Optimal design and operation of distributed electrical generation for Italian Positive Energy Districts with biomass district heating

R. Volpe*[1], M. Gonzalez Alriols[2], N. Martelo Schmalbach[2], A. Fichera[1]
[1]Department of Electrical, Electronics and Computer Engineering, University of Catania, Catania, Italy
[2]Biorefinery Processes Research Group (BioRP), Chemical and Environmental Engineering Department, University of the Basque Country, San Sebastian, Spain

*e-mail: rosaria.volpe@unict.it

ABSTRACT

The active participation of prosumers within the energy generation and distribution stages has revolutionized the energy market favoring the rising of decentralized energy supply configurations and representing a key path for targeting the transition towards sustainable and energy-efficient urban areas. The new Renewable Energy Directive 2018/2001 regulates the constitution of renewable energy communities and promotes the exploitation of solid biomass, biofuels, and biogas for district heating. In addition, energy communities can be considered Positive Energy Districts in case of an annual net-zero energy import and local surplus of renewable production. In alignment with these regulatory frameworks, this research proposes a model for the design of prosumer-centered thermal and electrical grids pointing to a positive balance between production and consumption. In detail, this research contributes to the *(i)* design of the electrical and thermal distribution grids, *(ii)* configure the optimal exchange scheme for electrical distribution among prosumers, and *(iii)* valorize the eventual positive surplus. The model is discussed for a candidate Positive Energy District in a real urban neighborhood in Sicily. Results demonstrate a good rate of interconnections among buildings of the area, especially in a spatial range of 200 m with almost 44% of distributed electricity production. From the environmental viewpoint, 73% of carbon emissions are avoided in comparison with the centralized electrical supply, whilst the 55% of emissions avoided have been estimated from biomass district heating, thus posing favorable conditions for a possible transition of the existing area towards the Positive Energy District model.

KEYWORDS

Energy distribution; Energy surplus; PV panels; Energy community; Prosumers; Sustainable Development Goals

1. INTRODUCTION

The path towards the decarbonization of the residential sector has its foundations on renewable sources integration and enhancement of energy performances of living areas, responsible for almost the 67 % of the global energy demand and, consequently, for more than the 60 % of carbon emissions [1]. Crucial steps have been done since the treaty of the Kyoto Protocol, back in 1997, and, more recently, since the Paris Agreement in 2015 [2].

One of the most revolutionary changes of the energy markets can be recognized in the active participation of *prosumers*, considered as the driving force for the transformation of both the energy sector and the entire society. Consequently, actions, tools, and regulations need to be modeled on their role and the effective synergies among the energy production, distribution, and consumption supply chain stages [3]. Novel ways and regulations orienting energy transition and focusing on the decentralized participation of consumers have been outlined in the Energy Union Strategy COM/2015/80 and the rulebook "*Clean Energy for all Europeans*" [4]. In particular, the regulation introduces the definition of a "*European Energy Union*", in which consumers will be empowered to have full access to the produced energy and to make "*informed energy consumption choices*" [4]. This can be achieved by reinforcing the renewable sources exploitation in urban areas and, most importantly, creating the physical and normative conditions for an interconnected energy distribution infrastructure actively managed by consumers. As an outcome of this regulation path, the European Union has adopted the Renewable Energy Directive 2018/2011 for the promotion of energy from renewable sources and introducing, *inter alia*, the concept of "*energy communities*" [5]. In this Directive, a particular focus is then related to the exploitation of biofuels, bioliquids, and biogases for district heating and cooling, and mobility.

When referring to active prosumers and energy communities, the Directive 2019/944 (amending the Directive 2012/27) should be also taken into consideration, since it regulates the internal energy market for electricity [6]. Both Directives are expected to deeply affect the European energy transition and are going to be transposed into national legislations from the Member States. In Italy, in particular, the transposition process began in February 2020 with the *Decreto Milleproroghe*, in which the definitions of "renewable energy community" and "prosumers owning renewable systems and acting collectively" have been introduced [7]. The path for the conclusive transposition is not yet finished, but a final draft is expected after the implementation of the Italian National Recovery and Resilience Plan, as part of the European Program "*Next Generation EU (NGEU)*" for the ecological transition, economic growth and social inclusion [8].

1.1 Positive Energy Districts

The development of Positive Energy Districts (PEDs) arose from the establishment of the Implementation Working Group (IWG) 3.2, in October 2018 [9], together with the JPI Urban Europe [10].

A final definition of Positive Energy Districts is not yet available. The White Paper from JPI Urban Europe proposed the following preliminary definition: "*Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net-zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems while securing the energy supply and a good life for all in line with social, economic and environmental sustainability*" [11].

The development of PEDs has been extensively considered crucial to foster the transition towards sustainable and climate-neutral neighborhoods. The IWG aims at developing a common European framework for the definition, understanding, and implementation of PEDs [9]. To this aim, an important initiative is currently active and coordinated together with the JPI Urban Europe for the constitution of 100 PEDs by 2025 [12].

Some results and lessons learned have made been available for the scientific community and urban planners, one of the most involved stakeholders during this dissemination stage [11], to support the diffusion and replication of PEDs. At the same time, a variety of national, European, and international programs and projects are working on common guidelines for the successful implementation of PEDs. Among these, the International Energy Agency (IEA), Energy Building and Construction (EBC) Annex 83 on "Positive Energy Districts" is working to define PED, to evaluate the energy production technologies performances, to carry on the sustainable assessment of PEDs and to evaluate existing case studies [13].

At this point, it is interesting to understand how to link the two concepts of energy communities and Positive Energy Districts. For instance, PEDs could be imaged as EC with a net positive balance and annual net-zero emissions. This statement is neither false nor exactly true. Energy communities, as defined and regulated in the Directive 2018/2001 and Directive 2019/944, are mainly focused on targeting the decarbonization of the energy sector recognizing the strategic role of consumers in achieving this aim. ECs produce energy from renewable sources and constitute a legal subject signing a voluntary commitment regulating the energy consumption and distribution within the community. PEDs do not have any statutory obligations, rather they are asked to have net positive energy and net-zero emission balances for the sustainable growth of urban areas. So, it is evident that the two concepts are interlinked and it might be interesting to study if and how an EC can achieve the net positive energy balance and, most importantly, how this community can plan to valorize it within the approved legal conditions and inside the spatial boundaries of the district.

1.2 Integration of renewable energy systems in urban areas

The diffusion of different renewable sources in urban areas has been widely addressed in the literature, especially by deepening the overall performances of multi-energy systems [14]. Gabrielli et al. configured a multi-energy system for the thermal and electrical supply of a neighborhood in Switzerland [15]. In their work, they developed two full-scale optimization models for the optimal design and operation of multiple energy production, conversion, and storage technologies, including the evaluation of cost and emission rates deriving from the proposed technological scheme. A technology-driven strategy is proposed by Mavromatidis and Petkov and is based on the definition of a dynamic optimization tool (MANGO) for the design, operation, and multi-location modeling of multi-energy systems [16].

Usually, the modeling of multi-energy systems presents different levels of aggregation in terms of energy supply and, in particular, referring to technologies, buildings, districts, or even regions [14]. On the other side, the evaluation may regard the integration of different types of renewable sources, i.e. biomass, solar, or wind.

