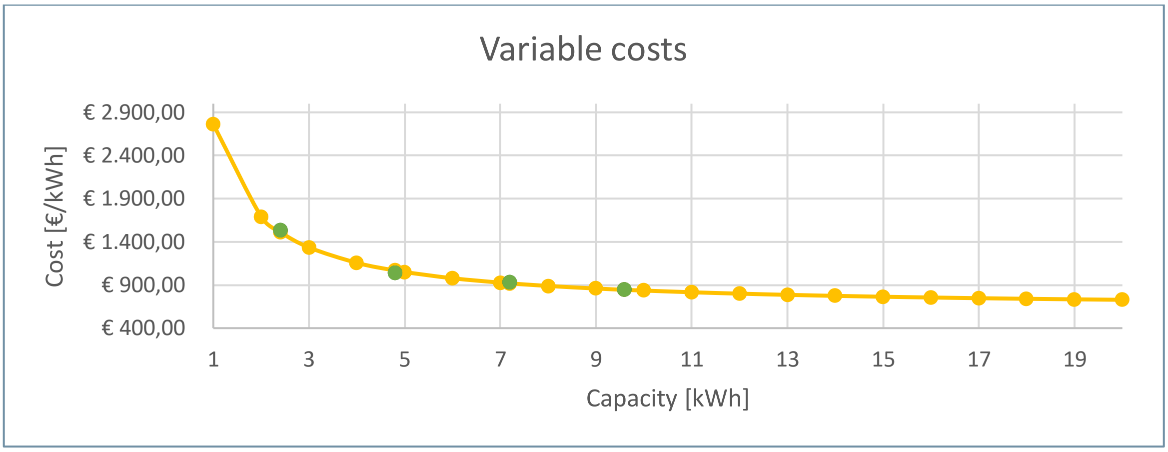


Figure 20: *Variable costs for electric storage.*

2.8. Solar Thermal Collector

The 'SolarThermalCollector' component of the oemof thermal package is considered for a second optimization, to be made after the first optimization process. This is to do a sensitivity analysis on the advantage of the integration of this technology using the remaining available space. This technology is only considered for domestic hot water production.

2.8.1. Overview on solar thermal collectors

According to IEA estimates [74], based on the past trend shown in Figure 21, direct solar thermal consumption will grow more than 2.5 times as fast during 2021-2026 in the Net Zero Emissions Scenario than anticipated in the previous IEA outlook. The addition is both from the installation of solar thermal water heaters in buildings and the take-off of solar heat for industrial processes. Accordingly, the number of dwellings using solar thermal systems rises from 250 million in 2020 to 400 million by 2030, and up to 1.2 billion in 2050.

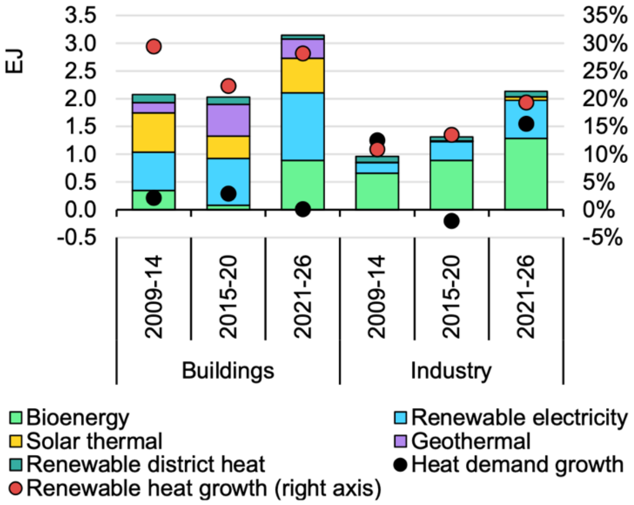


Figure 21: *Increase in renewable heat consumption by energy source 2009-2026.* [74]

To understand the state of the art of the studies about the penetration of this technology in the electrified thermal energy sector, some work has been examined. Reda et al. [75] compares two options for the satisfaction of thermal demand: the first one implements solar collectors and district heating, and the second one a photovoltaic driven air source heat pump. Results show that the solar assisted absorption heat pump is able to upgrade the low temperature solar thermal energy into useful heat for building heating supply, demonstrating that solar thermal energy can effectively contribute to supplying heat to buildings. The solar assisted absorption heat pump shows higher renewable energy share than the PV driven heat pump when comparing system solutions with the same area of installed solar technologies. However, the cost analysis shows that the electrically driven system is more economical viable.

Martorana et al. [30] investigates the energy performances of several configurations of solar-assisted heat pumps equipped with photovoltaic and photovoltaic-thermal panels as well as solar thermal collectors for domestic hot water production.

It emerges that solar thermal collectors do not properly support the daily heat pump operation, especially in winter, and present a certain electricity consumption for auxiliaries which results to be penalizing. Also in the analysis of Patteeuw et al. [51] it is evidenced that in a residential context, solar thermal collectors are mainly installed for partially supplying domestic hot water, and are not shown as primary optimization components in the models proposed.

For these reasons, the solar thermal collector is added in this work only after a first optimization process and implemented to cover the remaining available space (after the eventual installation of PV) with the aim of supporting the heat pump/electric boiler implemented for domestic hot water production.

Differences in costs, optimal dispatch and performances will be evaluated in a sensitivity analysis.

2.8.2. Solar Thermal Collector in oemof model

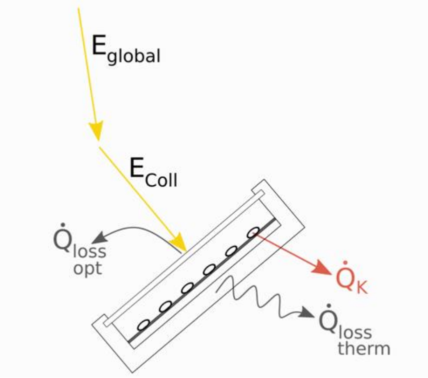


Figure 22: *The energy flows and losses of a flat plate collector.*

The 'SolarThermalCollector' is a component of the oemof.thermal package [38] and it's created to evaluate the usable heat of a flat plate collector based on temperatures and collector's location, tilt and azimuth (Figure 22). It is conceived to be then implemented in an energy system of the oemof.soph [37] package. A detailed thermal model corresponding to the one proposed in the oemof.thermal package is proposed by Hajabdollahi et al. [76]. As cited before, this component is considered only in a second step, after the first optimization process. It is assumed that, at that point, the available space remaining on each house (which corresponds to a node of the energy community) or on the collective roof of the multi-apartment building is known and can be integrated by the user in the input excel file. Also in this case, a selection between the 'AC' or the 'CER' is made by the user, and consequently he adds to the input file the overall remaining available space or the one peculiar to each user. The model will automatically consider one of the two cases as input.

Data about the optical efficiency and thermal loss parameters are the ones of the 'Viessman vitosol 200-fm' [77] solar flat plate collector model.

For what concerns latitude and longitude values, these can be directly inserted in the input file by the user, depending on the location of the energy community.

The hourly irradiance data (horizontal, global and diffuse) are generated using the 'Photovoltaic Geographical Information System' (PVGIS [62]) software of the 'EU SCIENCE LAB'. Then they are imported in the model through a dedicated csv file. The tool also returns the optimal values of azimuth and tilt. These will be integrated in the model, as it is assumed that the precise values for each user are not known.

The inlet temperature is assumed to a value of 20°C (value also considered by Hajabdollahi et al. [76]), as it should be extracted from the thermal storage cold side. The delta temperature due to the solar thermal collector is assumed to 10°C, basing on the study of Stanciu et al. [78] whose results are reported in Figure 23.

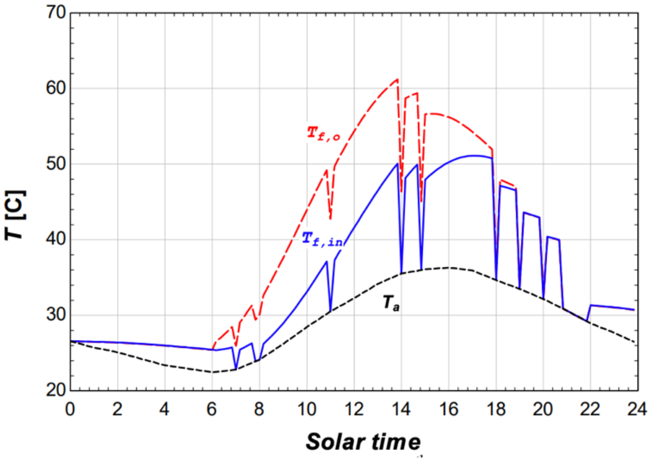


Figure 23: *Inlet and outlet fluid temperatures, July 15th*. [78]

2.9. Grid, excess, shortage

2.9.1. National electrical grid

One of the optimization study objectives is the evaluation of the effective profitability of installing renewable local energy sources for electricity generation with respect to buy it from the grid. For this reason, another source of electricity is added in the model: the national electrical grid. Formally, one electrical grid is created for each user, to be able to evaluate the furnishment of electricity to each specific node. However, the effective grid is only one and also the relative parameters. These are in particular the variable costs, which are directly set in the 'grid' sheet of the input excel file. In this way, the user can insert the actual electricity price. Also, the file is pre-disposed for the integration of other electricity sources, in case an additional sensitivity analysis would be made. The set electricity variable cost is the cost of electricity of year 2019, as the following prices have been unusual due to the Covid-19 pandemic (Figure 24).

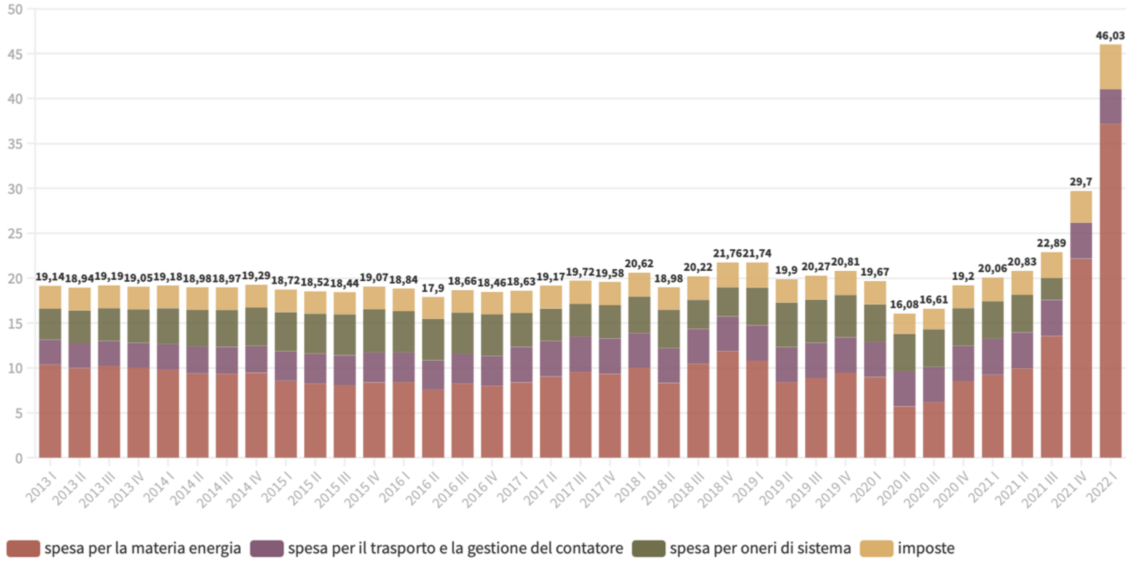


Figure 24: *Electricity price fluctuation in Italy, 2013-2022. (ARERA)*

2.9.2. Excess and shortage

To ensure that the energy balance is satisfied within the community, two additional components are considered: the energy excess and the energy shortage.

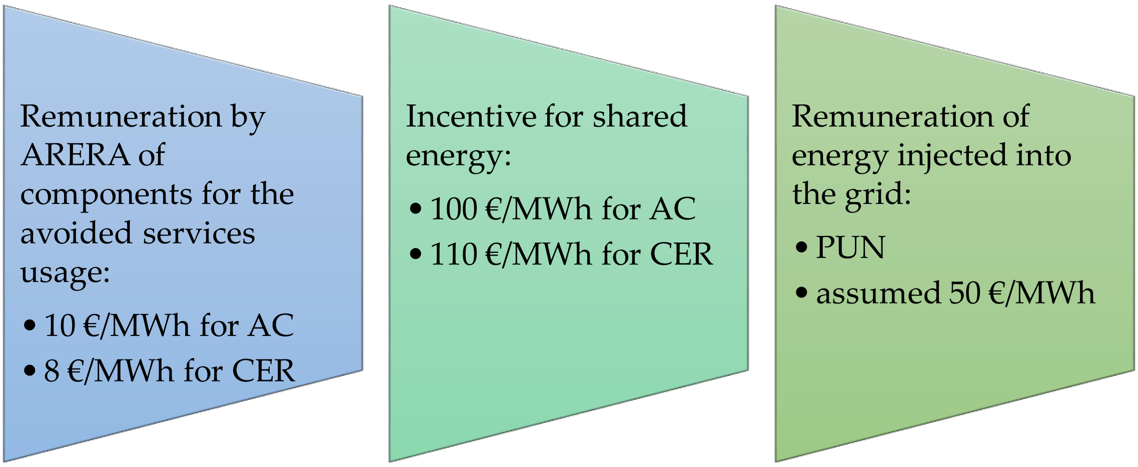
In this model, the excess is considered for all the fluxes (electricity, heat_output for space heating, heat_removed for space cooling, heat_dhw for domestic hot water production), while the shortage is set for all of them except for the electricity, for which is already defined the national grid in substitution to the excess. The shortage, in this case, is only a fictitious element implemented to enhance the energy balance in case particular problems occur. So, to disincentive its usage, a cost of 1€/kWh is attributed. It could also represent 'emergency' energy sources, such as diesel generators or biomass chimneys. For a sensitivity analyses on the effective advantages of using renewable energy sources for electricity production and the electrification of the thermal sector, the shortage cost has been identified as the one of electricity purchased from the national grid for space cooling and the one of methane (considering its lower heating value and traditional boiler efficiency) for DHW and space heating.

For what concerns the excess, its remuneration is set to the 'prezzo unico nazionale' (PUN). The excess of flows other than electricity are not valued.

2.10. Shared electricity

One of the principal characteristics of energy communities is the sharing of energy (in this case of electricity) between the community members. Shared electricity flows can be modelled in oemof.solph [37] thanks to the 'Link' class. This takes as input the two buses between the energy is shared (in both directions) and a conversion coefficient which is in this model considered equal to one, being it a 'virtual' sharing. If the two input buses are for example 'electricityA' (referred to node A) and 'electricityB' (referred to node B), the output flow 'electricityAshareelectricityB' represents the electricity flow shared between nodes A and B in both directions.

To promote the development of energy communities, different support schemes have been implemented according to 'Legge 8/2020', to the regulation model identified by ARERA and to the incentives system defined by MiSE ('Ministero dello sviluppo economico') Decree. All these economical supports are listed in the document by GSE [79] and represented in Figure 25.



Remuneration by ARERA of components for the avoided services usage:

- 10 €/MWh for AC
- 8 €/MWh for CER

Incentive for shared energy:

- 100 €/MWh for AC
- 110 €/MWh for CER

Remuneration of energy injected into the grid:

- PUN
- assumed 50 €/MWh

Figure 25: *contributes of the economic support scheme for energy communities.*

All these voices are integrated in the oemof Link component.
Thanks to these contributions, the energy injected into the grid is valued to the zonal price and the one which is then shared between the community members will have an advantageous cost, lowered by the incentives and remuneration components.

2.11. NPV and emissions

The Net Present Value is calculated for 20 years (during which EC self-consumed electricity is valorized through incentives) considering investment costs for PV and TES, and cashflows related to savings with respect to the import of electricity from the national grid. Details are reported in the following part.

Equation 11

$$PV_{self-cons} = PV_{prod} - excess$$

Equation 12

$$saving_{self-cons} = \left(PV_{self-cons} - shared\right)[kWh] \cdot Cost_{grid}$$

Equation 13

$$saving_{shared} = shared \cdot (remuneration + incentive + PUN)$$

Equation 14

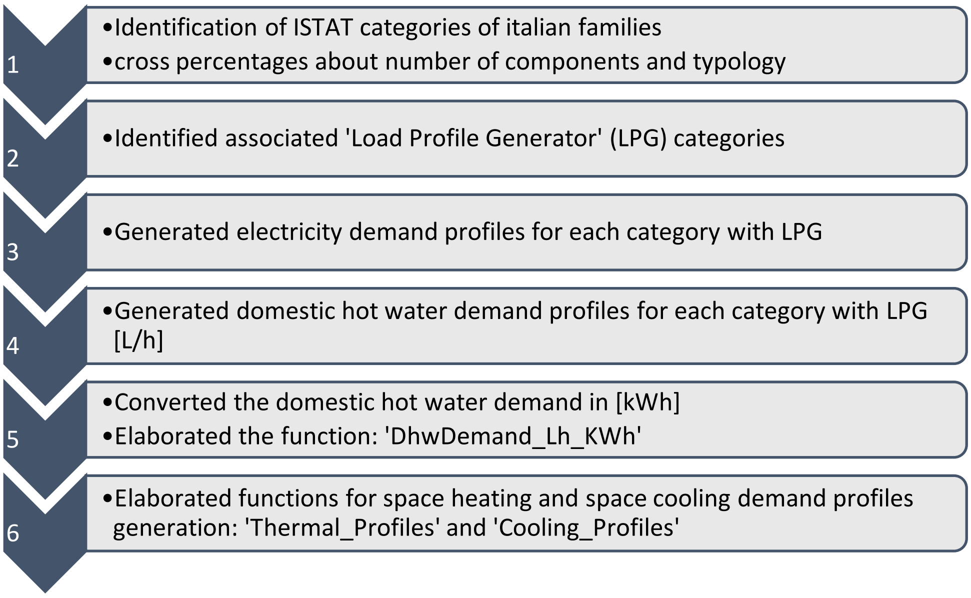
$$earning = excess \cdot PUN$$

Where PV_{prod} is the total electricity production of the EC from PV in one year, $excess$ is the electricity injected into the grid in one year, $shared$ is the total annual electricity shared within the EC, $Cost_{grid}$ is the price at which electricity is bought from the grid, remuneration and incentives are the ones described in section 2.10 for shared electricity in ECs. These values have been applied to the NumPy Financial [80] package functions and NPV, Internal Rate of Return (IRR) and payback period (PBP) have been evaluated for the different configurations. Emissions are calculated considering values reported in [81].For heat produced through traditional methane devices (e.g. boiler), emissions equal to 1.972 $\frac{kg_{CO_2}}{m^3}$ have been considered. Heat fluxes have been converted in consumed methane cubic meters applying a lower heating value of 35.25 MJ/m^3. For emissions related to electricity from the grid consumptions, an emission factor 0.276 kg_{CO_2}/kWh have been used, which considers the Italian energy mix [82].