The insertion of PV panels in the urban context is a widely treated argument within the scientific community. Several aspects are considered and evaluated, and researches range from more technological to operational issues. Recently, Kour and Shukla proposed an algorithm to reduce the shade dispersion and to enhance the power output of the PV array [17]. A comparison between exergy-based and energy-based optimization models has been proposed by Tonellato et al. [18] for two apartments located in Switzerland and Italy. Results demonstrated that the application of the two models leads to different technological applications: boiler and PV panels represent the best solution for energy-inspired approaches, whilst heat pumps and solar thermal panels for exergy methods. An exergetic study is also offered by Kilkis [19] for the evaluation of the impact of a nearly net-zero exergy district within interlinked energy, water, and environmental sustainability framework.

The diffusion of PV panels for energy trading among buildings is often evaluated from the economic viewpoint, as done by Karami and Madlener for the achievement of the energy self-sufficiency of communities [20].

Other studies dealt with the energy autonomy of private households and their impact on the decentralization by proposing optimization models for the minimization of the centralized supply [21] or agent-based models to account for the role of consumers’ decisions on the distribution [22].

The impact of decentralized energy systems has been evaluated from the literature also regarding political opportunities. In [23], the study of stakeholders' involvement, incentives, and the presence of decentralized actors in two different countries, Germany and Japan, have demonstrated that, although complex, the transition towards decentralized systems shows favorable results from the sustainability viewpoint.

Regarding the topic of district heating (DH), it is unquestionable that it contributed to the decarbonization of the energy sector as well as to enhance the profitability of the area in which they are inserted [24]. During the last decade and mainly due to these promising characteristics, a lot of studies focused on the development of tools, methodologies, and approaches for the optimal design and operation of biomass-based district heating.

The climate impact of biomass use in DH has been demonstrated by Hammar and Levihn [25], who measured how different biomass sources affect the total emission rates and the net power production. Referring to the economic evaluation, Terreros et al. [26] presented a methodology able to orient business models through a comprehensive techno-economic assessment for heat pumps in rural DH. A similar analysis, but including PV systems, is offered in the study of Aste et al.[27], who demonstrated the potentiality for successful integration in DH. On a broader scale, Sebestyen et al. [28] studied the profitability of a local thermal energy market for biomass DH located in rural areas. A detailed study grounded on the wholesale day-ahead market to evaluate the excess heat utilization using the DARKO model has been proposed by Doracic et al. [29]. The authors demonstrated the feasibility of introducing new renewable generation units and reducing the cost for end-users. Referring to the optimal design, a recent work of Dorotic et al. [30] developed a model to account for the supply capacities, technological sizing, and operation of DH and cooling systems. The authors implemented a multi-objective optimization tool and derived the best compromise between operational costs and emissions for DH during a yearly time horizon if compared to the traditional separate production.

Balaman and Selim [31] dealt with the design and management of biomass supply chains integrated with DH. The main goal of this study was to maximize the satisfaction of the heat demand of specific areas, considering seasonality and thermal energy storage. The optimal location and size of biomass DH is then evaluated by Jayarathna et al. [32]. The developed tool, after a careful implementation of geographical and spatial data in a GIS system, allows for the optimal location of biomass plants coupled to the local availability and cost. A similar study is also conducted by Sanchez-Garcia et al. for specific wood-fired plants [33].

As emerged from the discussed contributions, the exploitation of renewable energy is undoubtedly crucial to foster the transition towards sustainable urban areas. To this scope, the modeling of different renewable sources for energy efficiency, design, and economic issues has been tackled intensively in the literature. At this point, however, it is auspicial to evaluate their impact also in relation to their practical implications on urban territories in terms of energy distribution, supply, and infrastructure of autonomously organized communities.

1.3 Renewable sources in the Italian energy mix

Among the renewable sources to be integrated into districts, PV panels and biomass are eligible for the constitution of an integrated and interconnected energy sharing configuration. Indeed, photovoltaic panels are the most diffusively installed in or on buildings and biomass derives from on-site agricultural and forest residues favoring logistics and presenting limited emissions rates. Under this scenario, photovoltaic panels and biomass district heating can represent viable candidates to promote the self-sufficiency of urban areas.

Overall, solar energy is the most diffused renewable source for building integration. On the other side, the exploitation of residual biomass is attracting interest for its potentiality of ensuring a programmable energy supply and promoting the circular bio-economy culture of agricultural waste valorization and urban settlement of the territory. Posing particular attention to the Italian energy mix, in 2019, Italy has been the second and third country in Europe with the highest electricity production from solar energy and biomass, respectively [34]. Energy data on the installed capacity of these two renewable sources in Italy have been extracted from the IRENA database [34], as shown in Fig. 1.

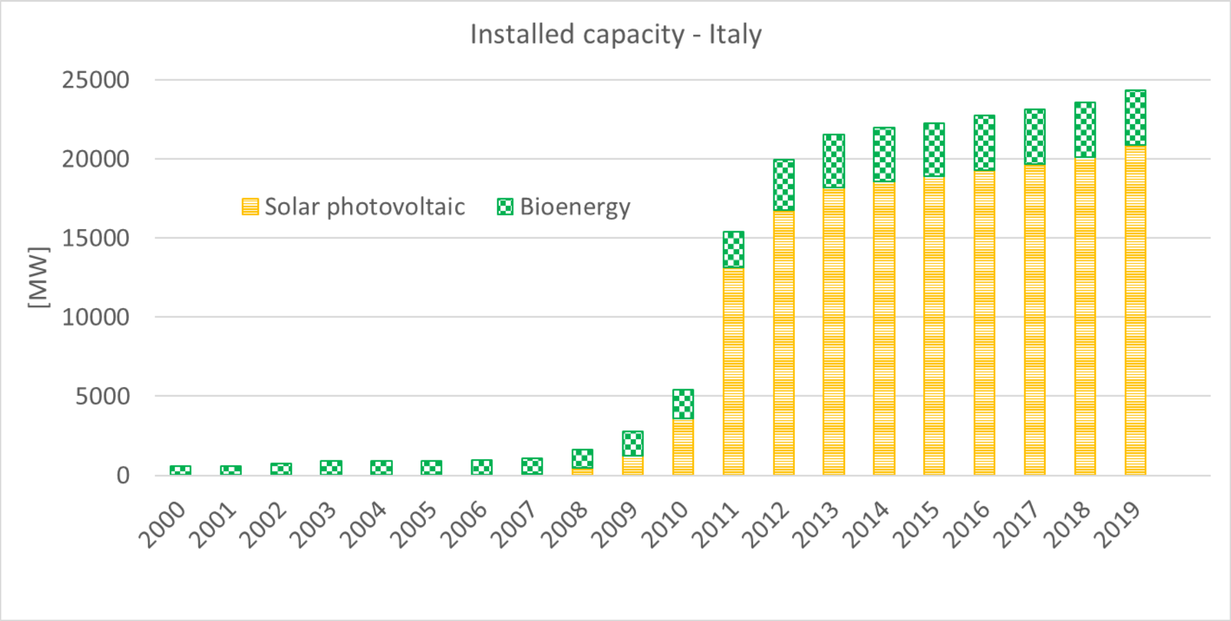
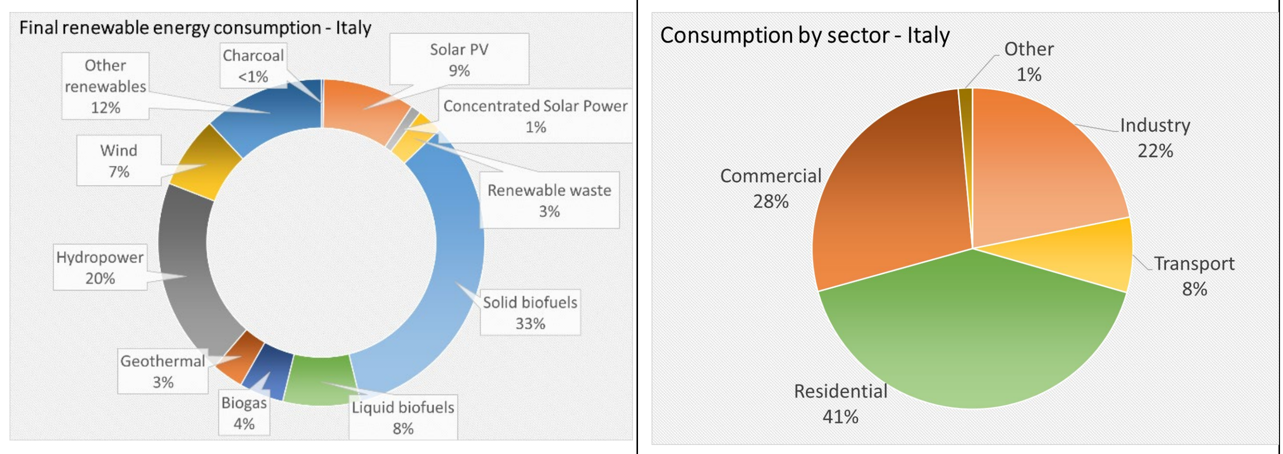


Fig. 1 Solar photovoltaic and bioenergy technology installed capacity in Italy [34]

The total installed capacity of renewable energy systems in Italy for 2019 is 59,232 MW, of which 20,865 MW refer to solar photovoltaic and 3,454 MW to bioenergy, representing 35.23 % and 5.83 % of the total renewable park [34].

Fig. 2 reports the final renewable energy consumption and details the impact of the different sectors on the global Italian energy consumption. As can be observed from Fig. 2 (a), the highest percentage, i.e. 33 %, of final consumption relates to solid biofuels, followed by hydropower and solar photovoltaic, with around 9 %. Concerning the energy consumption by sector, as shown in the pie chart of Fig. 2 (b), the highest percentage belongs to the residential sector, leading with a significant percentage of 41 % and confirming the urgent need to address focused actions on urban areas. Particular attention, however, should be also paid to the commercial sector, equally critical for populated districts.



(a) (b)

Fig. 2 (a) Final renewable energy consumption and (b) consumption by sector in Italy [34]

1.4 Aim of this study

The design of renewable systems should be also be accompanied by the planning of energy strategies for the active involvement of buildings, considered for their consumption and production capabilities. This implies, as a most evident consequence, that buildings organize themselves in local hybrid energy communities and interact to balance their energy production with their energy demands. The study of these emerging distribution configurations is a non-trivial task, also in light of the operational uncertainties deriving from the energy demand profiles, energy production from intermittent renewable sources, and, *inter alia*, energy exchanges at the local level. Thus, energy distribution models should be able to evaluate the optimal energy distribution infrastructures arising from the local energy sharing, balance the demand and supply for and among prosumers, and valorize the positive surplus of the community.

As said, if aiming to target the global energy self-sufficiency of built areas, biomass district heating and solar production from photovoltaic panels can be considered reliable candidates. The insertion of PV panels on the rooftops of edifices implies decentralization of the electrical supply and, thus, distribution needs to be managed differently from the past. A peculiar characteristic of decentralization lies in the peer-to-peer electricity interactions among buildings as highlighted by Tonellato et al. under different technological [18] and by Kilkis in an interlinked application considering the energy, water, and environmental frameworks [19], which will be crucial also for PEDs.

Under this depicted energy framework, it is crucial to develop bottom-up tools and models to support the definition of energy strategies focusing on urban districts and deepening the design and operation of the distribution infrastructure. This paper aims at contributing to the existing state-of-art for Positive Energy Districts proposing a building-centered optimization model to:

- Design the optimal energy distribution infrastructure of electricity exchanges within the area pointing to be recognized as a PED;
- Evaluate the import/export operation scheme with the grid;
- Estimate the positive surplus of the PED and propose solutions for its sustainable valorization.

In addition, the insertion of a biomass boiler for the Positive Energy District is proposed and its size is determined by making adoption of the standardized procedures deriving from the Italian normative regulations and calculating the environmental impact of solid biomass exploitation.

2. MATERIAL AND METHODS

The proposed energy model aims at determining the optimal energy distribution infrastructure of energy communities to achieve energy self-sufficiency and to target a positive energy balance for the area. Fig. 3 provides a holistic representation of the energy connection layers modeled in this study. Buildings are connected to a biomass district heating network (BDHN), to the electrical main grid (GRID), and are allowed to exchange electricity produced from PV panels in a peer-to-peer (P2P) electrical distribution network (DEN).

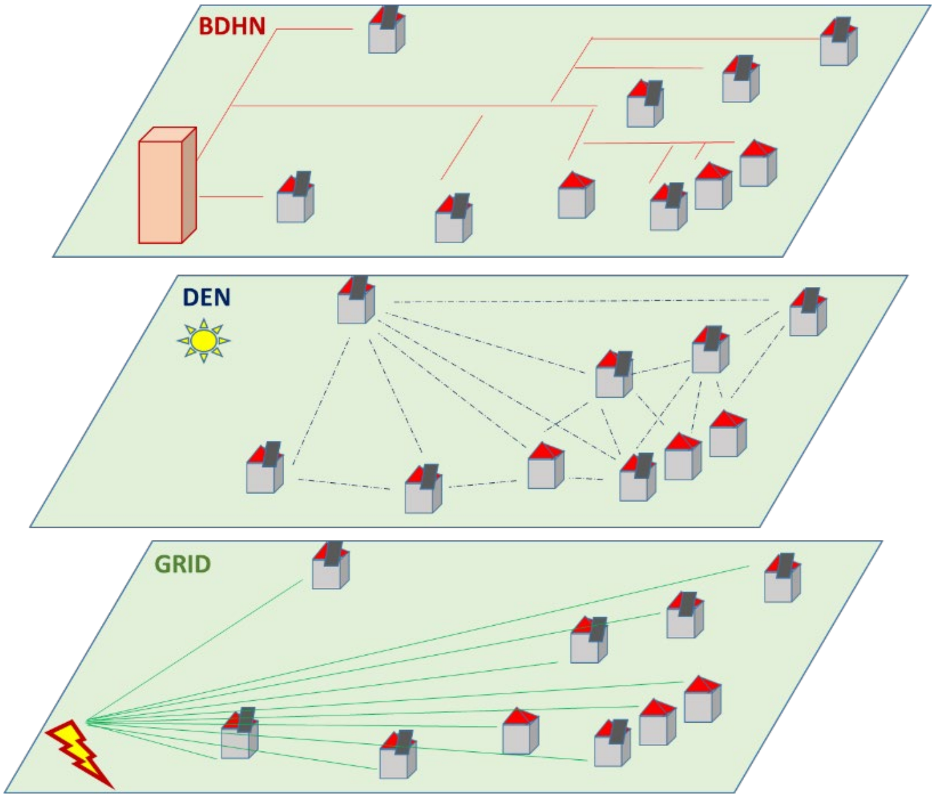
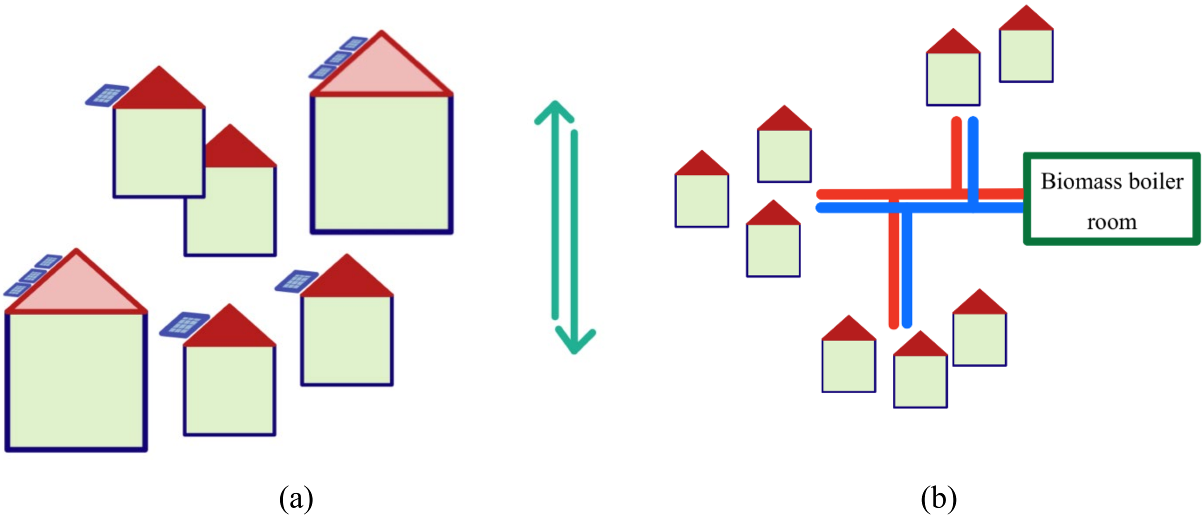