2.12. Demand Profiles

To run the optimization tool, demand profiles about electricity, space heating, space cooling and domestic hot water production must be evaluated.

The ones used in this model are made with the aim of proposing data which can reflect the Italian situation and that can be used in case precise profiles of the community members are not available.
In Figure 26 a scheme representing the demand profiles evaluation process is reported.


1
- Identification of ISTAT categories of italian families
- cross percentages about number of components and typology

2
- Identified associated 'Load Profile Generator' (LPG) categories

3
- Generated electricity demand profiles for each category with LPG

4
- Generated domestic hot water demand profiles for each category with LPG [L/h]

5
- Converted the domestic hot water demand in [kWh]
- Elaborated the function: 'DhwDemand_Lh_KWh'

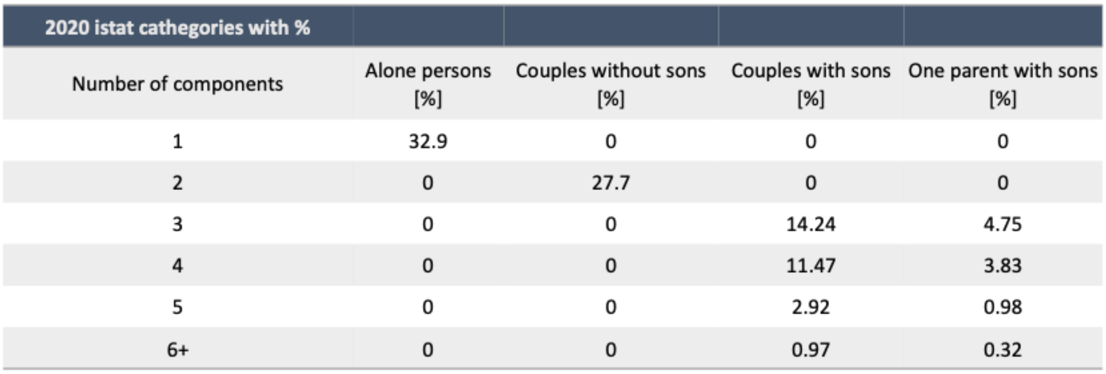
6
- Elaborated functions for space heating and space cooling demand profiles generation: 'Thermal_Profiles' and 'Cooling_Profiles'

Figure 26: *demand profiles evaluation process scheme.*

2.12.1. ISTAT data

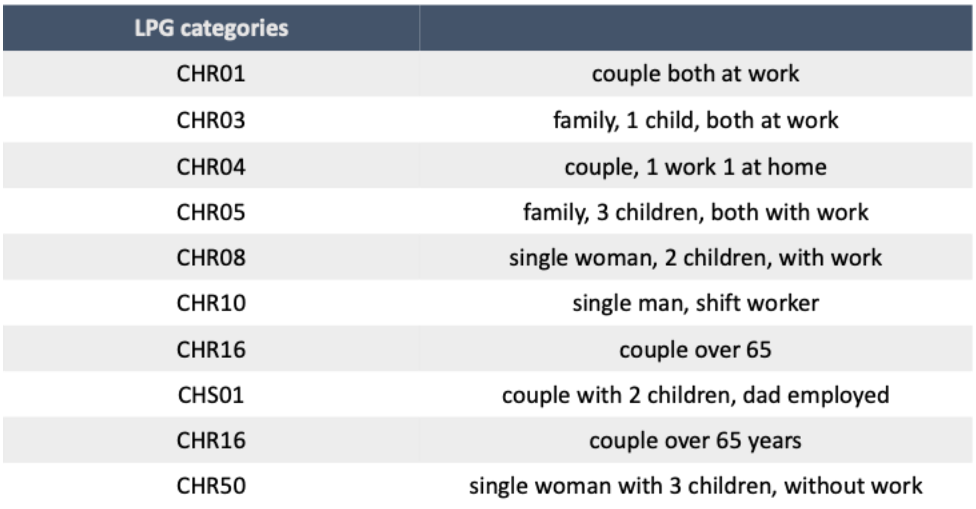
'Istituto Nazionale di Statistica' (ISTAT) proposes statistics data about the Italian population composition, and in particular about families. Two types of data have been selected: the ones about families' number of components and the ones about families' typologies (e.g. couple with sons, copule without sons). The percentages relative to these classes have been crossed, obtaining the values reported in Table 14. Each category identified by ISTAT data crossing has been associated to a category of 'Load Profile Generator' (LPG), which is a tool used to generate demand profiles depending on several factors, such as type of house and type of household. The identified categories are about the household typologies and are listed in Table 15.

The resulting composition of the model population is obtained by the combination of the two set of data and is explained in Table 16.



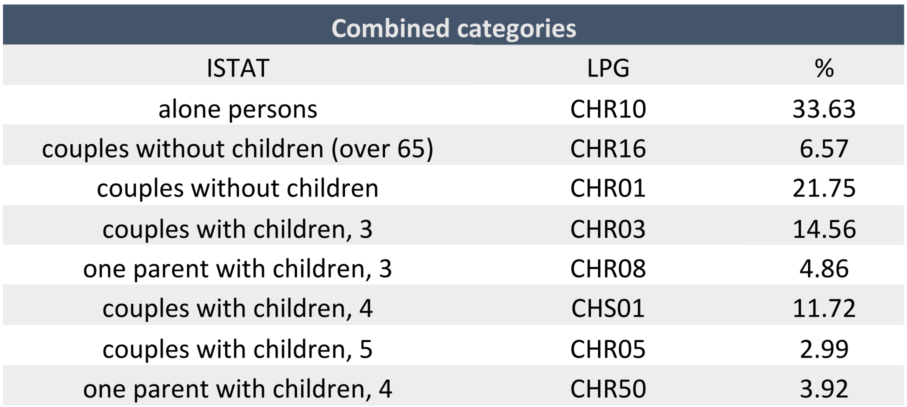
2020 istat cathegories with %				
Number of components	Alone persons [%]	Couples without sons [%]	Couples with sons [%]	One parent with sons [%]
1	32.9	0	0	0
2	0	27.7	0	0
3	0	0	14.24	4.75
4	0	0	11.47	3.83
5	0	0	2.92	0.98
6+	0	0	0.97	0.32

Table 14: *crossed percentages of ISTAT data on families.*



LPG categories	
CHR01	couple both at work
CHR03	family, 1 child, both at work
CHR04	couple, 1 work 1 at home
CHR05	family, 3 children, both with work
CHR08	single woman, 2 children, with work
CHR10	single man, shift worker
CHR16	couple over 65
CHS01	couple with 2 children, dad employed
CHR16	couple over 65 years
CHR50	single woman with 3 children, without work

Table 15: *Load Profile Generator households' categories.*



Combined categories		
ISTAT	LPG	%
alone persons	CHR10	33.63
couples without children (over 65)	CHR16	6.57
couples without children	CHR01	21.75
couples with children, 3	CHR03	14.56
one parent with children, 3	CHR08	4.86
couples with children, 4	CHS01	11.72
couples with children, 5	CHR05	2.99
one parent with children, 4	CHR50	3.92

Table 16: *Italian population categories with data obtained from ISTAT and Load Profile Generator.*

2.12.2. Electricity

For each one of the categories described in section 2.11.1, an hourly electrical demand profile expressed in kWh has been generated by using the 'Load Profile Generator' tool.

This is peculiar to each type of household considered.

Electricity demand profiles are imported from the input file 'ProfilesGeneration.xlsx'.

2.12.3. Domestic hot water

For each one of the categories described in section 2.11.1, an hourly domestic hot water demand profile in liters has been generated by using the 'Load Profile Generator' tool.

This is peculiar to each type of household considered. DHW demand profiles are imported from the input file 'ProfilesGeneration.xlsx'.

However, to be suitable for being implemented in the oemof model, the profile should be expressed in kWh.

For this reason, a function that converts the demand profile from hourly liters to kWh has been created. This is called 'DhwDemand_Lh_KWh'. The function takes as input the hourly DHW demand profiles expressed in liters and returns the hourly DHW demand in thermal KWh, the total annual DHW demand in KWh and the normalized DHW demand profile.

The considered calculations for the conversion are expressed in Equation 15.

Equation 15

$$Q\ [KWh] = \rho \cdot V \cdot c^{\mathrm{L}} \cdot (T_H - T_C)/3600$$

Where:

$$\rho\ \ is\ the\ density\ of\ water\ \left[\frac{kg}{L}\right]$$

$$V\ is\ the\ volume\ [L]$$

$$c^{\mathrm{L}}\ is\ water\ specific\ heat\ capacity\ \left[\frac{kJ}{kg * K}\right]$$

$$T_H\ and\ T_c\ are\ hot\ and\ cold\ water\ temperature$$

The hot temperature considered in Equation 15 is assumed equal to 48°C, indicated by 'UNI 9182' [83] as maximum temperature at which hot water must be furnished at the distribution point. For what concerns the cold temperature, it corresponds to the cold domestic water supply one, and it's different for winter and for summer (respectively 6°C and 15°C, as cited in section 2.4.5). So, in the function, a list containing '1' if it is winter and '0' if it is summer is created, and then the values corresponding to the season are assigned.

2.12.4. Space heating

Space heating demand profiles created with the 'Load Profile Generator' tool are not peculiar for each type of user but only to the selected type of house. For this reason, they are not suitable for the model considered.

So, to generate a space heating demand profile peculiar for each user, a function was created ('Thermal_Profiles') following the instructions of the EN 15316-4-2:2018 regulation [84]. This is based on the bin-method, which allows to obtain the yearly SH and SC profiles only considering the trend of the ambient temperature and the energy label of the building. In particular, a 'balancing ambient temperature' is considered, at which thermal losses of the building are balanced by the free heat contributions (e.g. men heat). Then, a linear correlation between the heat required and the environmental heat is created. Calculations are explained in Equation 16 and Equation 17.

Equation 16

$$Q_{SH,i} = Q_{max} \cdot \delta_i \cdot \frac{T_{bil} - T_{amb,i}}{T_{bil} - T_{design}}$$

Where:

Equation 17

$$Q_{max} = \frac{Q_{annual}}{\sum_i^{year} \delta_i \cdot \frac{T_{bil} - T_{amb,i}}{T_{bil} - T_{design}}}$$

Q_{max}: $maximum\ energy\ required\ in\ the\ coldest\ condition$
T_{design}: $minimum\ ambient\ temperature$
δ_i : $1\ when\ system\ is\ ON,\ 0\ when\ system\ is\ OFF$
Q_{annual}: $yearly\ energy\ demand\ for\ the\ house,\ depends\ on\ the\ energy\ class$
T_{bil}: $external\ ambient\ temperature\ at\ which\ space\ heating\ is\ no\ more\ necessary$

The function takes as input the annual energy required by the user (which will be precisely defined for each user; details in the section 'Energy community model details') in thermal kWh, T_{bil}, the list containing the hourly ambient temperature for the considered period and location, the surface of the user's house (details in the section 'Energy community model'), the climatic zone in which the energy community is located. T_{bil} is indicated in the same regulation considered above as 16°C.

In the function, an 'on list' for space heating is created based on the climatic zone, according to 'Decreto del Presidente della Repubblica n.74 del 16 aprile 2013, art. 4'[60]. The climatic zone is detailed by the user in the input excel file. Then, calculations indicated in Equation 16 are applied and the resulting list is multiplied by the 'on list', to only account for the periods in which space heating is switched on. The outputs are an hourly space heating demand profile in thermal kWh and a normalized space heating demand profile.

2.12.5. Space cooling

In the case of space cooling demand too, the profiles created through 'Load Profile Generator' are peculiar to the type of house, and not to the type of household, making them unsuitable for the model.

The same procedure of the space heating demand profiles is followed in the created function 'Cooling_Profiles', but using different values and an additional difference. This last one is that the 'on profile' for space cooling is not defined within the function because no legislation indicates it, but it is imported. The 'on list' is extrapolated from a general air conditioning demand profile of 'Load Profile Generator'. For what concerns the different values, they are the balancing temperature, which in this case represents the temperature at which air conditioning doesn't work and the annual energy consumption. The balancing temperature is considered as the comfort temperature at which the internal ambient should be set to (25°C, from 'UNI EN ISO 7730:2006' [53]). Precise details on the set of values given as input in the function can be found in the section 'Energy community model details'.

2.13. Energy community model details

All the components and the demand profiles described in the previous sections have been integrated in a generic energy community model, which can be fitted to the considered case and used to optimize the EC energy system. Details about the structure of the input file are presented in section 2.13.

In this part, details about the EC model are described.

It is assumed that precise information about the EC members is not known, so the model is made in order to be able to represent the generic Italian situation.
The energy community is made of a determined number of users. Each one represents a single node, with its devices and defined energy demands and flows. In Figure 27 a scheme of the energy community's users and relative electricity flows is detailed. Electricity can be self-produced by the user through the PV source, imported from the national grid or imported from a shared flow from other users (which however passes through the national electrical grid). It is then used to run electrical devices (for the satisfaction of electric or heat or DHW demand).

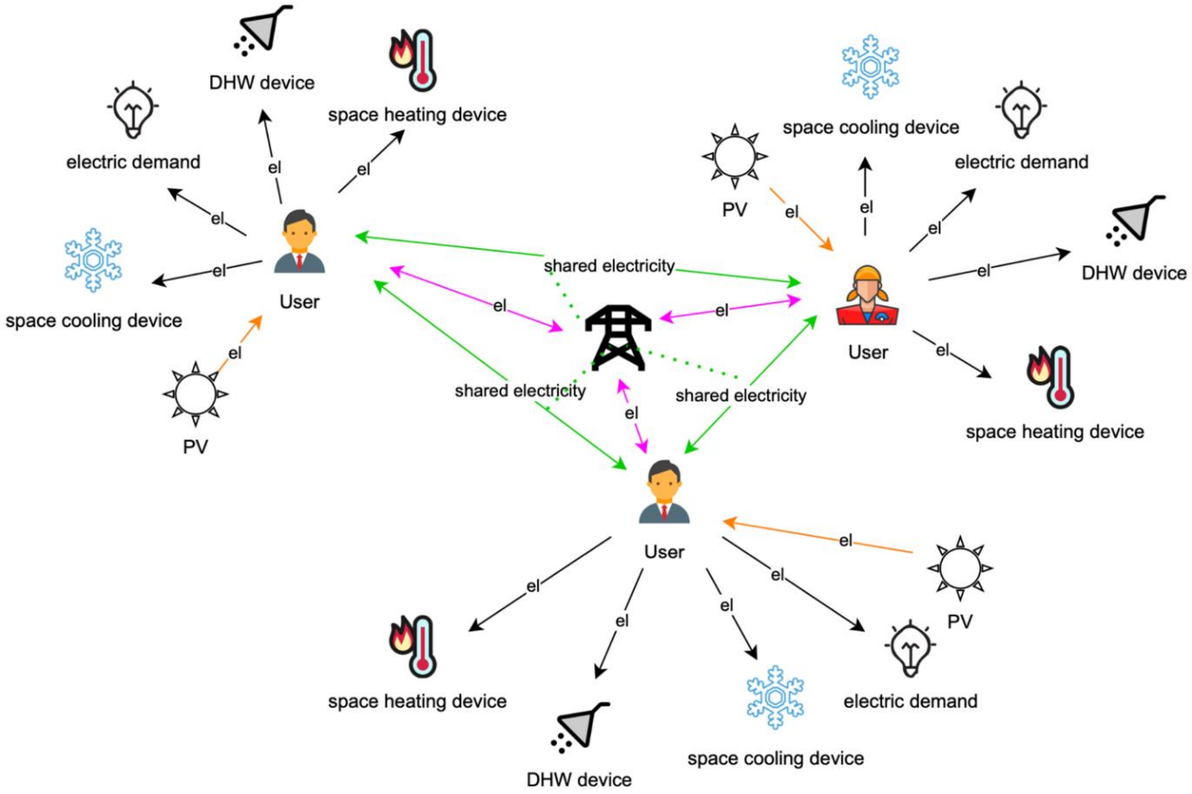


Figure 27: *EC scheme with electricity flows.*

2.13.1. Users

First, it is necessary to identify and characterize the users of the EC.

The 'Users' dictionary and users' categories

A dictionary called 'Users' is created to collect all the data about the EC users.

Python dictionaries are ‘associative arrays’, which means that, unlike sequences, which are indexed by a range of numbers, they are indexed by keys. In this way a data ‘name’ (the key) is associated to its value, creating a key:value pair.

In the input file, the user selects the number of households composing the EC, which is imported in the model. A function called ‘users_statistics’ is created to represent, known the number of users, the Italian families’ composition according to data reported in section 2.11.1. The function takes as input the number of users and assigns them to the LPG-ISTAT classes (2.11.1) basing on the percentage corresponding to each class.

The outputs are:

- a dictionary containing the generic LPG and ISTAT data: LPG categories, related ISTAT percentages, number of users per category
- a list of users named with alphabet letters
- a dictionary containing the effective users of the EC named with alphabet letters and the related categories
- an overall dictionary (‘Users’) containing both general LPG and ISTAT information and the one peculiar to each user (effective users of the EC named with alphabet letters and the related categories)

The overall dictionary ‘Users’ will be then updated with additional information. In fact, to obtain demand profiles for each user, other data are necessary.