Fig. 3 Holistic representation of the three distribution layers: Biomass District Heating Network (BDHN), Electrical Distribution Network (DEN), traditional power grid (GRID)



(a) (b)

Fig. 4 Conceptual scheme of the (a) electrical and (b) thermal flows within the PED

Buildings' information derives from geo-referenced data elaborated in a GIS environment [36]. Each building i in the PED is characterized by an electrical demand Eel_i and a thermal demand Eth_i. Fig. 4 reports the conceptual schemes adopted within the model for the electrical and thermal flows characterizing the PED. Referring to the electrical side, all buildings maintain their connections to the power grid, as requested from the Directive 2018/2001 [5]. To account for the evaluation of the decentralized distribution, buildings with integrated PV panels may share the produced electricity (green lines, marked as DEN). Electricity flows are incoming if the buildings have residual demand to be met (purple line) or outgoing (light blue line) if the buildings have exceeding production to be distributed. Any further positive surplus of the district is then released to the main grid. Conversely, buildings without PV on their rooftops receive electricity from the other buildings of the PED or, if needed, from the main grid. The thermal flow configuration has a hot and cold-water pipelines circuit connected to each building, again ensuring the centralized connection to the gas network.

2.1 The electrical distribution network modeling

The insertion of PV panels on the rooftops of edifices implies the decentralization of the electrical supply, and distribution is managed through bi-directional connections among buildings. The middle layer of Fig. 3 outlines this electrical distribution network (DEN), in which buildings are connected in a peer-to-peer (P2P) configuration and exchange electrical energy within the district. The Directive 2018/2001 does not pose particular constraints or preferred conditions to select the buildings that will constitute the energy community. An energy community is a legal entity constituted by actors who choose to adhere voluntarily and should be located in proximity to the renewable systems owned by the community [5]. In this study, to account for P2P distribution and to enhance the evaluation of the electrical flows occurring within the PED, it has been chosen to introduce a distance criterion to connect the buildings through virtual electricity transmission lines. The operation rule for electricity management implies that two buildings i and j can be considered as connected if their spatial coordinates (x_i, y_i) and (x_j, y_j) for latitude and longitude respect the constraint:

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \leq d \tag{1}$$

According to this, two buildings can be considered connected in a P2P configuration if their reciprocal distance d is comprehended within a given spatial boundary that can be selected during the legal constitution stage of the energy community underlying the PED. Therefore, to establish these connections, beyond the explicit longitudinal and latitudinal coordinates, the territorial coverage of the area of the district should be known. Each building i can share the residual electrical production after the satisfaction of the own electrical demand. This amount can be shared within the PED and can be calculated as:

$$Eel_{distr,i} = p_i \cdot Eel_{prod,i} - Eel_i \tag{2}$$

The electricity produced from PV panels, $Eel_{prod,i}$, is first used to meet the electrical demand $Eel_{\,i}$ of the building i if panels are installed. The integration of PV on the rooftop of the building i is defined through the binary variable p_i, with $p_i = 1$ if panels have been installed or $p_i = 0$ on the contrary. Afterward, the exceeding production is distributed within the district and respecting the established connections as in Eq. (1). The residual electrical demands are then covered by the main grid and, conversely, any eventual electrical excess from the PV is released to the main grid: therefore, the bottom layer (GRID) and the middle layer (DEN) dynamically communicate to balance electricity production and demand. The term $Eel_{distr,i}$ can be either positive or negative. For building i, if $Eel_{distr,i} > 0$, there is a certain amount of electricity that can be distributed within the EC. On the contrary, if $Eel_{distr,i} < 0$, building i has residual demand to be satisfied and receives it from other buildings. Posing these constraints at the district level results in a map of interconnected buildings and bi-directional electricity flows. Therefore, the electrical distribution problem can be formulated as an optimization model with the main objective of enhancing distribution among buildings of the PED and connected in a P2P configuration through the minimization of the electrical demands requested to the centralized main power grid. Indeed, a PED with *N* buildings can be characterized by $N(N-1)$ potential P2P electricity interactions for the DEN layer and N interactions with the GRID. These interactions are expressed as in the adjacency matrixes of Eq. (3) and Eq. (4), reported for the DEN and the GRID layers, respectively:

$$\begin{array}{c|cccc}
\text{DEN} & 1 & 2 & \dots & \text{N} \\
\hline
1 & 0 & a_{12} & \dots & a_{1N} \\
2 & a_{21} & 0 & \dots & a_{2N} \\
\dots & \dots & \dots & 0 & \dots \\
\text{N} & a_{N1} & a_{N2} & \dots & 0
\end{array} \tag{3}$$

$$\begin{array}{c|c}
\text{DEN} & \text{GRID} \\
\hline
1 & x_{1G} \\
2 & x_{2G} \\
\dots & \dots \\
\text{N} & x_{NG}
\end{array} \tag{4}$$

The terms of the DEN adjacency matrix assume the values reported in Eq. (5), depending on both the connections established through the distance criterion and on the direction of the electricity flow, here assumed positive if the sharing direction is from building i to building j, and negative for the opposite. If two buildings i and j do not share electricity the corresponding element of the adjacency matrix is nil, as in the following:

$$a_{ij} = \begin{cases} 1, if\ electricity\ is\ shared\ from\ building\ i\ to\ building\ j \\ -1, if\ the\ electricity\ is\ shared\ from\ building\ j\ to\ building\ i \\ 0, if\ building\ i\ and\ building\ j\ do\ not\ share\ electricity \end{cases} \tag{5}$$

It is worth noting that the diagonal of the adjacency matrix contains nil elements, considering that the distribution of a building to itself does not concur to the distribution configuration of the DEN, rather is it achieved as the electrical balance at each building, as in Eq. (2). Analogously, the terms of the adjacency matrix in Eq. (4) for the power grid assume the values reported in Eq. (6):

$$x_{iG} = \begin{cases} 1, if\ the\ building\ i\ is\ served\ from\ the\ main\ grid \\ -1, if\ the\ building\ i\ release\ electricity\ to\ the\ grid \\ 0, if\ the\ building\ i\ does\ neither\ receive\ nor\ release\ to\ the\ grid \end{cases} \tag{6}$$

The objective function can therefore be expressed as:

$$\min \sum_{i=1}^{N} (Eel_i - p_i \cdot Eel_{prod,i} - a_{ij} \cdot Eel_{P2P,i\leftrightarrow j} + x_{iG} \cdot Eel_{i\leftrightarrow grid}) \tag{7}$$

For each building i, the terms of Eq. (7) refer to the residual amount of electricity requested to the central grid, obtained by curtailing to the initial electrical demand of the buildings Eel_i the amounts deriving from the electrical production from PV $Eel_{prod,i}$, the electricity distribution derived from the P2P exchanges from building i to building j and indicated as $Eel_{P2P,i\rightarrow j}$ and, finally, balancing the electricity produced by PV panels neither consumed nor distributed and thus released from each building to the main grid, $Eel_{i\leftrightarrow grid}$. The electrical balance at the building level is:

$$Eel_i = p_i \cdot Eel_{prod,i} + \sum_{j=1}^{N} a_{ji} \cdot Eel_{P2P,i\leftrightarrow j} + x_{iG} \cdot Eel_{i\leftrightarrow grid} \tag{8}$$

Eq. (8) states that the electrical demand of each building i, Eel_i, is balanced by the electrical production from PV panels $Eel_{prod,i}$ (if installed), from the electrical energy received from the other j buildings of the district and, finally, from the electrical energy supplied by the main centralized grid $Eel_{i\leftrightarrow grid}$.

The electrical balance referring to the total electricity produced is expressed as:

$$\sum_{i=1}^{N} Eel_{prod,i} = \sum_{i=1}^{N} Eel_{buildPV,i} + \sum_{i,j=1}^{N} a_{ji} \cdot Eel_{P2P,i\leftrightarrow j} \tag{9}$$

It is the sum of the total electricity produced by the PVs and consumed by each building i, $\sum_{j=1}^{N} Eel_{buildPV,i}$, and the mutual exchanges of electricity within the district, $\sum_{i,j=1}^{N} Eel_{P2P,i\leftrightarrow j}$.

Beyond the optimal distribution configuration of electricity flows, the optimal set of electricity connections $i - j$ among buildings and the optimal topology of the DEN infrastructure can be derived from the optimization model described above. Indeed, the minimization of the electricity supply from the main grid also affects the peer-to-peer distribution of the PED.

Finally, if positive, the last term of Eq. (7), $Eel_{i\leftrightarrow grid}$, represents the surplus that can be exploited for the benefit of the district rather than for the release to the grid. As an example, the electricity excess can be used to ensure adequate heating to other consumers not directly belonging to the PED but needing affordable access to electricity or heating systems and, therefore, to promote the reduction of energy poverty. Other solutions can be directed to mobility solutions and, generally, to all options improving the economic, energetic, and social sustainability of the district [37].

The environmental performances of the DEN can be estimated by comparing the production from PV panels to the production from the traditional fossil supply chain, characterized by a specific value of the emission rate dedicated to electricity production.

2.2 The biomass district heating network

The top layer of Fig. 3 illustrates the biomass district heating network (BDHN), with red links standing for the pipelines infrastructure that connects each building of the PED with the biomass boiler room. The thermal balance for each building of the district is:

$$Eth_i = Eth_{BDHN\rightarrow i} + Eth_{aux\rightarrow i} \tag{10}$$

In Eq. (10), Eth_i is the thermal demand of building i, $Eth_{BDHN\rightarrow i}$ the thermal supply from the BDHN and, if necessary, $Eth_{aux\rightarrow i}$ the thermal energy supplied by the auxiliary boilers connected to the centralized natural gas network.

The energy conservation principle referring to the thermal production and transportation from BDHN can be expressed as:

$$\dot{Q}_{biom} - \dot{Q}_{loss} - \dot{L}_{pump,k} = c_p \cdot \dot{m}_w \cdot (T_h - T_c) \tag{11}$$

In Eq. (11), $\dot{Q}_{biom}$ is the thermal power of the biomass combustion system, $\dot{Q}_{loss}$ the thermal losses, $\dot{L}_{pump,k}$ the pump power for each branch k of the thermal network, c_p the specific heat of water, $\dot{m}_w$ the hot water mass flow capacity and $T_h - T_c$ the temperature difference for hot and cold water. Data have been derived from the guidelines of the Italian Technical Standards UNI/TS 11300 [35].

The power of the boiler is calculated to cover the thermal demands for sanitary hot water (SHW), defined in Eq. (12), and heat, defined in Eq. (13), respectively:

$$P\ (W) = \frac{\left[m(kg) \cdot cp\left(\frac{kJ}{kg \cdot {}^{\underline{o}}C}\right) \cdot \left(T_{REQUIRED} - T_{NET}\right)\right]}{3600 \cdot 0.5} \tag{12}$$

$$P\ (W) = S(m^2) \cdot B\left(\frac{W}{m^2}\right) \cdot C \cdot D \cdot 85 \tag{13}$$

In Eq. (12), $P\ (W)$ is the power of the boiler required to cover the demands of sanitary hot water (SHW), $m(kg)$ is the mass of water that needs to be heated from T_{NET} to $T_{REQUIRED}$ in half-hour (0.5) by the defined power of the boiler, $cp(kJ/kg \cdot {}^{\underline{o}}C)$ the specific heat of water, $T_{REQUIRED}$ is the temperature at which water is heated and T_{NET} is the temperature of the water from the network. In Eq. (13), $P\ (W)$ is the power of the boiler required to cover the thermal demands for heating; $S(m^2)$ is the surface of the room to be heated; $B(W/m^2)$ is a parameter related to the orientation, C is a dimensionless factor regulating the demand for physical and technical aspects, such as the type of construction and isolation, the year of construction. D is a dimensionless factor that depends on the climatic zone. Finally, the value 85 is a correction factor for intermittency. These values can be directed determined by following the national normative, as the UNI/TS 11300 in Italy [35].

The thermal power generation station in Fig. 5 is constituted by the biomass storage room and the boiler room, in which the biomass boiler, the thermal storage (buffer tank), the expansion deposit, and distribution pumps are located. Both rooms are placed as separate constructions but connected so that the boiler can be fed with the stored biomass. The location of the station is defined as a compromise solution between the best accessibility for the biomass provider to fill the biomass storage room and the closest location to the thermal demanding buildings trying to minimize the network routing. Isolated pipelines exit the station and transfer the hot water to the different buildings and bring back the cold water to the station in a closed loop.