Houses surface

Another necessary information is each household’s house surface. As mentioned above, it is assumed that details about each user’s house surface is not known, so the aim is to represent the Italian situation. For doing this, Italian ISTAT data have been analyzed. In particular, the ones about the surface of the house with respect to the number of components of the family are considered. The value emerged are reported in Table 17.

	House surface								
n_members	**0-49**	**49-99**	**99-149**	**150+**	**Total**	**0-49**	**49-99**	**99-149**	**150+**
1	981089	4148550	1511925	513756	7155320	0,137	0,580	0,211	0,072
2	351084	3639510	1951958	706963	6649515	0,053	0,547	0,294	0,106
3	158596	2467090	1636645	622978	4885309	0,032	0,505	0,335	0,128
4	88727	1826105	1451700	608982	3975514	0,022	0,459	0,365	0,153
5	25241	459799	400000	201424	1086464	0,023	0,423	0,368	0,185

Table 17: *Statistics about the surface in squared meters vs the number of family members.*

In this case surfaces are directly associated to the LPG-ISTAT categories and successively assigned to each user.

If there is only one category representing a determined number of members, the surface with the highest portion is associated, otherwise, if two categories with the same number of members are present, the first two surfaces (intended as the more spread ones according to ISTAT data) are assigned. Details are described in Table 18.

LPG category	Surface
CHR01	74
CHR03	124
CHR05	74
CHR08	74
CHR10	74
CHR16	124
CHR50	74
CHS01	124

Table 18: *House surface in squared meters assigned to each LPG class.*

Energy classes

Another important information relative to each user is the energy class its house belongs to. Two options are possible for this kind of assignment: the case the EC is an AC or the one in which the EC is a CER. The choice is implemented by the user in the input file as reported in the previous sections. If the EC is an AC, the energy class of the multi-apartment building is expected to be known, so it's set by the user in the input file (sheet 'EnergyClass'), imported and assigned to each user. If the EC is a CER, the energy class is assigned to each user by using the created function 'EnergyClass_assignment'. This takes as input the number of users of the EC and assigns the energy class to each of them based on the ENEA [85] data relative to the Italian energy classes distribution (Figure 28).

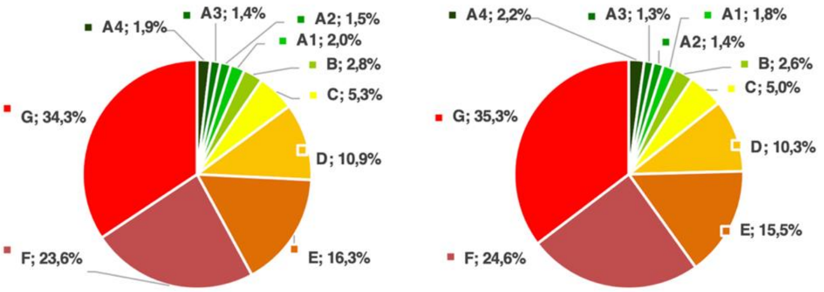


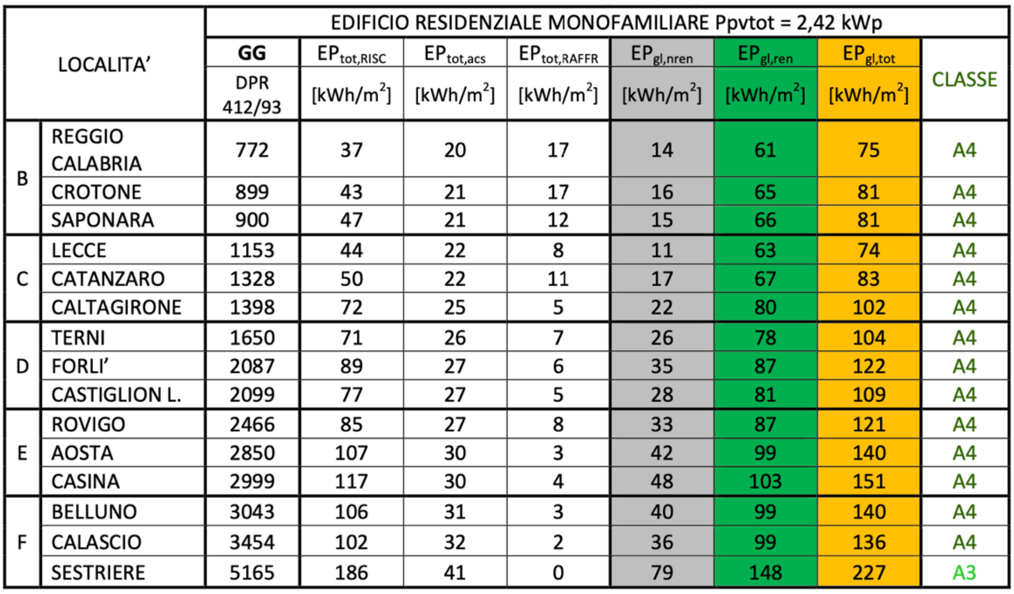
Figure 28: *Distribution of APE certificates for energy class in year 2019 (left) and 2020 (right).* [85]

The main point of the energy classes is the correlated energy consumptions for space heating and cooling. Italian energy classes and the relative energy consumption are detailed by MiSe ('Ministero dello sviluppo economico') [86] and reported in Table 19.

	Classe A4	$\leq 0{,}40\ EP_{gl,nren,rif,standard\ (2019/21)}$
$0{,}40\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe A3**	$\leq 0{,}60\ EP_{gl,nren,rif,standard\ (2019/21)}$
$0{,}60\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe A2**	$\leq 0{,}80\ EP_{gl,nren,rif,standard\ (2019/21)}$
$0{,}80\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe A1**	$\leq 1{,}00\ EP_{gl,nren,rif,standard\ (2019/21)}$
$1{,}00\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe B**	$\leq 1{,}20\ EP_{gl,nren,rif,standard\ (2019/21)}$
$1{,}20\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe C**	$\leq 1{,}50\ EP_{gl,nren,rif,standard\ (2019/21)}$
$1{,}50\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe D**	$\leq 2{,}00\ EP_{gl,nren,rif,standard\ (2019/21)}$
$2{,}00\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe E**	$\leq 2{,}60\ EP_{gl,nren,rif,standard\ (2019/21)}$
$2{,}60\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe F**	$\leq 3{,}50\ EP_{gl,nren,rif,standard\ (2019/21)}$
	Classe G	$> 3{,}50\ EP_{gl,nren,rif,standard\ (2019/21)}$

Table 19: *Italian energy classes and relative energy consumptions.* [86]

The energy classes' energy consumptions values are relative to the EP,gl,nren,rif,standard, which is the global nonrenewable energy performance index, which accounts for the nonrenewable primary energy consumption for space heating and cooling, ventilation and domestic hot water production. The calculation of the contribution of each of the cited voices depends on the characteristics of the building (e.g. envelope characteristics), however, to obtain values appliable to a general Italian case, some deepening have been made. In particular, ENEA [87] studied the EPgl,nren composition for different climatic zones in Italy (Table 20).



LOCALITA’		EDIFICIO RESIDENZIALE MONOFAMILIARE Ppvtot = 2,42 kWp							
		GG	$EP_{tot,RISC}$	$EP_{tot,acs}$	$EP_{tot,RAFFR}$	$EP_{gl,nren}$	$EP_{gl,ren}$	$EP_{gl,tot}$	CLASSE
		DPR 412/93	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	
B	REGGIO CALABRIA	772	37	20	17	14	61	75	A4
	CROTONE	899	43	21	17	16	65	81	A4
	SAPONARA	900	47	21	12	15	66	81	A4
C	LECCE	1153	44	22	8	11	63	74	A4
	CATANZARO	1328	50	22	11	17	67	83	A4
	CALTAGIRONE	1398	72	25	5	22	80	102	A4
D	TERNI	1650	71	26	7	26	78	104	A4
	FORLI’	2087	89	27	6	35	87	122	A4
	CASTIGLION L.	2099	77	27	5	28	81	109	A4
E	ROVIGO	2466	85	27	8	33	87	121	A4
	AOSTA	2850	107	30	3	42	99	140	A4
	CASINA	2999	117	30	4	48	103	151	A4
F	BELLUNO	3043	106	31	3	40	99	140	A4
	CALASCIO	3454	102	32	2	36	99	136	A4
	SESTRIERE	5165	186	41	0	79	148	227	A3

Table 20: *EP indicator per climatic zone, 2020* [87].

From these data, percentages relative to the contributions of the primary energy for space heating and cooling peculiar to each climatic zone have been extrapolated and summarized in the following part. In particular, values have been obtained assuming that the DHW demand keeps constant for the different energy classes (for a determined climatic zone), according to ‘EN 16147’ [88].

EPh (space heating) percentage for each climatic zone:
A: 40% (from trend)
B: 53%
C: 60%
D: 70%
E: 76%
F: 75%

EPc (space cooling) percentage for each climatic zone:
A: 29% (from trend)
B: 21%
C: 13%
D: 5%
E: 2%
F: 1.5%

So, in order to take into account, the described information and assign to each user the peculiar energy consumptions for space heating and space cooling, based on the climatic zone and the energy class, two functions have been created. The first one is called '**EnergyClass_assignment_ClassIsKnown**' and is used in case an AC is implemented, while the other one is called '**EnergyClass_assignment'** and is used in case the CER option is chosen. The first one takes as input the number of members of the EC, the climatic zone in which the EC is located and the energy class of the multi-apartment building (all this information are set by the user in the input file) and returns a list containing the energy consumption values for each user for space heating and cooling and a dictionary containing general both the information. The second class is similar but in this case, being the energy class of each user unknown, it is assigned to each EC member as cited before reflecting ENEA data [85].
The assigned energy consumptions values are useful for the application (for each user) of the space heating and space cooling demand profiles creation functions described above.

The 'Users' dictionary's structure

The information contained in the 'Users' dictionary are:
Cons_per_class_cool: Epc assigned to each category
Cons_per_class_heat: Eph assigned to each category
consumption_per_user_cool: Epc assigned to each user
consumption_per_user_heat: Eph assigned to each user
Cooling: space cooling demand profile for each category
Dhw: dhw demand profile for each category
Electricity: electricity demand profile for each category
en_classes: list of all energy classes
EnClass_for_user: energy class assigned to each user
Heating: heating demand profile for each category
istat_percent: ISTAT % assigned to each category
LPG_cathegories: list of LPG categories
surface_m2: surface of house assigned to each category
Users: alphabet list of users
users_cathegories: category assigned to each user
users_en: number of users for each energy class
users_per_cat: number of users for each category

It emerges that:

- energy classes are assigned to each user
- house's surface is assigned to each user
- energy consumptions for space heating and cooling are assigned to each user
- space heating and cooling demand profiles are created for each user
- domestic hot water demand profiles and electricity demand profiles are assigned to each LPG category

Note: Information in the 'Users' dictionary, as cited above, can be referred to users or to the categories. All the information classes are lists. If the information is referred to the users, indexes of the lists correspond to the index of the user (in the capital alphabet letter list representing users), otherwise, if they are referred to LPG categories, information indexes correspond to the ones of the LPG category.

2.13.2. DSM application

The DSM is applied for each demand profile of each user. In particular, when DSM is applied, domestic hot water and electricity demand profiles are assigned to each user and implemented in the SinkDSM oemof component, while space heating and cooling demand profiles are directly taken from the 'Users' dictionary for each user and implemented in the SinkDSM component.

2.13.3. Devices

The heat pumps and electric boiler described in the previous sections have the same characteristics for each user, being the control and treatments options homogeneous for the entire EC (as assumed before). For this reason, their characteristics are collected in the 'devices' list. This list contains all the heat pumps typologies and the electric boiler with the relative temperatures, efficiencies, coefficients of performance. All the data about one device of the mentioned ones are collected in a dictionary, inserted in the 'devices' list.

Then, the devices list is read and all the contained devices are implemented in oemof for each user. Their effective installation will be evaluated through the optimization tool.

In the following part, notes about the described components' implementation in the energy community are described.

Thermoregulation function

To apply the climatic_regulation function, the 'on profile' for space heating is necessary. This will be the one relative to the climatic zone and described by regulations, as cited before. To create it, the 'on_profile_climatic_zone' function has been detailed and implemented.

Periodic treatment function

To apply the periodic_treatment function, the 'on profile' of domestic hot water is necessary. However, this can't be the one relative to each users' demand profile because the devices have to be univocally defined. So, an approximation is introduced: the profile relative to the category 'CHR16' is used as it is the 'worst' case, intended as the more active one in term of hours.

COP

A technical limit of 5 is attributed to COP for (reversible) heat pumps in heating mode and of 4 for heat pumps in cooling mode, according to data reported in different commercial models datasheets [89][90].

2.14. Input file structure

In this section the input file's structure is detailed.
In particular, sheet names and contained information are described, followed by the specifics on the parameters which have to be set by the user (in orange).

'buses'

Buses, activation of excess and shortage for each of them, relative costs.
Parameters about PUN ('prezzo unico nazionale') and electricity costs, useful for the valorization of shared flows.
CER or AC activation options for the EC.

Shortage and excess costs for each flow.

PUN and electricity cost.

CER or AC activation (1 if active, 0 if not).

'pop_categ_legend'

Legend of the LPG categories and related ISTAT data. It results in the details about the composition of the EC (percentage values).

'EnergyClass'

Information about the energy class: if it is known (case of AC) and in case it is known what is it.

Class is known? 1 if yes, 0 if no.

ClassIfKnown: set the energy class (capital alphabet letters).

‘users’

Number of users and example of users’ names.

Number of users. (int)

‘grid’

Information about the national electrical grid (or other electricity sources that can be added). Bus fed by the source and variabl costs in €/kWh.

Activation of the source (1 if active, 0 if not).

Variable costs (€/kWh).

‘demand_dsm’

Details on the DSM implementation. For each DSM demand: activation, bus that feeds the demand, associated demand profile, maximum ‘up’ and ‘down’ capacity for the DSM, maximum demand that can be applied to DSM, portion of the demand capacity that can be moved up or down, number of hours in which the load can be shifted, costs associated to shift up or down of demand.

Activation of DSM for the different demand profiles (1 if active, 0 if not). Other parameters comes from detailed analysis and so are strongly suggested.

‘climatic_zone’

Climatic zone in which the EC is located.

Climatic zone (capital alphabet letter).

‘temp’

Hourly ambient temperature profile relative to the location of the EC, with associated date.

Hourly ambient temperature profile.

‘sources’

Available renewable energy sources. For each one: activation, normalized profile name (contained in another sheet), capex, lifetime, WACC, fed flow, capacity.

The capacity in this model can be neglected because the investment option is used.

Activation of the renewable energy sources (1 if acive, 0 if not), relative data if not present.

'time_series_so'

Hourly normalized profiles of renewable energy sources (in the selected location) with the relative date.

Hourly normalized profiles.

'settings'

Settings about the treatments for DHW (periodic or continuous treatments) and the regulation options for space heating (fixed-point or thermoregulation).

Activation of options (1 if active, 0 if not).

'mode'

Information about all the available heat pumps and electric devices typologies. In particular: conversion factor name, input and output flows, active or not, temperatures, delta temperature, supply temperatures, minimum and maximum flow temperatures if it is a water system, configuration for cooling system (heat gains).

Activation of available devices (1 if active, 0 if not), heat gains configuration of the house units between the ones described above (also reported in the input file).

'SolarColl'

Information about the solar thermal collector component: latitude and longitude of the EC's location, thermal loss coefficients one and two (reported in datasheets), tilt and azimuth (if not known, use the optimized ones suggested by PVGIS), available area for each user after the first optimization or available collective area (if AC) after the first optimization.

Latitude, longitude, tilt, azimuth, available areas $[m^2]$.

'TES'

Here all the TES (Thermal energy storage) models used for the losses evaluation are listed with the relative size, dimensions, price, temperatures and characteristics. However, these won't be used in the EC model but are reported here to understand

the thermal loss analysis done with the single user's code and implemented in the EC model.
One thermal storage for DHW and one for space heating are randomly activated only for the implementation of the right bus and maximum and minimum storage levels.

Min and max storage levels.

'q_grades'

Corrective coefficient for the COP of all the heat pumps considered. It depends on the source of heat/cool.

Activation of the desired source for heat/cool for heat pumps for space heating/DHW or chillers (1 if active, 0 if not).

'Profile_c_ex'

'On profile' for space cooling derived from LPG analyses.

'On profile' for space cooling if precisely known, other wise use the suggested one.

3 Case studies

In this section different case studies and sensitivity analyses are proposed, to evidence the potentiality of the model as well as results concerning the integration and electrification of thermal sector in an EC model. A summary of the principal analyzed configurations characteristics and the related electricity dispatch, emissions and economic results can be found in Table 22, Table 23, Table 24, Table 25 and Table 25.

3.1. Case study n.1

The energy community considered is composed by five members, which characteristic reflect the Italian situation as described above. Meteorological data (temperature and irradiance) are referred to Milan and generated by using the PVGIS [62] software and ARPA database [52].

For this case study different configurations concerning water treatments, space heating and cooling operation, electricity prices, sources and other aspects are considered. EC users characteristics are summarized in Table 21.

User	LPG class	Energy class	SH consumption $[\mathrm{kWh/y \cdot m^2}]$	SC consumption $[\mathrm{kWh/y \cdot m^2}]$	House surface $[\mathrm{m^2}]$	EL demand [kWh]
A	CHR10	A1	30.4	0.8	74	4122.84
B	CHR10	E	197.6	5.2	74	4122.84
C	CHR01	F	266.0	7.0	74	5198.25
D	CHR03	G	304.0	8.0	74	4854.90
E	CHS01	G	304.0	8.0	124	6290.95

Table 21: *EC users characteristics.*

The differences in total electricity consumptions between the EC users, which comprehend SH, SC, DHW, EL ones, can be appreciated in Figure 29.