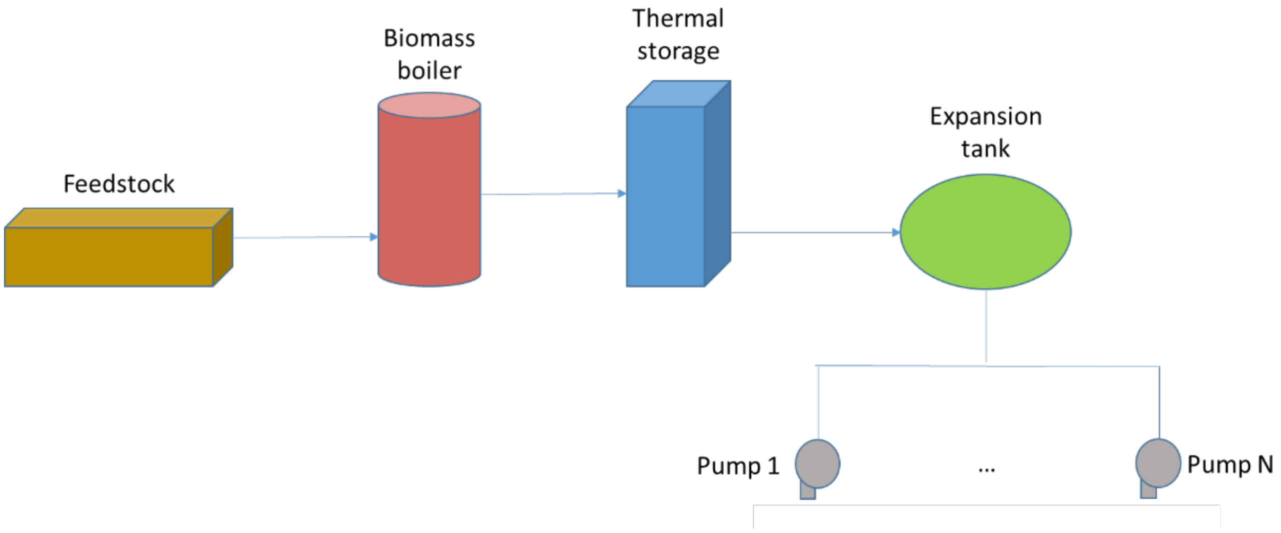


Fig. 5 Biomass District Heating Network (BDHN) plant configuration

The BDHN can be sized for base or peak load designs. In the first case, the biomass system covers only the base load of the annual demand and requires an auxiliary system to provide the difference between the peak and base loads. In the second one, the power is calculated to respond to the punctual peak demand, oversizing the unit. The main characteristics of the base configuration are a higher energetic efficiency while the dependency of fossil fuels is required and it makes it difficult for potential future expansions of the net. On the other hand, the second configuration maximizes the use of biomass as fuel and offers flexibility for future increases in the demand but the operation efficiency decreases due to overestimated operation conditions for the majority of the time which results in an increased biomass consumption. Here, both the pipelines and the pumps are dimensioned for the peak load demand to be able to supply the maximum flow capacity when the heat peak load is maximum. The environmental impact of the BDHN can be assessed by following the guidelines of the Directive 2018/2001 for solid biomass exploitation [5]. The Directive recommends using the emission rate of 0.133 $kgCO_2eq/kWh$ when wood biomass is combusted. In this way, a direct calculation of the avoided carbon emissions can be pursued, by simply comparing the emission rates of natural gas for heat production.

2.3 Case study

The area selected as a case study comprehends twenty buildings in Southern Italy (climatic zone B), the majority of them of residential use, depicted in Fig. 6. The area counts 407 inhabitants and 45 workers.

Fig. 6 Case study area

Table 1 lists some features characterizing the buildings of the district, labeled as in the first column and characterized for the final use. Surfaces and volumes of the buildings are known, as well as the number of floors and inhabitants.

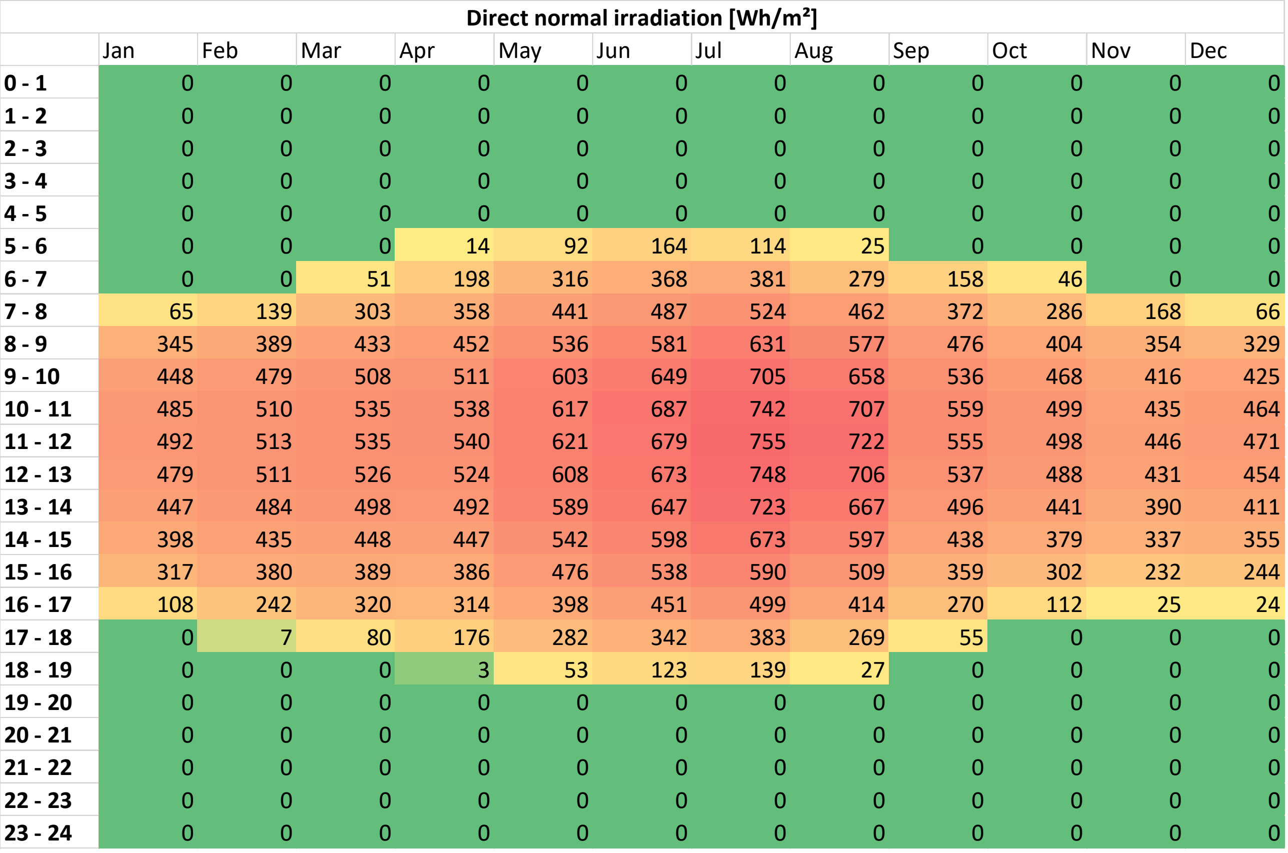
Table 1. Building's main characteristics

Building_id	Building's use	Surface [m^2]	Volume [m^3]	Floors	Inhabitants
1	Residential	250.95	2760.45	3	28
2	Residential	250.95	2760.45	3	28
3	Residential	96.60	289.80	1	3
4	Residential	251.70	2768.70	3	28
5	Residential	251.70	2768.70	3	28
6	Residential	101.76	356.16	1	4
7	Residential	250.80	2758.80	3	28
8	Residential	250.80	2758.80	3	28
9	Residential	128.59	450.07	1	5
10	Residential	250.65	2757.15	3	28

11	Residential	250.65	2757.15	3	28
12	Residential	127.20	890.40	2	9
13	Residential	189.63	568.88	1	6
14	Residential	42.40	296.80	2	3
15	Residential	478.14	2151.63	3	64
16	Residential	478.14	2151.63	3	64
17	Commercial	142.94	571.77	1	-
18	Commercial	641.52	6415.22	1	-
19	Commercial	641.52	6415.22	1	-
20	Residential	227.76	2505.36	3	25

Concerning the data collection, energy data have been collected from apartment owners and commercial edifices participating in the constitution process of the energy community. It is worth noting that, although other buildings in the neighborhood of Fig. 6 may represent viable candidates for this study, they have not been included in the analysis since they did not take part in the energy community agreement. Electrical and thermal consumption data have been made available for this study in an aggregated form, so estimations have been made necessary to evaluate the electrical and thermal profiles of each building. In particular, the electrical demand has been coupled with the information available from a previous mapping campaign conducted on a district in a similar urban area and with similar urban features and energy consumption trends [22]. Coupling this knowledge with the information of Table 1, the yearly electrical demand of this district has been estimated to be around $374.89\ MWh_{el}$.Electrical production from PV has been assessed from the global irradiance of the area and applying a conversion factor of 65% for the net electricity production, as suggested by Huld [38]. The hourly values of the direct normal irradiation for each month have been extrapolated from Global Solar Atlas [39] for the modeled geographical site as reported in the heat color map of Fig.7.

The optimal electrical distribution of the area has been simulated for different values of the distance of connection with the main aim of studying the electricity infrastructures arising among buildings under the concept of PEDs established by the Implementation Working Group 3.2 [11]. Three main distance values for P2P connection characterizing three different distribution scenarios have been simulated: #Sc1 with a distance of 100 m from one building to the other; #Sc2 with a distance of 150 m and finally #Sc3 accounting for a distance of 200 m.



Direct normal irradiation [Wh/m²]												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	0	0	0	0	0	0	0	0
5 - 6	0	0	0	14	92	164	114	25	0	0	0	0
6 - 7	0	0	51	198	316	368	381	279	158	46	0	0
7 - 8	65	139	303	358	441	487	524	462	372	286	168	66
8 - 9	345	389	433	452	536	581	631	577	476	404	354	329
9 - 10	448	479	508	511	603	649	705	658	536	468	416	425
10 - 11	485	510	535	538	617	687	742	707	559	499	435	464
11 - 12	492	513	535	540	621	679	755	722	555	498	446	471
12 - 13	479	511	526	524	608	673	748	706	537	488	431	454
13 - 14	447	484	498	492	589	647	723	667	496	441	390	411
14 - 15	398	435	448	447	542	598	673	597	438	379	337	355
15 - 16	317	380	389	386	476	538	590	509	359	302	232	244
16 - 17	108	242	320	314	398	451	499	414	270	112	25	24
17 - 18	0	7	80	176	282	342	383	269	55	0	0	0
18 - 19	0	0	0	3	53	123	139	27	0	0	0	0
19 - 20	0	0	0	0	0	0	0	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0

Fig.7 Heat color map for the direct normal irradiation from Global Solar Atlas [39]

Monthly heat demands for space heating and domestic hot water have been estimated from the building's characteristics and following the Italian normative indications [35]. The average heat demand is 172 kW and the energy demand is 4,139 kWh at the design day. The annual energy demand of the district is around 439.82 MWh_{th}.

The selection of the central heating unit is a multi-criteria decision in which several aspects need to be considered, such as the distance to the different buildings, the accesses, and any available spots. In this case, as can be observed from the highlighted green contour in Fig. 6, there is one free spot close to the buildings with suitable dimensions and accessibility, making it a suitable location to locate the central unit heating. The dimensioning of the biomass boiler for domestic hot water and space heating has been conducted from Eq. (12) and Eq. (13) and using the Carbon Trust Biomass Decision Support Tool, maintained by the University of Strathclyde [40]. The tool needs as data input the heating design temperature, the building final use, the heat demand, internal heat gains, ventilation losses, and sanitary hot water demand. The values of these data have been selected from the Italian normative [35] and the ANSI/ASHRAE [41] for the buildings' characteristics reported in Table 1 and calculated from Eq. (10) and Eq. (13). In particular, the internal heat gains for residential buildings have been estimated to be around 130 $W/person$ and 12 W/m^2 for lighting. Ventilation rate and ventilation heat losses have been selected as 10 $l/s/person$ and 72 W/K, respectively. Finally, 80 $l/person$ is the rate of domestic hot water chosen for the calculation. Other required inputs are the total building floor area and the level of occupancy, derived from the information in Table 1. The hourly load profile of the chosen district corresponding to the coldest day is reported in Fig.8. The load profile curves represent the cumulative load of all residential (continuous line) and commercial buildings (dashed line), and the total demand, in which the distribution losses, here assumed as the 15% of the total load, have been included, as suggested by [40]. The peak load is then identified and marked in Fig.8.