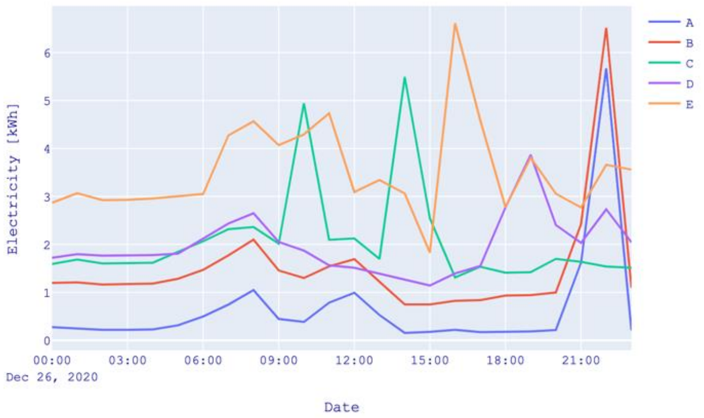


Figure 29: *Total electricity load for different EC users.*

3.1.1. Configuration n.1 (reference case)

This configuration is characterized by:

- CER
- Meteorological data: Milan
- Electricity price: 200 €/MWh (referred to 2020 values)
- PUN: 50 €/MWh (referred to 2020 values)
- Thermoregulation for space heating
- Periodic treatment for DHW
- Configuration n.2 for space cooling
- Excess valorized to PUN
- Air source heat pumps

3.1.2. Configuration n.2 (reference case for water systems)

This configuration has the same characteristics of Configuration n.1 but activates only air to water systems (HP) both for SH and SC. So, this will be the reference case for the evaluations about air to water systems.

This configuration is characterized by:

- Configuration n.1
- Only air to water systems active for space heating and cooling
- Shortage cost of 110 €/MWh,th for SH and DHW

3.1.3. Configuration n.3

This configuration has the same characteristics of configuration n.1 except for the heat/cool source, which in this case is the ground (with the use of heat exchangers). So, the corrective factor for the COP in this case will be equal to 0.55 (for air it is 0.4).

This configuration is characterized by:

- Configuration n.1
- Ground source heat pumps with heat exchangers

3.1.4. Configuration n.3b

This configuration is characterized by:

- Configuration n.1
- Ground source heat pumps with heat exchangers
- Only ground to water systems active for SH and SC

3.1.5. Configuration n.4

This configuration is developed to investigate the impact of flexible settings for SH and DHW temperatures regulation. In particular, Fixed-point regulation is chosen for SH and Continuous treatment for DHW. Only air to water systems (HPs) are activated to evidence the effect of settings.

This configuration is characterized by:

- Configuration n.1
- Fixed point regulation for space heating
- Continuous treatment for DHW
- Only air to water systems active for SH and SC

3.1.6. Configuration n.5

In this case, the characteristics are the same of Configuration n.1 except for shortage costs.
In fact, shortage costs for DHW, space heating and cooling are no more 1€/kWh to incentive the electrification fed by RES, but they are set equal to the costs of different traditional sources which can cover the demand in place of renewables. These are methane for space heating and DHW production and electricity purchased from the national grid for space cooling. The methane cost in kWh is evaluated considering methane cost in €/m^3, its higher heating value and efficiencies of boilers. The resulting value is 0.11 €/kWh.

This configuration is characterized by:

- Configuration n.1
- Cost of DHW and SH shortage

3.1.7. Configuration n.6

This configuration is implemented to analyze the impact that Solar Thermal Collectors installation has on results.

This configuration in characterized by:

- Configuration n.1
- Solar Thermal Collectors implemented in the available space

3.1.8. Configuration n.7

This configuration was made to evaluate the electrification of the thermal sector in the EC, even if not fed by RES. At this scope, PV are deactivated in the input file and shortage costs are implemented (methane for SH and DHW, electricity from the grid for SC), together with the electricity from the grid ones.

This configuration is characterized by:

- Configuration n.1
- Deactivation of PV
- Shortage costs for SH, DHW, SC

3.1.9. Configuration n.8

This configuration is made to evaluate the impact of sector coupling on the EC. So, electrical devices for the coverage of SH and DHW demand are deactivated, and only traditional sources (in this case methane at the cost of 0.11 €/kWh) are considered. For SC a heat pump with a fixed COP of 3 and fed by the national electrical grid is considered.

This configuration is characterized by:

- Configuration n.1
- Deactivation of devices for thermal sector electrification
- Shortage options for SH, DHW, SC

3.1.10. Configuration n.8b

This configuration is developed to investigate the effective advantages of integrating the electrified thermal sector in the EC model. In this case, the PV install capacity is considered equal to the one of Configuration n.8, to be able to compare the two cases.

This configuration is characterized by:

- Configuration n.8 (optimal PV capacity kept constant)
- Electrified thermal sector coupling

3.2. Case study n.2

The energy community considered is composed by five members, which characteristic reflect the Italian situation as described above. Meteorological data (temperature and irradiance) are referred to Brindisi and generated by using the PVGIS [62] software and ARPA database [52].
For this case study different configurations concerning water treatments, space heating and cooling operation, electricity prices, sources and other aspects are considered. The EC composition is the same of Case study 1 (Table 21).

3.2.1. Configuration n.1

This case study considers the same settings of Configuration n.1 of Case study 1 but in a different geographical location, which is Brindisi, in South of Italy.

This configuration is characterized by:

- Configuration n.1, Case study 1
- Meteorological data: Brindisi
- Climatic Zone: C

3.2.2. Configuration n.2

In this configuration the impact of solar thermal collectors installation is investigated for the current EC location.

This configuration is characterized by:

- Configuration n.1
- Solar Thermal Collector installation

4 Results

In this section the main results concerning the analyzed case studies are reported. A summary of the principal analyzed configurations characteristics and the related electricity dispatch, emissions and economic results can be found in Table 21, Table 22, Table 23, Table 24 and Table 25.

Configuration / Case study	Location	SH settings	DHW settings	Heat/cool source	PV	A/A HP	A/W HP	Solar Thermal Collectors
1 / 1 (ref)	Milano	Thermoregulation	Periodic treatment	Air	yes	yes	no	no
2 / 1	Milano	Thermoregulation	Periodic treatment	Air	yes	no	yes	no
3 / 1	Milano	Thermoregulation	Periodic treatment	Ground with hex	yes	yes	no	no
3b/ 1	Milano	Thermoregulation	Periodic treatment	Ground with hex	yes	no	yes	no
4 / 1	Milano	Fixed point regulation	Continous treatment	Air	yes	no	yes	no
6 / 1	Milano	Thermoregulation	Periodic treatment	Air	yes	yes	no	yes
8 / 1	Milano	-	-	-	yes	no	no	no
1 / 2	Brindisi	Thermoregulation	Periodic treatment	Air	yes	yes	no	no
2 / 2	Brindisi	Thermoregulation	Periodic treatment	Air	yes	yes	no	yes

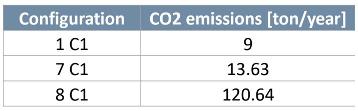
Table 22: *Principal configurations characteristics with respect to the reference one*.

Configuration/ Case study	PV [kW]	SH storage [kWh]	DHW storage [kWh]	PV [kWh]	Grid [kWh]	HP cons SH [kWh]	HP cons SC [kWh]	HP cons DHW [kWh]	EL demand [kWh]	Self-sufficiency [%]	Shared [%]	Excess [%]
1 / 1	23	31	0	29839.40	33490.86	19447.7	636.5	4477.48	24589.79	31.86	18.28	47.70
2 / 1	29	35	121	37691.69	37051.49	26056.44	636.5	4498.72	24589.79	33.58	12.08	50.31
3 / 1	23	30	0	29893.4	33270	19349.6	636.5	4024.42	24589.79	31.54	18.96	48.72
3b / 1	23	26	60	29893.4	33663.8	20630.4	636.5	4014.36	24589.79	32.50	17.94	45.78
4 / 1	29	42	69	37691.69	41178,98	29124.07	636.5	5895.45	24589.79	31.65	11.75	49.41
6 / 1	23	26	60	29893.4	33361	19447.7	636.5	3982.11	24589.79	33.26	13.87	45.87
8 / 1	11	0	0	14296.84	16509.35	0	0	0	24589.79	32.86	64.04	43.48
1 / 2	23	39	0	29893.4	31274.35	15276	2127.92	4036.79	24589.79	36.42	18.34	43.92
2 / 2	23	40	0	29893.4	31088.84	15276	2013.87	3539.54	24589.79	36.33	17.01	44.80

Table 23: *Electricity dispatch results for different case studies and configurations.*

	Configuration / Case study							
	1 C1	2 C1	3b C1	4 C1	6 C1	8 C1	1 C2	2 C2
NPV	27519.78	27876.93	27714.18	29985.82	27282.11	19817.22	30095.61	29384.95
IRR	0.14	0.12	0.14	0.12	0.14	0.21	0.15	0.15
PBP	8	10	8	9	8	6	8	8

Table 24: *Economic results.*



Configuration	CO2 emissions [ton/year]
1 C1	9
7 C1	13.63
8 C1	120.64

Table 25: *Emissions results.*

In the following section results are deepened for the different case studies and configurations.

As cited before, **Configuration n.1 of Case study 1** represents the reference one to be compared with the others. Different aspects can be analyzed for this configuration. In Figure 30 it is represented the electricity which enters/exits each node (user). It's possible to notice that PV are only installed for three out of five users, which are the one with the major electricity demands. These users then self-use or share their self-produced electricity but also inject it into the national electrical grid. In some cases, they exchange each other the self-produced electricity depending on the balance between production and consumption in the precise moment. All the users still rely on the national grid, used to cover electricity low-production periods of PV.

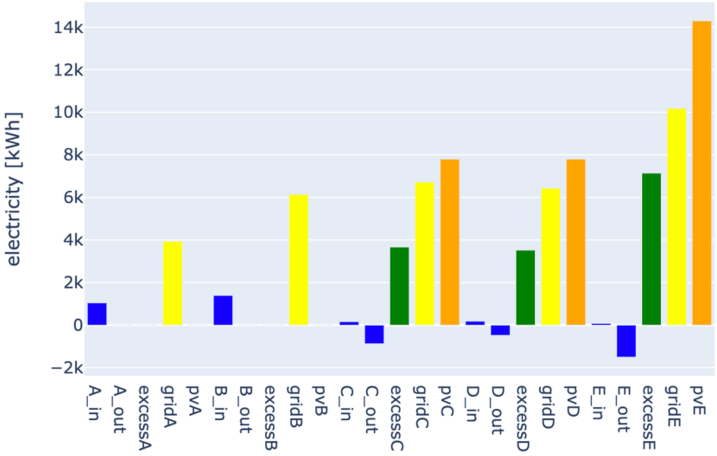


Figure 30: *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

For a more detailed analysis, in Figure 31 the electricity yearly production from PV for each user versus the one imported from the national grid is represented. Also, in Figure 32 and Figure 33 the differences in PV electricity production for summer and winter can be noticed, together with the differences in the electricity supply from the national grid.

In Figure 34 the correspondence between the over-production and consequent sharing-out of electricity from PV of users ‘C’,’D’ and ‘E’ and the sharing-in of users ‘A’ and ‘B’ is evidenced for a winter day.

The DSM application to demand profiles can be noticed in Figure 35 and Figure 36 for user ‘D’, where the correspondence of the DSM shift of the demand, the PV production and the operation of the DHW storage is evidenced. Also, in Figure 37Figure 37 the DSM operation (shift, up and the difference between the two which compensates) is represented. In the case of DHW, the one reported is the optimal case, which means that the user accepts to change its habits thanks to remunerations and costs and energy savings awareness. The DSM operation can also be seen in Figure 38 for SC. Demand profile of user ‘D’ is adapted to match PV electricity production profile.

As mentioned in the previous sections, a detailed evaluation of the COP for different heat pumps technologies has been implemented. The detail of their variation in time, related to ambient temperature and supply temperature is represented in Figure 39 and Figure 40. This last one reports the variation in time of the flow temperature of floor heating heat pumps, of the ambient temperature and of the difference between the two. It can be noticed that the COP decreases as the temperature difference increases. Also, the ‘thigh’, which is the flow temperature of hot water in the floor heating system, varies continuously due to the thermoregulation operating option.

The COP strictly depends on the heat/cool source, which in this configuration is air, that determines a correction factor of 0.4. The ideal case COP (Carnot), obtained considering a correction factor of 1, is represented in Figure 41.

In this configuration, the optimization leads to the implementation of air heat pumps for space heating.

The positive NPV, an IRR equal to 14% and a PBP of 8 years show that the investment in the EC with electrified thermal sector integration is profitable, and leads to a deep emissions reduction, which are here 9 tons per year instead of 120 tons per year produced by traditional energy sources (methane for SH and DHW and grid electricity for EL and SC).

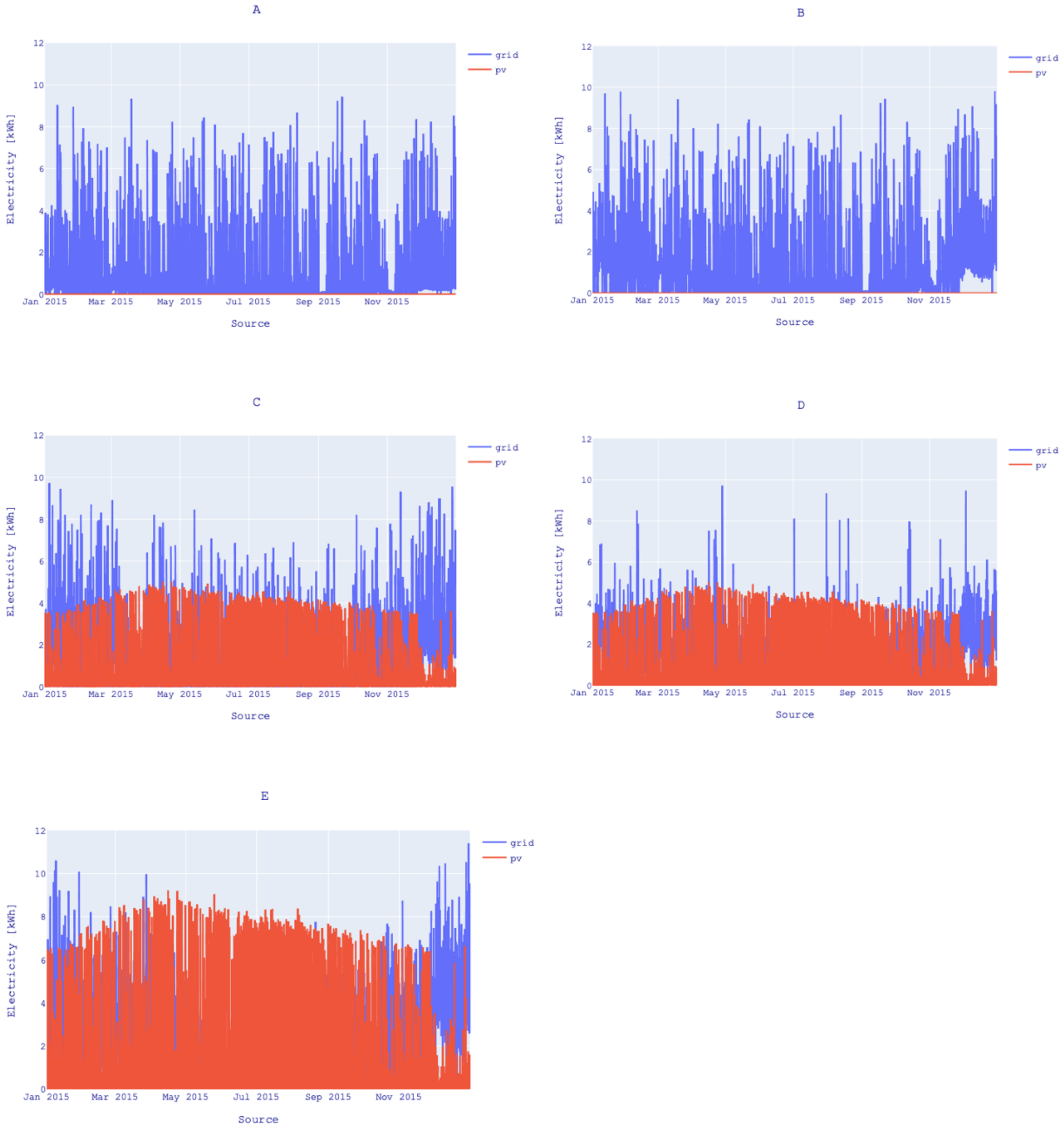


Figure 31: *Electricity produced from PV vs electricity imported from the national grid for each user.*

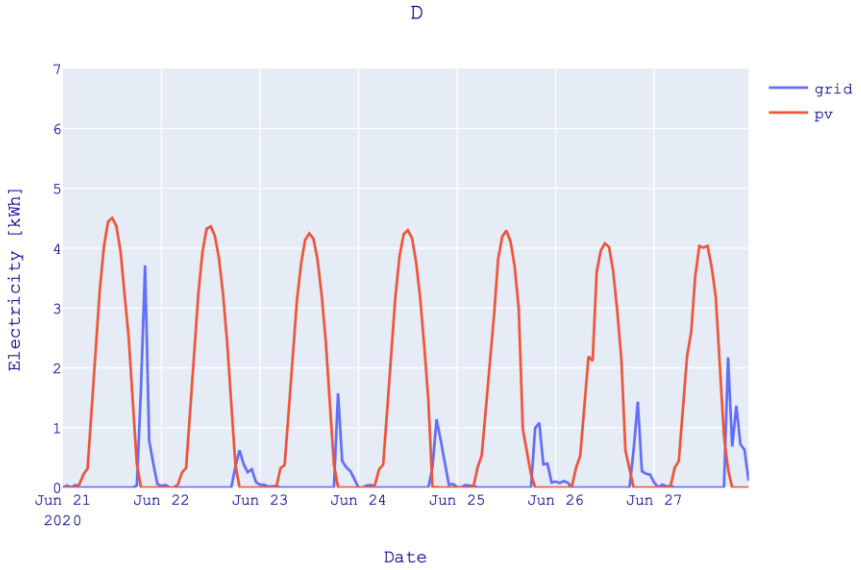


Figure 32: *PV electricity production vs the one imported from the grid in a summer week.*

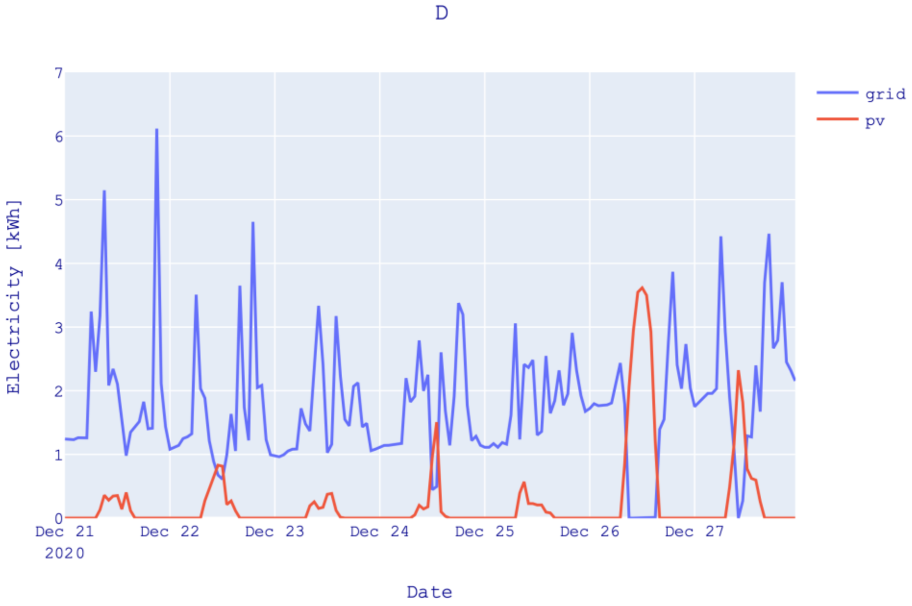


Figure 33: *PV electricity production vs the one imported from the grid in a winter week.*

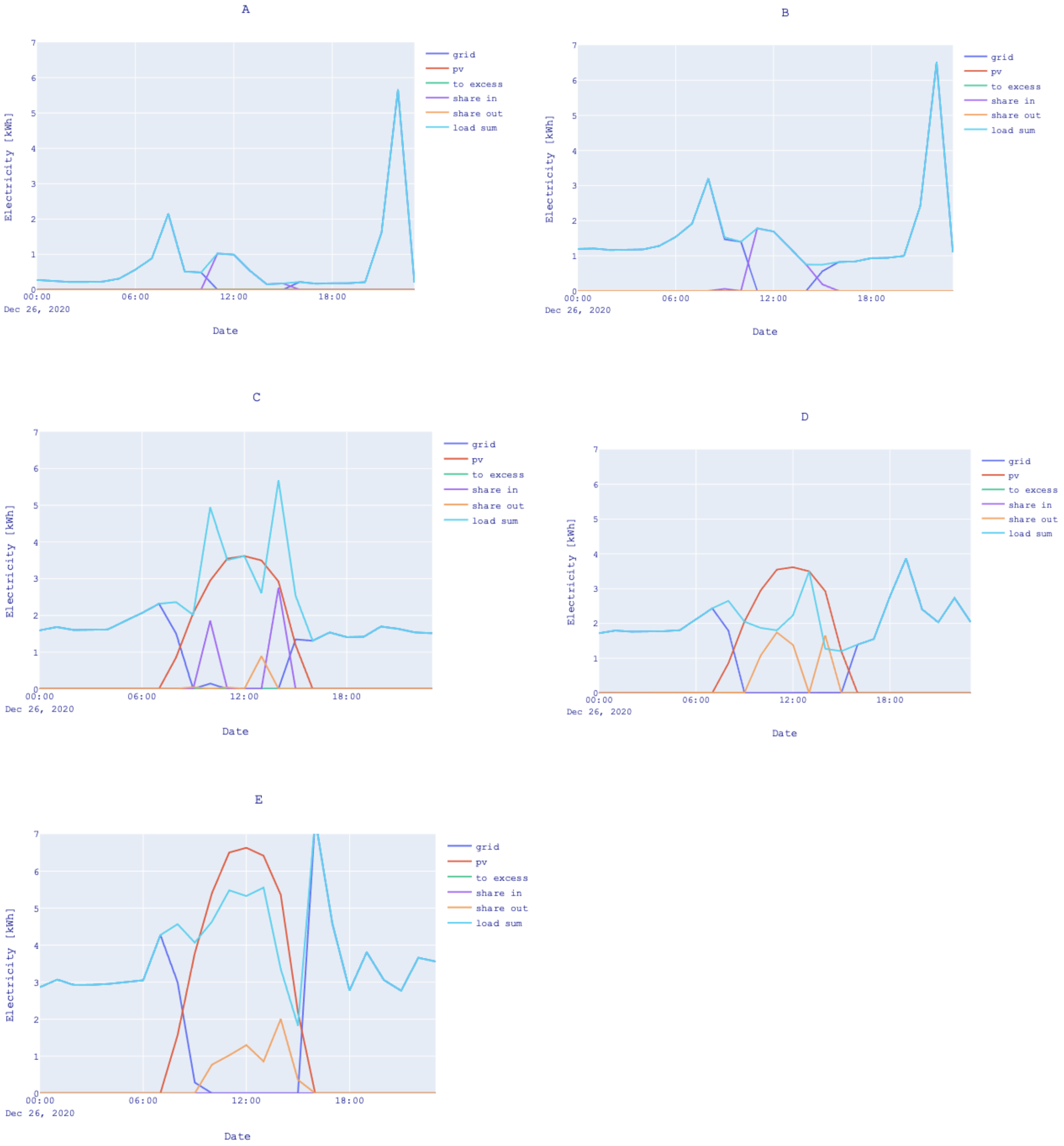


Figure 34: *Electricity flows analysis, 26th December.*

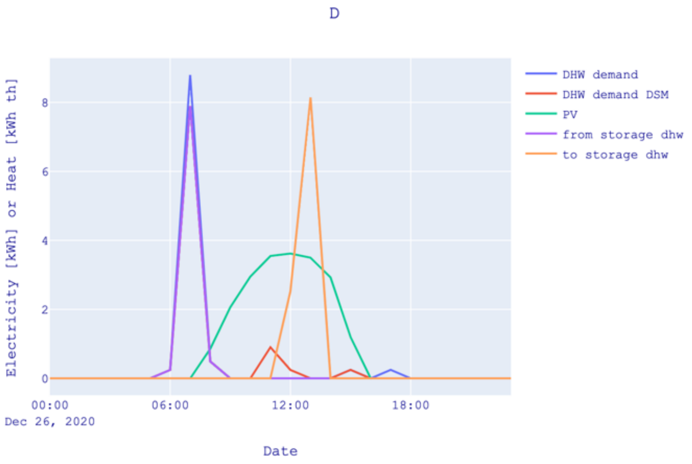


Figure 35: *DHW demand vs DHW demand with DSM related to PV production and storage.*

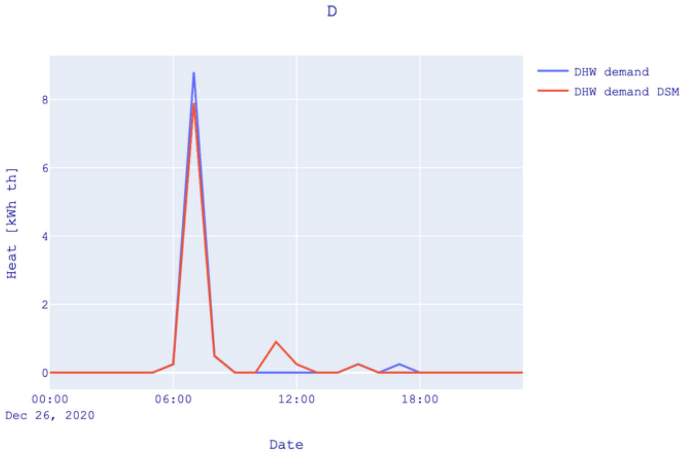


Figure 36: *DHW demand vs DHW demand with DSM.*

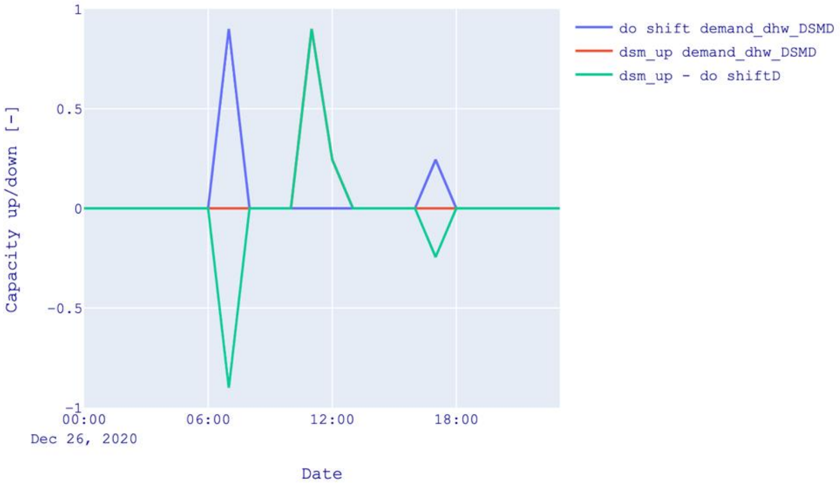


Figure 37: *DSM operation.*

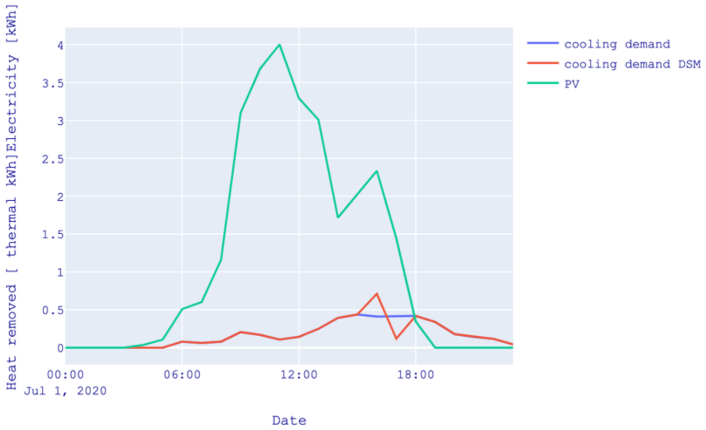


Figure 38: *Cooling demand vs Cooling demand DSM related to PV production.*

Figure 39: *COP of heat pumps dedicated to space heating variation in time.*

Figure 40: *Temperature variation in time for AW/W hp floor.*

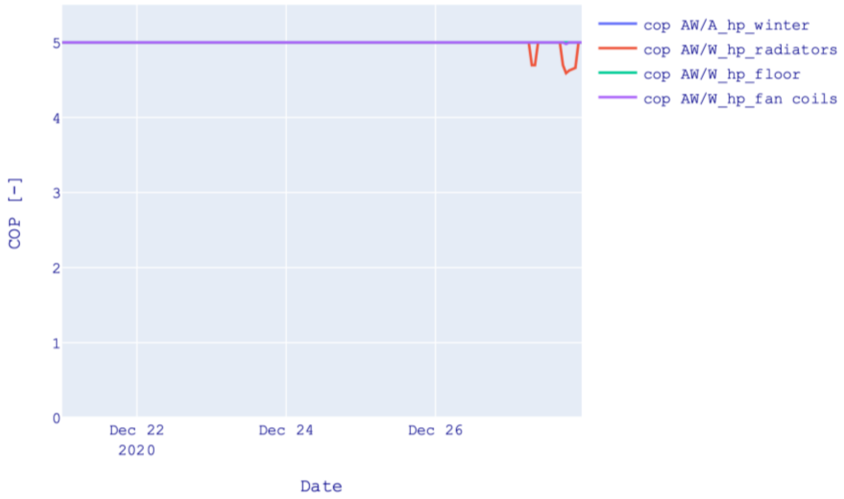


Figure 41: *COP of Carnot case variation in time.*

In Figure 42 electricity production or import from the grid and the electricity consumptions related to electricity demand and electrification of space heating and DHW production are represented for a winter week. The same is reported in Figure 43 for a summer week, with the electricity consumption relative to the electrification of the space cooling and DHW production. It can be noticed that the optimization leads to the implementation of two types of heat pumps systems for space cooling, which is due to the equivalent COP of the two. The user will be free to choose one of the two devices based on their cost and availability.

In Figure 44 it can be noticed that nearly half of the electricity in the context of the EC is produced from PV. However, half of it is injected into the grid (dark portion in the figure), and the rest is self-consumed by the EC.

In Figure 45 the total electricity production per source (for PV only EC self-consumed energy is considered) and the consumption per load is represented. The major consumption is given by heat pumps dedicated to space heating. In this configuration, if only the electrified thermal sector electricity load is considered, the PV production could cover the 63,76% of it, while if we consider the overall load covered by the electricity produced by PV and self-consumed it is nearly the 31,86%. From an analysis of fluxes, it is possible to notice that the priority of the electricity produced by PV is given to self-consumption, then followed by the sharing and finally to the excess.

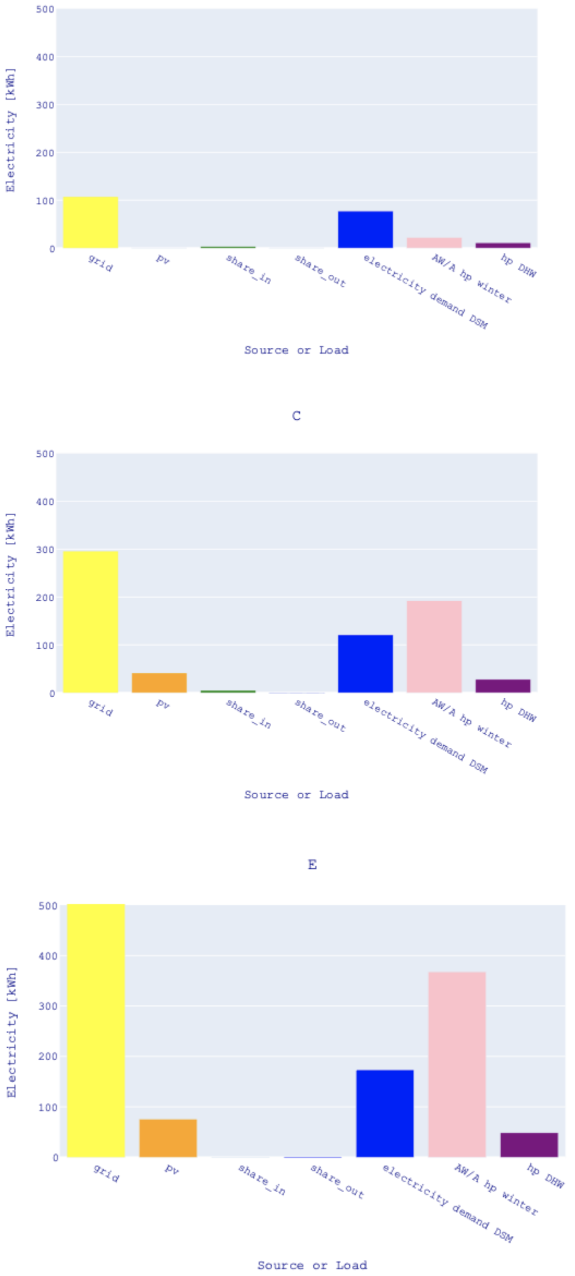


Figure 42: *Electricity production and consumption in a winter week.*

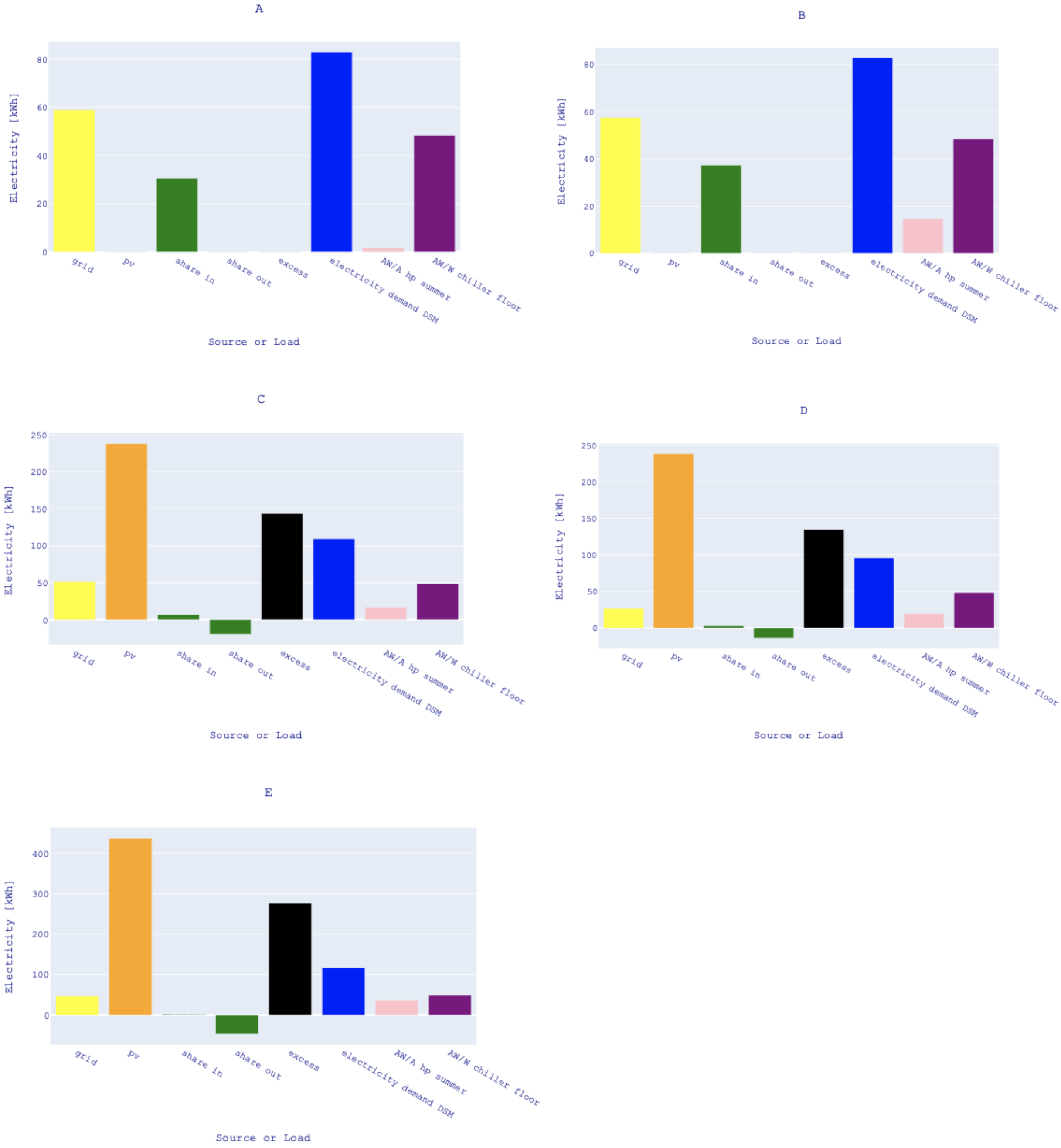


Figure 43: *Electricity production and consumption in a summer week*

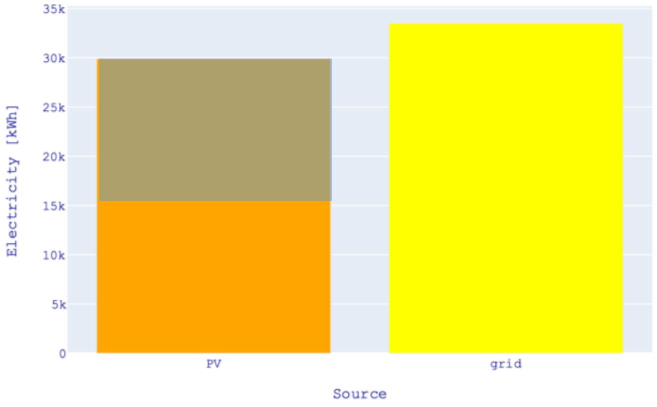


Figure 44: *Total electricity production from PV and imported from the grid.*

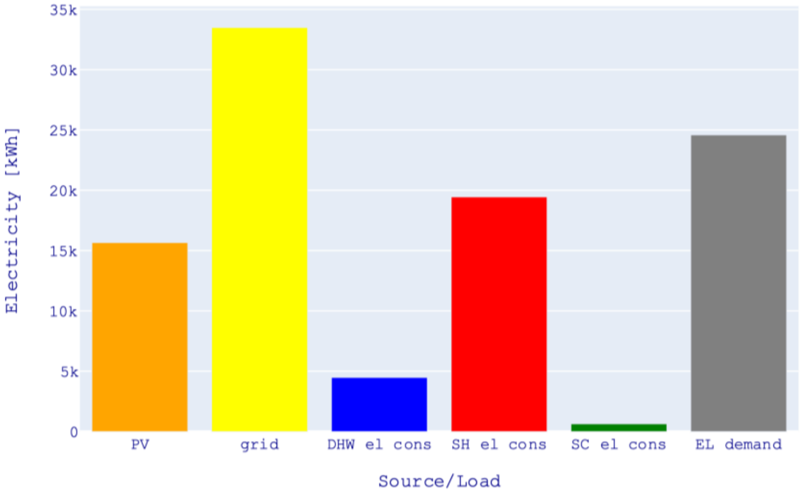


Figure 45: *Total electricity production and consumption of the EC per source/load.*

The impact of different HPs systems implemented is investigated in **Configuration n.2 of Case study 1**. Also, costs for SH and DHW production from traditional sources (methane) are considered in the shortage option. However, these are not implemented by the solver as optimized option. In Figure 46 it is possible to see the electricity that enters/exits each node. PV are installed for four out of five EC members, while user 'A' only benefits from the sharing. The self-consumed electricity (by the EC) produced by PV represents here the 49,69%, while the one of Configuration n.1 is the 52,48%. Within this portion, the shared energy is the 12%, which means that the remaining part is self-consumed by the user who owns the PV plant. The lower portion of energy shared is mainly due to the higher TES installed capacity, but also to a higher PV installed capacity, aspects which lead to a better match between demand and production profiles.

With respect to Configuration n.1, an increase of the 34% in the electricity consumption for SH can be noticed, due to the implementation of water systems, which have a lower COP (Figure 39). The optimized configuration involves floor heating systems. The SC consumption doesn't change, as cooling devices operate in both configurations at their COP technical limit, equal to 4. This happens because, according to chillers COP definition, it could rich higher values, but in this work a limit is given due to the considerations on the application of reversible heat pumps, which limit SC performances.

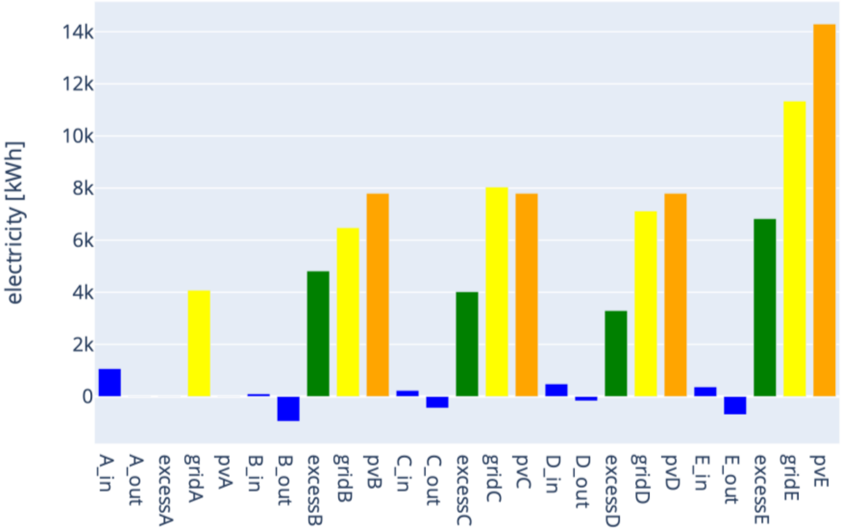


Figure 46: *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

Details on the distribution of cumulative annual values of electricity produced and consumed per load/source can be found in Figure 47.

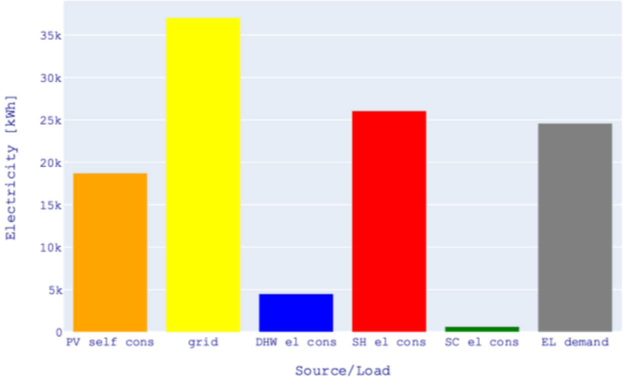


Figure 47: *Total electricity production and consumption of the EC per source/load.*

This configuration demonstrates the influence of lower COPs for heat pumps related to different choices about implemented thermal systems, which lead to higher PV and TEs installed capacities, higher percentages of electric energy injected into the grid, lower sharing, and lower economic performances coefficients (IRR equal to 11% and PBP of 10 years). The investment in an EC with this configuration is less convenient.

Configuration n.3 of Case study 1 is made to evaluate the influence of the heat/cool source (ground or air) on results, considering in this case the ground one and comparing it with the air source of Configuration n.1. Here changes are not so evident because air heat pumps are implemented, and the COP is always near the technical maximum value. So, the scheme of the electricity entering/exiting each node is the same of Configuration n.1 (Figure 48). What can be noticed is the difference in COP values for water systems (Figure 49), which are higher than the ones in Configuration n.1. In Figure 50 the total electricity production and consumption per source/load is represented.

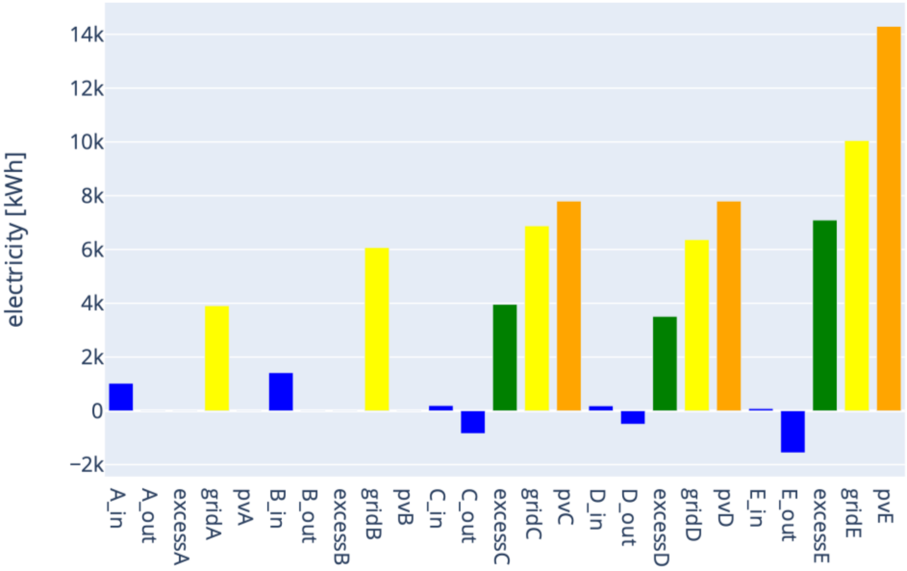


Figure 48: *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

Figure 49: *COP of heat pumps dedicated to space heating variation in time.*

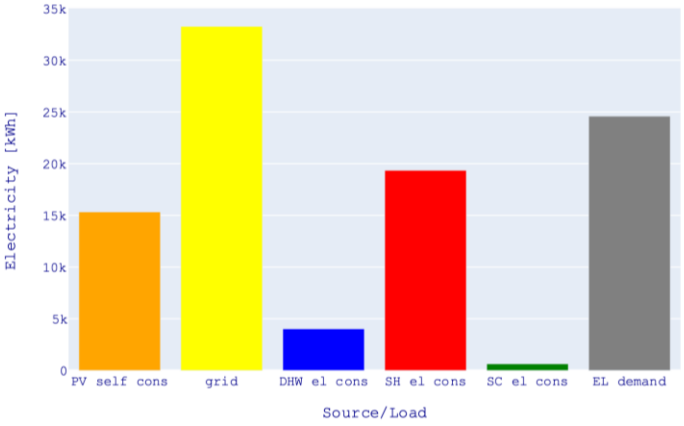


Figure 50: *Total electricity production and consumption of the EC per source/load.*

The major reduction in electricity consumptions is the one for DHW productions (of -10.12%), and this because at this scope water systems are implemented in both Configuration n.1 and n.3, so the effect of the higher COP correction factor is evident.

To better understand the energy consumption changes related to the use of ground source heat pumps with respect to the air source ones, a subcase is implemented

(**Configuration n.3b of Case study 1**), in which only ground to water HPs systems are activated for SH and SC. It's interesting to notice, from Figure 51, that in this case, differently than Configuration n.1 and n.2, the choice on the PV installation doesn't change with respect to Configuration n.3 (and so to n.1). This is due to the higher correction factor for the COP, which limits the impact of lower HP performances for water systems. With respect to Configuration n.2, in which only air to water systems (HPs) were implemented but with the air source instead of the ground one, there is a decrease in the electricity consumption for SH of the 20,82%, and a decrease in electricity consumption for DHW of 10,77% (Figure 52). Also, the shared electricity is nearly the 18%, while in Configuration n.2 it was stacked to 12%, even if the installed TES capacity was higher. This one emerges within Case study 1 as the best configuration, with an NPV of 27714€, an IRR of 14% and a PBP of 8 years. The electricity injected into the grid represents the 45.8% of the total produced one, instead of the 50.31% of Configuration n.2 and the 47.7% of Configuration n.1. The self-sufficiency of the EC (which means the portion of total electrical demand covered through self-production) reaches the 32.5%. Also, the valorization of the electricity injected into the grid has to be considered. So, this configuration shows that good performances of electrified thermal devices related to the choice of the ground source and the installation of thermal energy storage lead to profitable investments and good self-consumption and sharing values for the EC.

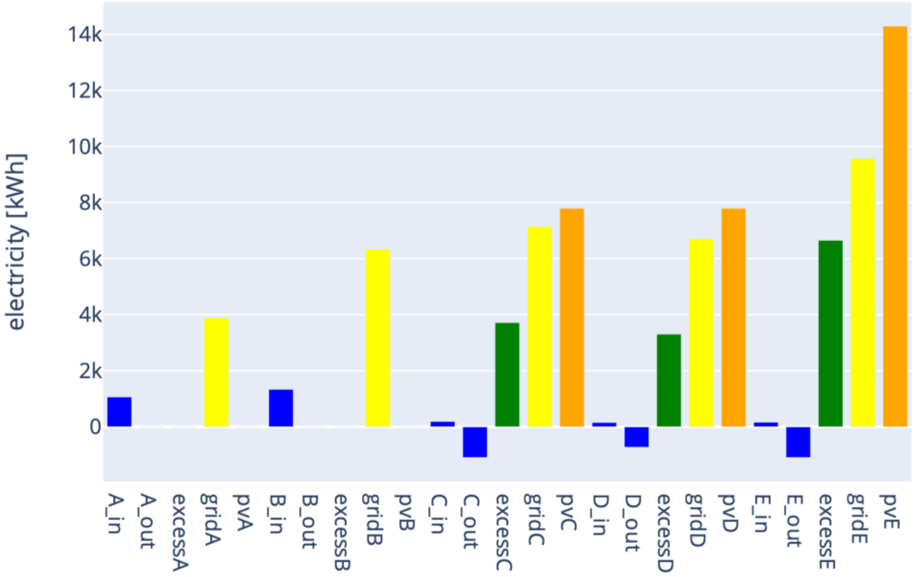


Figure 51: *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

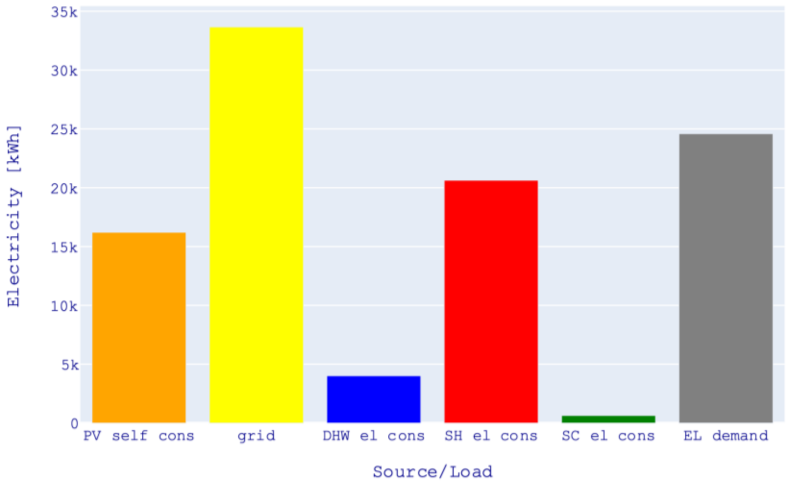


Figure 52: *Total electricity production and consumption of the EC per source/load.*

Configuration n.4 of Case study 1 is developed to investigate the impact of flexible settings for SH and DHW temperatures regulation. In particular, Fixed-point regulation is chosen for SH and Continuous treatment for DHW. Only air to water systems (HPs) are activated to evidence the effect of settings.

As it is possible to notice in Figure 53, the optimized configuration for what concerns the PV installation is different from the one of Configuration n.1, as in this case the PV are also installed for user B, leading to a PV production which is 26.31% higher. However, also the energy imported from the grid is majored of 22.95%. These increases are due to the higher electricity consumption of the electrified thermal sector, which has increased by the 45%, due to the overall higher flow temperatures of water to implement fixed point regulation and continuous treatments. All these aspects are represented in Figure 54.
The thermal load increase is principally due to the increase in SH load (49.75%), which in this case only relies on air to water systems without thermoregulation, but also to the increase in DHW load (31.66%), only due to the choice of the continuous treatment instead of the periodic one.
It is possible to notice that the COP of the three heat pump technologies is lower than the one reported in Configuration n.1, due to the fixed-point regulation (Figure 55).

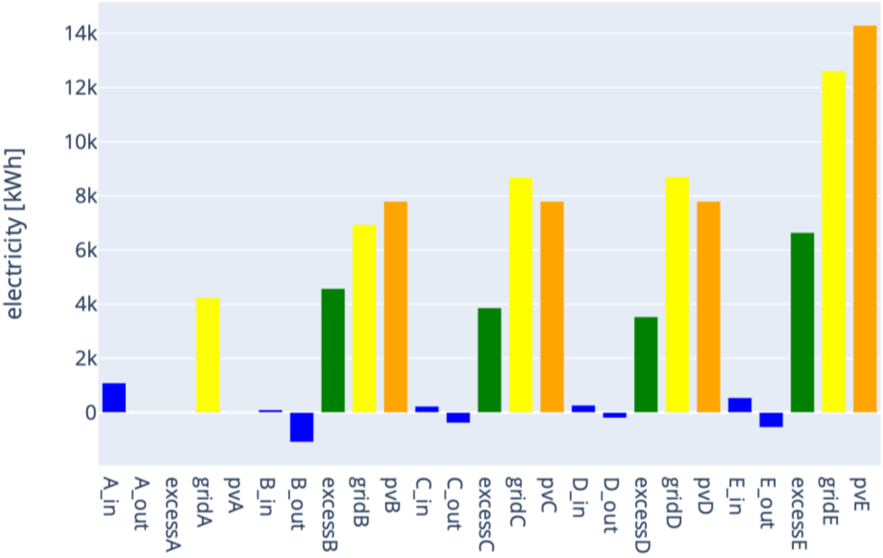


Figure 53: *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

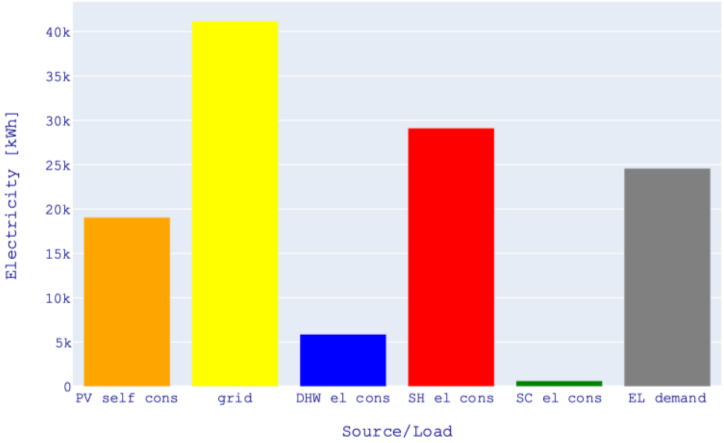


Figure 54: *Total electricity production and consumption of the EC per source/load.*

Figure 55: *COP of heat pumps dedicated to space heating variation in time.*

As an example, in Figure 56 and Figure 57 the differences between the DHW production in configuration n.1 and the one considered in this one are reported for a winter week. In fact, in the period, the electricity consumption for DHW production is different in the two cases. The lower COP value of the HP is also evidenced. Emerged values are reported below.

Configuration 1

Mean COP: 3,74
Electricity consumption: 10,89 kWh
DHW production: 39,8 kWh th

Configuration 4

Mean COP: 2,73
Electricity consumption: 14,93 kWh
DHW production: 39,8 kWh th

In Figure 58 the distribution of electricity production and consumption for a winter week can be appreciated, together with the differences between the users, each one with its peculiar energy class, house surface and composition characteristics.

The NPV of the investment is positive, and even higher than in Configuration n.1. This is due to the fact that the higher demand (due to lower COPs) lead to major PV installed capacity, to which it follows a higher PV production.

Being the self-sufficiency at 31.65% (not far from the 31.86%), the savings due to the electricity self-consumed and not bought from the grid reach significative values. However, the PBP is increased and the IRR decreases.

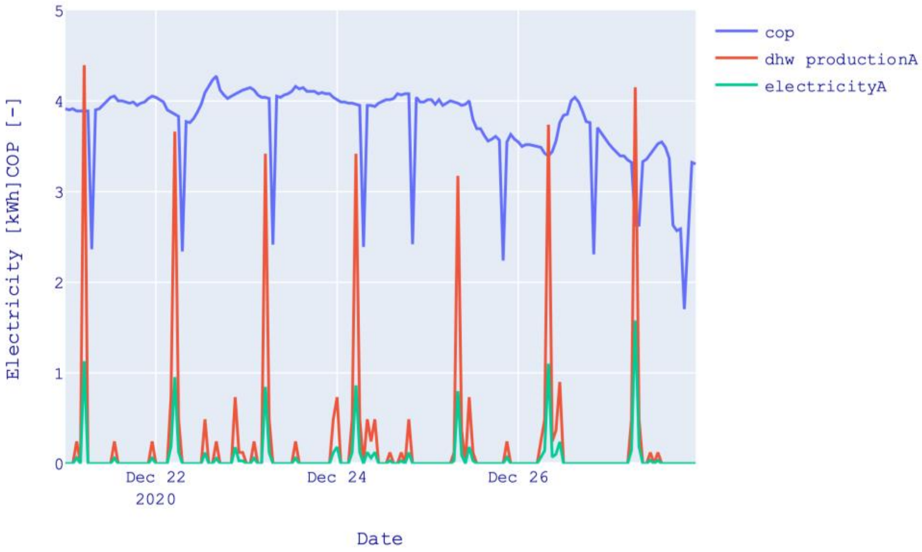


Figure 56: *DHW production vs HP electric consumptions vs HP COP for Configuration n.1.*

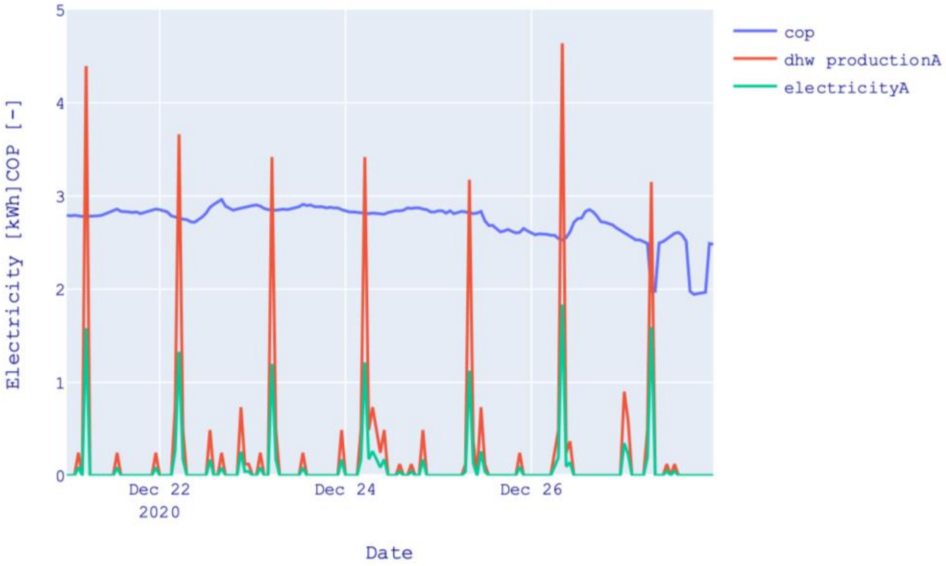


Figure 57: *DHW production vs HP electric consumptions vs HP COP for Configuration n.4.*

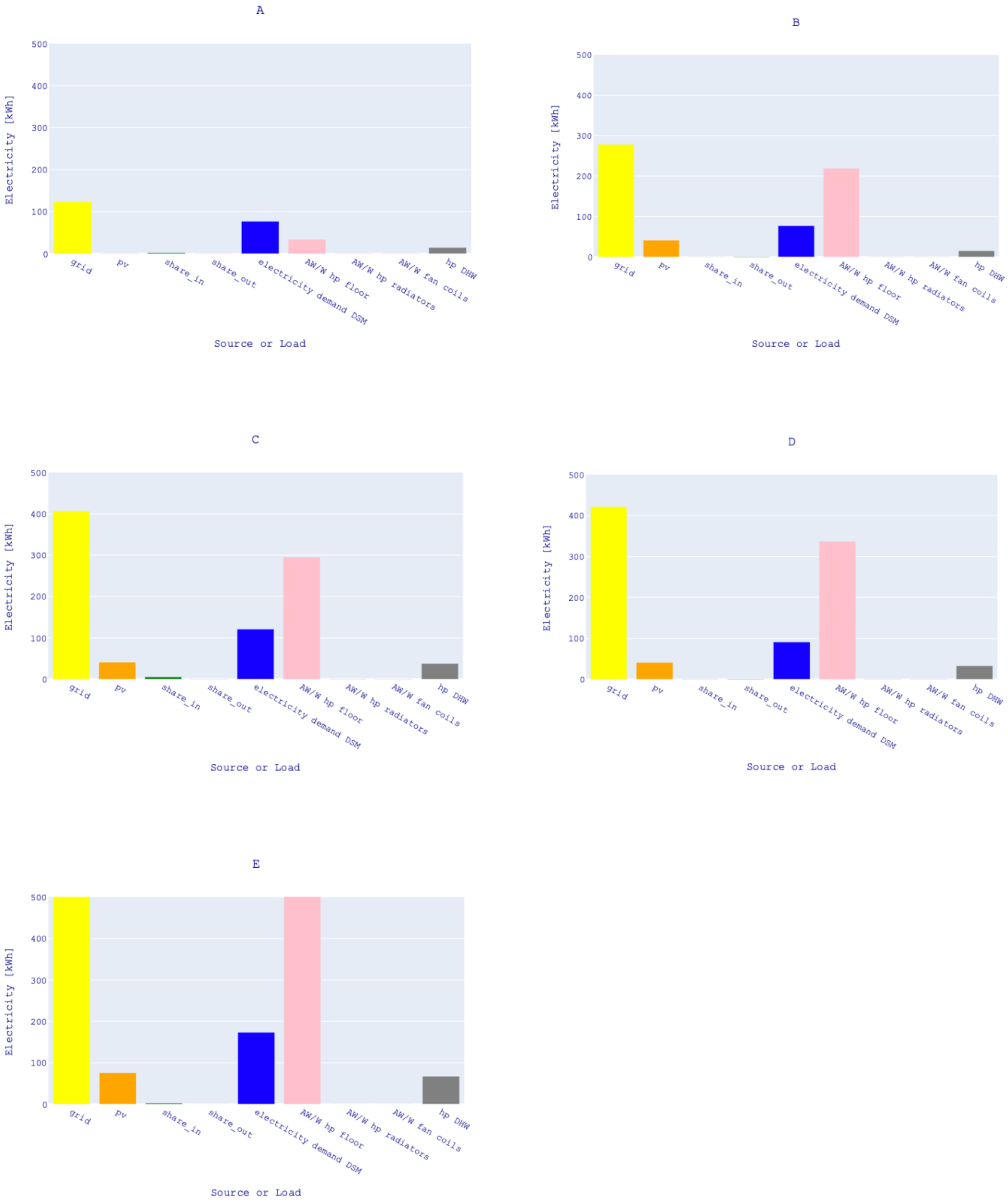


Figure 58: *Electricity production and consumption in a winter week.*

In **Configuration n.5 of Case study 1** costs of methane and electricity from the national grid was considered to evaluate the effective advantages of the thermal sector electrification. The optimization shows the same results as in Configuration n.1 (considering periodic treatment for DHW and thermoregulation for SH) and n.2 (considering continuous treatment for DHW and fixed-point regulation for SH), which evidences that the shortage option is not used nor for DHW nor for SH. This means that the production of DHW and SH from renewable energy sources through the electrified devices implemented in the model is more advantageous than their production from traditional energy sources.

Configuration n.6 of Case study 1 is implemented to analyze the impact that Solar Thermal Collectors installation has on results.

Starting from Configuration n.1, the available surface for each user has been evaluated, considering the installed PV capacity. The emerged values have been inserted in the input file and the Solar Thermal Collector component has been activated, to support DHW production. For users 'C', 'D', and 'E' the maximum PV capacity related to the available space was installed, so the available surface for Solar Collectors installation is the one related to users 'A' and 'B' (and only the 50% of it is considered as described in previous sections). Data about users' house surface can be found in the 'Users' dictionary.
Results demonstrate that the Solar Thermal Collector can give only a minor contribution to DHW production. Electricity consumption of HP dedicated to DHW is lowered of 11% and the PV installation proposed is the same of Configuration n.1. DHW production from solar collectors for users 'A' and 'B' are reported in Figure 59 and Figure 60 for the whole year and in a winter week in Figure 61 and Figure 62.

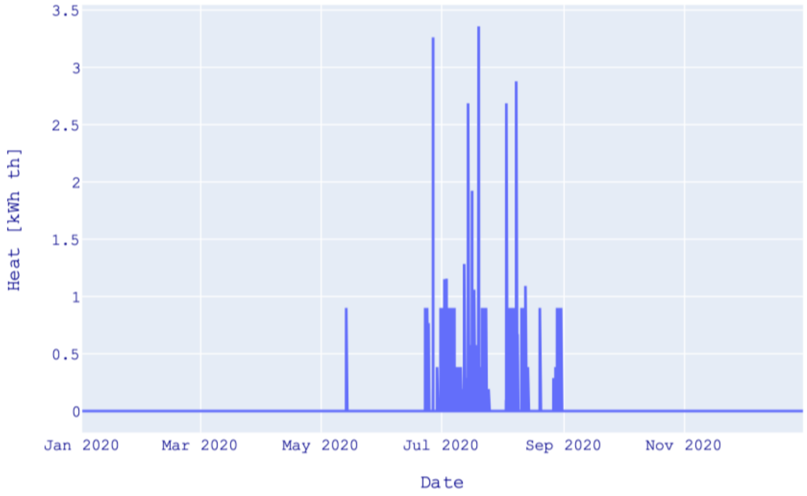


Figure 59: *DHW production from solar collector for user A.*

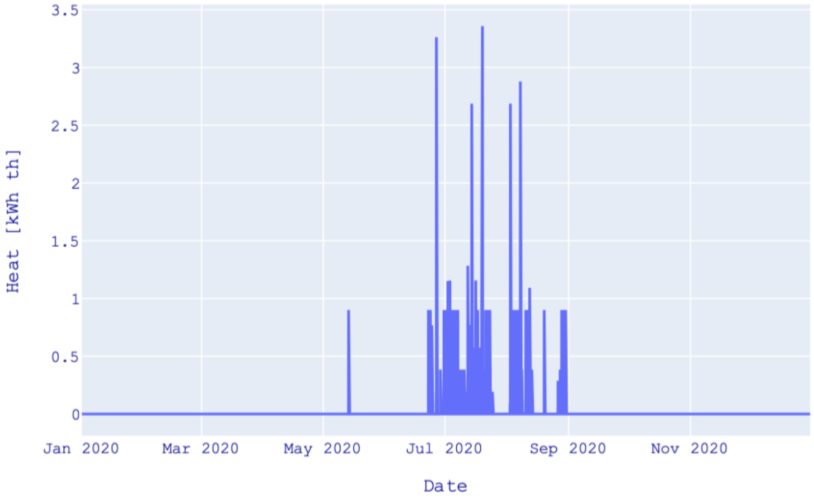


Figure 60: *DHW production from solar collector for user A.*

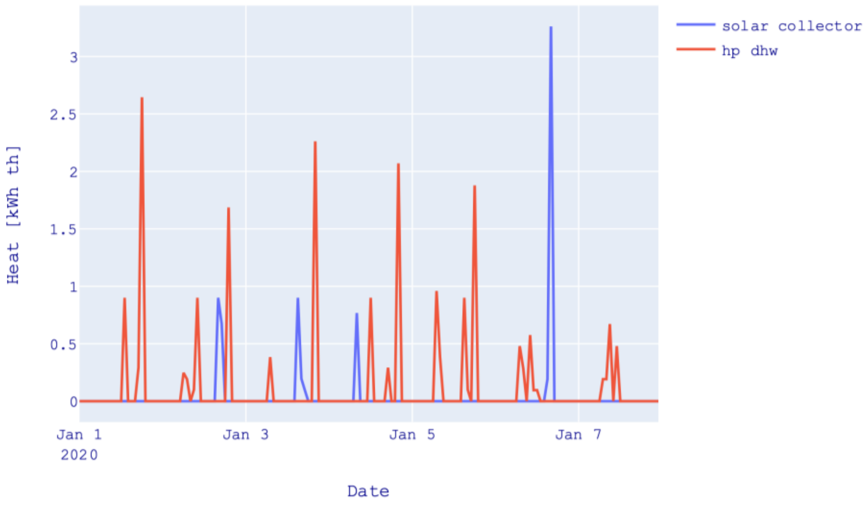


Figure 61: *DHW production from solar collector for user A in a winter week.*

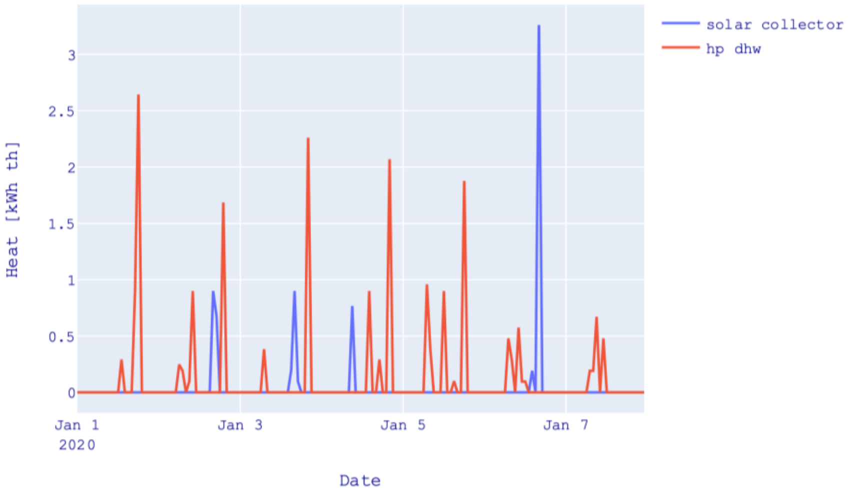


Figure 62: *DHW production from solar collector for user A in a winter week.*

The configuration analyzed shows good values of self-sufficiency (33.26%) because part of the DHW demand is covered by the STC, and so the impact of electrified thermal demand is lower and can be better covered by PV production.

Economic parameters show that the investment is profitable, however in this case investment costs of STC were not considered, because the aim was to explore its impact if installed at maximum capacity and without constraint in the operation (costs).

If STC investment costs are considered, (e.g. vitosol…) the NPV reaches low values (nearly 16500 €), and so the IRR (nearly 8.5%), while the PBP increases (12 years). These results show that STC is not a good investment to be integrated in the EC.

Configuration n.7 of Case study 1 is made to evaluate the electrification of the thermal sector in the EC, even if not fed by RES. At this scope, PV are deactivated, and shortage costs are implemented (methane for SH and DHW, electricity from the grid for SC), together with the electricity from the grid ones.

Results (Figure 63) show that the choice is still the electrification of the thermal sector, even if fed by electricity from the national grid. Shortage options, and so traditional energy sources, are not implemented. Emissions in this case are higher (13.63 tons/year) than in Configuration n.1 due to the deactivation of RES, and to the emission factor of the electricity production from the Italian energy mix. However, they are lower than in Configuration n.8, in which only traditional energy sources are considered (methane for SH and DHW, electricity from grid for SC and EL).

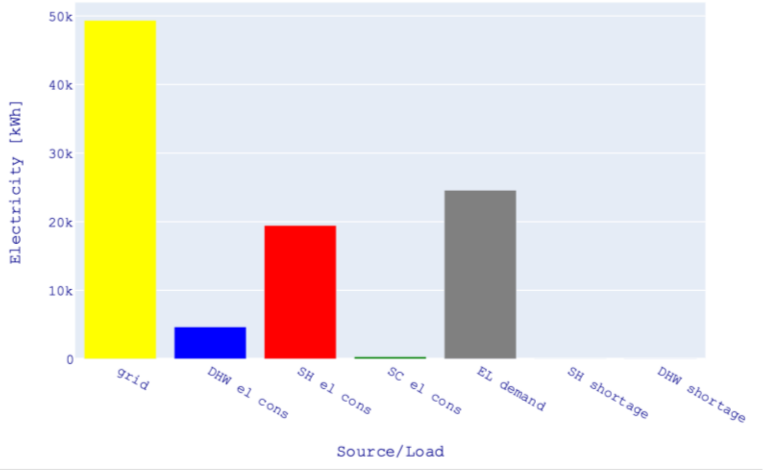


Figure 63: *Total electricity production and consumption of the EC per source/load*

The aim of **Configuration n.8 of Case study 1** is to evaluate the impact of sector coupling on the EC. So, electrical devices for the coverage of SH and DHW demand are deactivated, and only traditional sources (in this case methane at the cost of 0.11 €/kWh) are considered. For SC a heat pump with a fixed COP of 3 and fed by the national electrical grid is considered. It can be noticed, from Figure 64, that PV are only installed for one user, which shares electricity to the other ones.

The installed PV capacity decreases because it only must cover the EL demand, now fed by PV for nearly the 33% (vs a self-sufficiency of nearly 32% in Configuration n.1, not so far). Emissions drastically increase due to the usage of methane to supply SH and DHW. The IRR seems to make the investment the most advantageous one, however the thermal demand is not covered and higher costs for each thermal kWh (0.11 €/kWh th) than in the electrified configuration (0.2 €/kWh el /COP) must be considered. The sharing increases due to economies of scale, which make the PV installation for only one user the optimal solution.

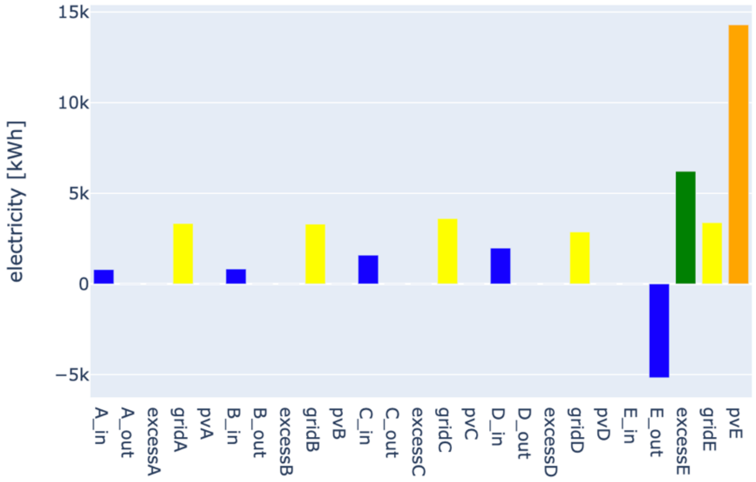


Figure 64: *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

An additional case is considered, **Configuration n.8B of Case study 1**, which consists in Configuration n.8 with the introduction of sector coupling (with thermal sector electrification and PV constant capacity). This is done by activating the thermal sector electrification devices and considering an installed PV capacity equal to the one of Configuration n.8.

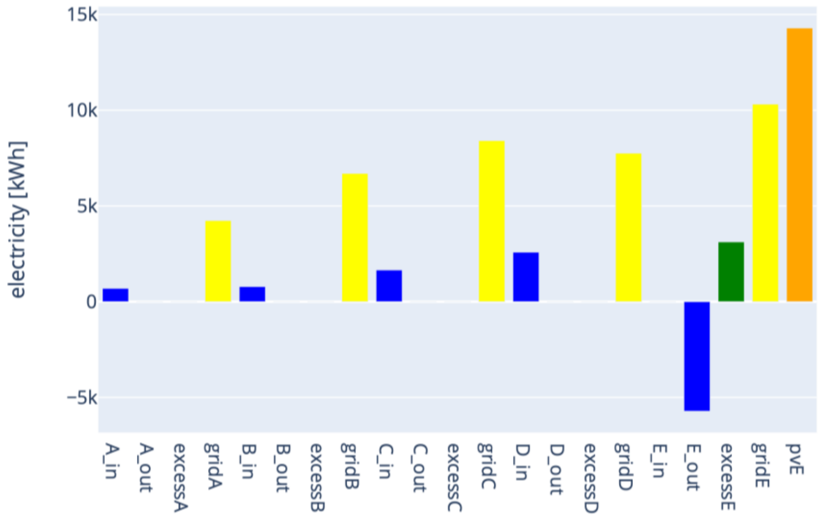


Figure 65: *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

This configuration shows a deep increase in the electricity self-consumption by the EC (excess from 43% to 21%) and a decrease in the sharing (64% to 51%) due to a better fit between demand and production profiles. The NPV increases together with IRR, which is now equal to 26%, and the PBP decreases to 5 years. However, the NPV is still higher in Configuration n.1, in which capacities are optimized for both electrical and thermal demands. These considerations show the advantages of thermal sector coupling and electrification in ECs. It can also be noticed that Economies of scale enhance the sharing between the EC members; however, their application is limited in configurations in which PV capacity is not fixed and the limit to PV installation (available surface) for different users is reached due to the higher demand related to sector coupling.

Analyzing **Case study n.2** it's possible to evaluate the impact that geographical location has on EC optimization results. A first configuration (**Configuration n.1**) is considered, with same technical settings of Configuration n.1 of Case study 1. In this case, the optimized PV capacity installed (Figure 66) is the same of Configuration n.1, however, differences in the dispatch are present.
It can be noticed, in Figure 67, that electricity consumptions for the electrified SH and DHW production are lower than in North Italy location case. This has been obtained in the model through different hourly temperatures (extrapolated from ARPA database), different irradiance profiles (generated through PVGIS [62]) and a different climatic zone, which leads to different weights of the thermal demand components on the overall consumption.

Also, higher COP (Figure 68) influence the electricity consumptions for SH, SC and DHW production. The electricity consumption for SH is lowered by 21,45%, and the one for DHW by 9,84%. The electricity consumption related to SC is increased by the 234%. Overall thermal consumptions are lowered by the 12,7% with respect to Configuration n.1, due to the low impact of SC consumption on the overall ones. Higher PV production due to major values of irradiance and lower thermal demands lead to an increase of the self-sufficiency of the EC, which reaches here the 36.4%, while it was 31% in Configuration n.1 of Case study 1. This contributes to lower the electric energy injected into the grid. The EC investment in Brindisi is more profitable than in Milan, due to favorable conditions. For the same PV capacity installed and a difference of 9 kWh of TES capacity installed (higher in this case), the NPV increases of nearly 10% and IRR reaches the 15%.

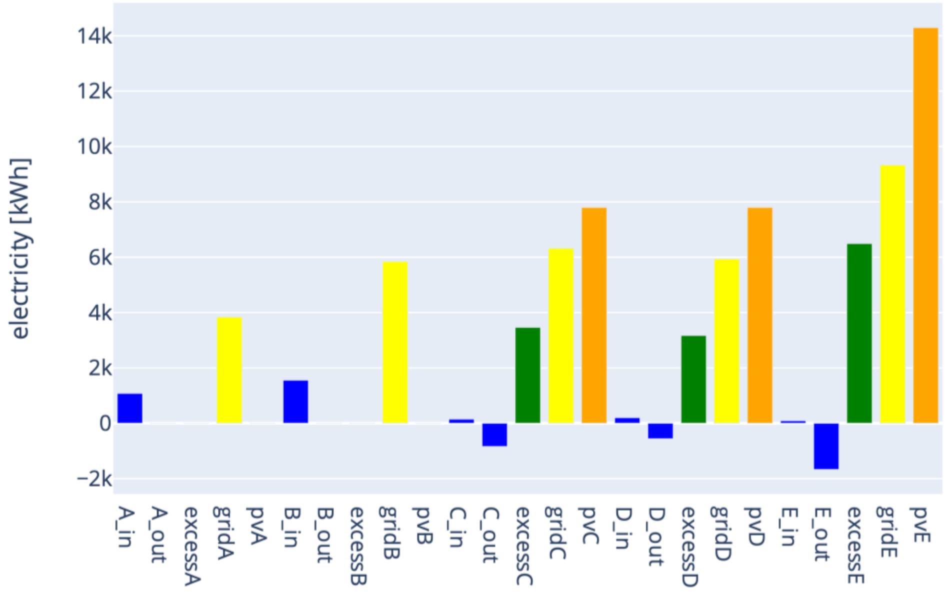


Figure 66 : *Electricity produced through PV, imported from the national grid, imported/exported in/from the node for sharing, electricity to excess (injected in the national electrical grid).*

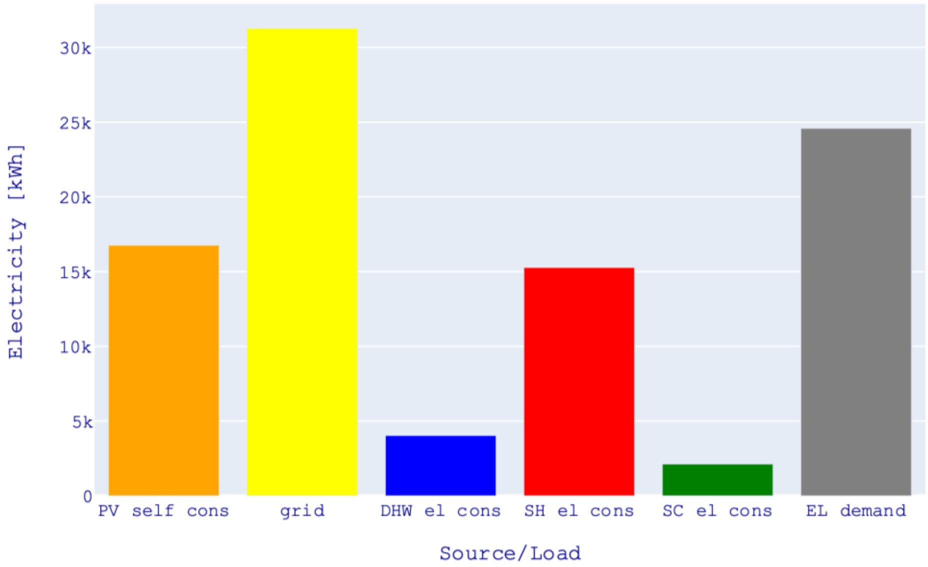


Figure 67: *Total electricity production and consumption of the EC per source/load*

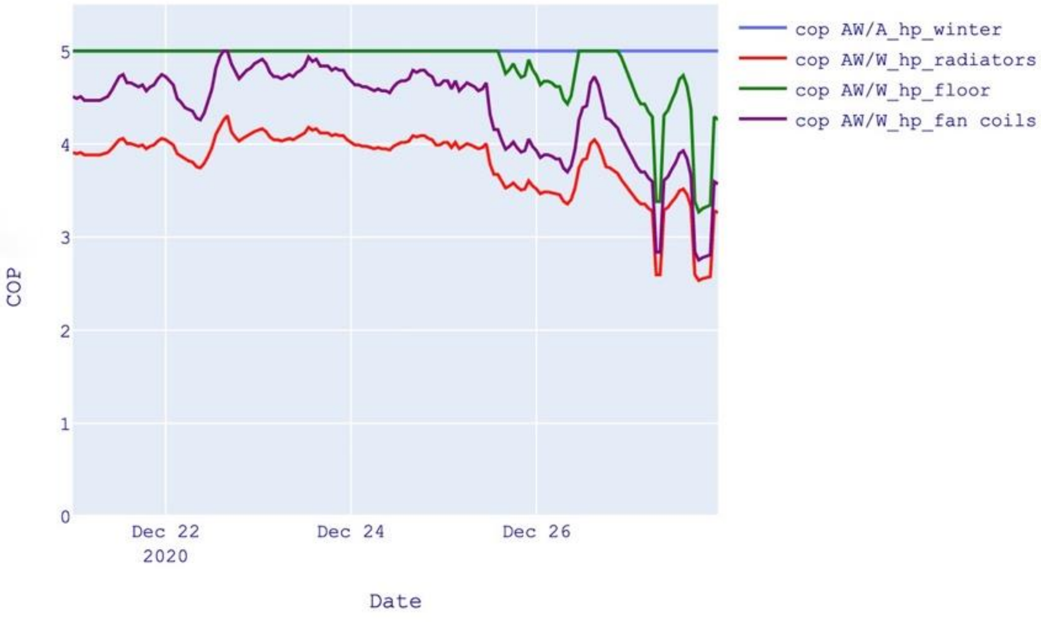


Figure 68: *COP variation in time for SH devices in a winter week.*

The impact of STCs installation is studied for **Case study 2 in Configuration n.2**. The procedure for the surface limits implementation for STC is the same explained in section 3.1.7. Also in this case, the impact of the STC installation is limited, leading to DHW electricity consumption savings of the 12%, which is a little higher with respect to the one of Case study 1 due to major irradiance.

The NPV is lower than the one of Configuration n.1, due to minor values of sharing and higher values of excess (in fact savings coming from shared electricity are major than incomes from excess). Also, investments related to STC are not considered. If considered, the result would have been a NPV of 18584€ (vs 30095€ of Configuration n.1), an IRR of 9% and a PBP of 12 years.
STCs are not a profitable investment, even if irradiance values are major than in Case study 1.

5 Conclusions

ECs are becoming a key element of the green energy transition. In recent times new support schemes to favor their spreading have been adopted. However, a literature overview showed lacks in the development of EC models, in particular for what concerns the thermal sector integration and its electrification. This work aimed at developing a versatile model for an EC (which can be both a CER or an AC scheme) with focus on the thermal sector electrification. The model was developed by using Oemof, an open-source energy modelling framework, and in particular the Oemof solph and the Oemof thermal packages. Attention was given to many aspects. First, DSM was integrated in a precise way in the model to optimize energy consumptions for all the demand profiles, each one characterized by peculiar parameters. Then, the single user model was developed, analyzing in detail all the components. In a second step, the single user model was integrated into the EC one, in which each member is represented as a node. HPs were configured basing on different sources, domestic system typology, device functioning and flexible operating options. The user can set these choices in the input file, together with the availability of the devices. Different configurations lead to different COPs, which is an hourly value calculated basing on peculiar temperature profiles, external ambient temperature, and heat/cool source. The user can also choose to activate the electric boiler for the DHW production. Thermal energy storage was considered, integrated with thermal losses calculation and economies of scale. Electric storage too is present, to explore all the options (with peculiar costs). The main RES implemented is the PV one, whose limits are detailed for each scheme (CER or AC) and for each user in the case of CER.

In this case too economies of scale were introduced. As a sensitivity analysis to be conducted after a first optimization process, STCs were considered for the support of DHW production. Electricity fluxes have been valorized considering incentives, remunerations and incomes deriving from the electricity injection into the grid, allowing an analysis on the impact of different choices and configurations on the optimization and on the economic parameters (NPV, IRR, PBP). Also, CO_2 emissions were calculated to provide a complete overview of the cases described. The focus in this work is also on the characterization of EC users, made to reflect the Italian situation. The EC composition was defined basing on ISTAT studies on the Italian population composition and crossing these data with the categories identified by LPG. Electricity and DHW demand profiles were generated through the LPG software, and corrected through created functions, while SH and SC demand were developed by using peculiar functions elaborated basing on legislation. Also, energy classes and surface of the users' buildings were assigned to reflect the Italian situation, based on ENEA statistics. Two case studies were developed to explore the potentialities of the model and to investigate the impact of thermal sector electrification and integration in ECs, together with the one of technical and flexible operation choices. The first case study was in Milan, while the second one in Brindisi, to underline the impact of the geographical location. For both cases different configurations were characterized. Results show the impact of the technical settings, which lead to different COP of HPs and so different electrical consumptions, different optimal capacities for PV and TES, and differences in the electricity dispatch, which in some cases valorizes the sharing while in others the self-consumption. Investments on ECs with thermal sector electrification resulted to be profitable. The electrification of the thermal sector emerges as the optimal solution too in the case PV are not activated, and so the system relies on the national grid. Relevant advantages of the electrified thermal sector integration in the EC were demonstrated, both in economic, emissions and energy dispatch terms. At the contrary, STCs have not been evaluated as a profitable investment, and their contribution for DHW production was limited.

A more complete analysis could develop a Multi-Objective model, which considers emissions optimization. Future developments of the work could also include the electrified transport sector integration, as well as the district heating option for the thermal one.

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ARERA *Autorità di regolazione per energia reti e ambiente*
AC Autoconsumo Collettivo
CER Comunità energetica rinnovabile
DHW domestic hot water
DSM Demand Side Management
EC Energy community
EL electrical
epc equivalent periodical costs
IRR internal rate of return
MiSE Italian Ministry of Economic Development
NPV net present value
Oemof open energy modelling framework
PBP payback period
PUN national single price
PV photovoltaic
PVGIS Photovoltaic Georaphical Information System
RES renewable enregy sources
SC space cooling
SH space heating
STC solar thermal collector
TES thermal energy storage

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