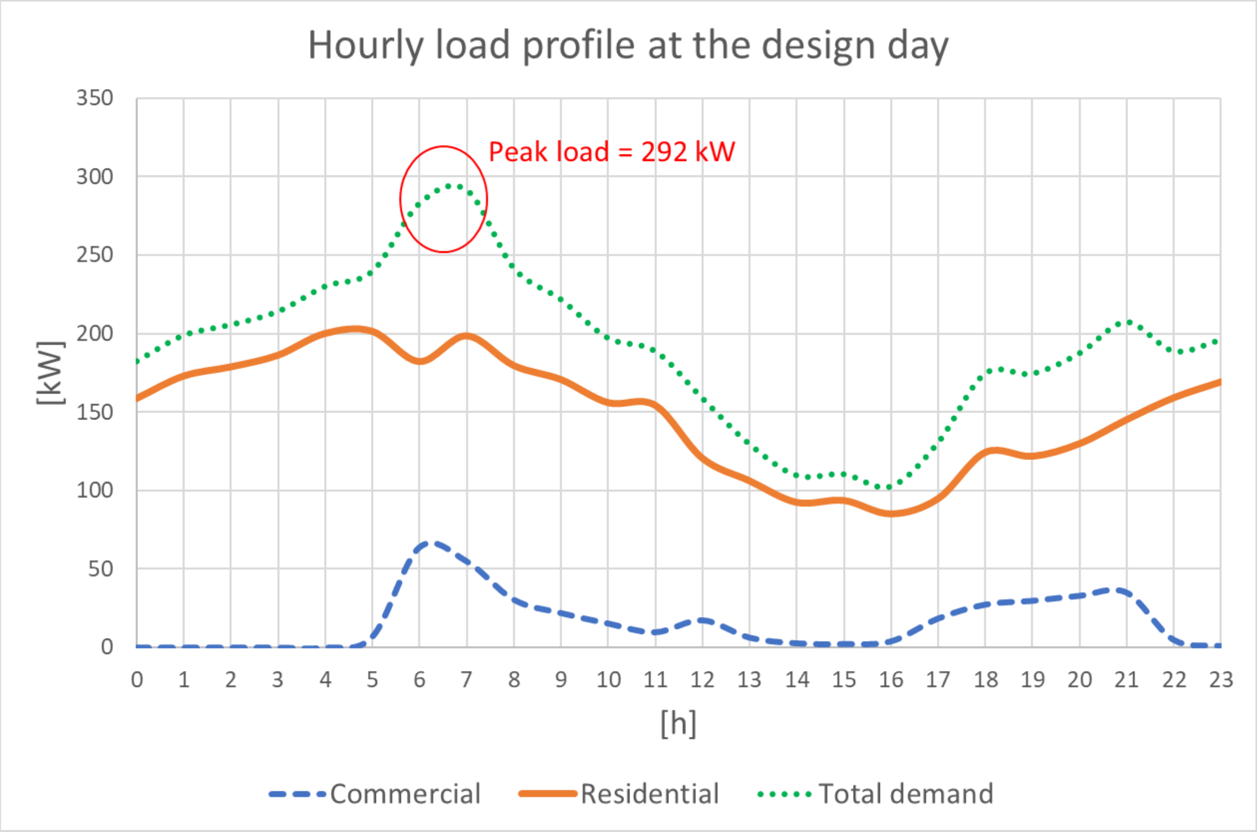


Fig.8 Hourly heat load profiles at the design day

3. RESULTS AND DISCUSSION

The optimization model presented in Section 2 has been implemented in MATLAB [43]. The optimized electrical scenarios obtained for the PED chosen as a case study are here reported and discussed. The analyzed district counts twenty buildings, and in each of them, PV panels installation has been simulated considering technical and physical constraints, such as the rooftop area available for the panels as well as the area needed for maintenance and cables, typology of the roof (span or flat), inclination, and shading. The simulated electrical self-consumption and electrical production from PVs are plotted in the bar chart of Fig.9 for each building of the area.

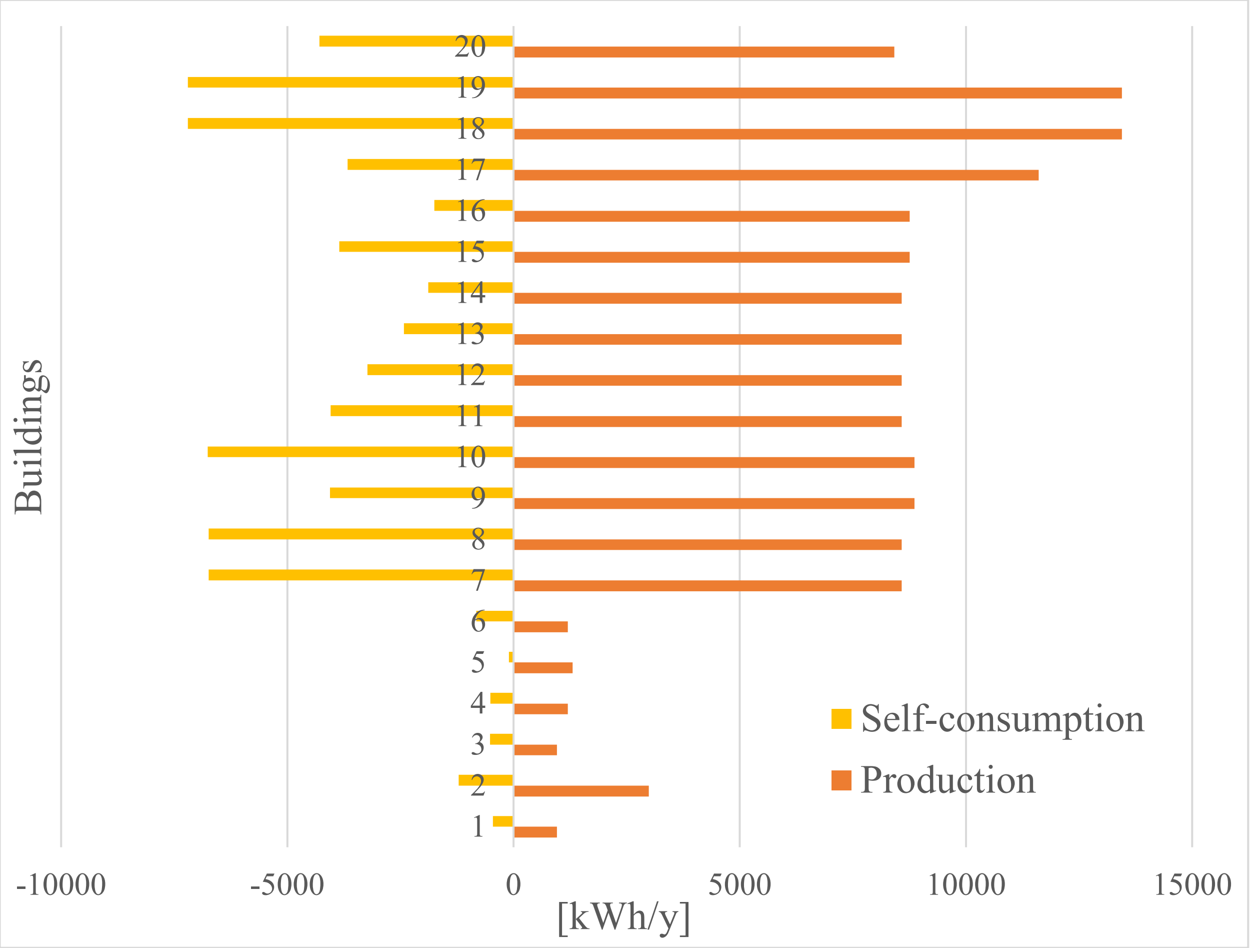


Fig.9 Self-consumption and energy production for the twenty buildings of the PED

Depending on the above-listed physical constraints, the electrical production of the panels varies, as can be observed from the right side of the chart. The bars on the left show the portion of the electrical demands met by the PV production. In some cases, e.g. buildings 1, 3, 4, and 6, the electrical production from the panels is mainly devoted to the satisfaction of the demands of the buildings, with minor or nil advantages from the communitarian viewpoint. Buildings labeled as 18, 19, and 20 are commercial buildings and have higher space availability for PV installation and, consequently, for higher production, reaching more than 13,000 kWh/y in two cases. Other buildings have a significant amount of electrical production that is not used for self-consumption and, therefore, can be distributed to meet the demands of the other buildings or, eventually, to address any urban action aiming at enhancing the sustainable growth of the community. On average, the majority of buildings produce more than 8,500 kWh/y, with an actual demand exceeding 6,000 kWh/y for only three residential buildings out of seventeen (labels 7, 8, and 10). The most favorable positive balances are achieved from buildings 14, 16, and 17 in which a significant electrical production (around 8,500 kWh/y and 12,000 kWh/y) is coupled with low electrical demands. Overall, a net positive balance between production and self-consumption is achieved from the district, thus justifying the choice of constituting a PED for the autonomous satisfaction of the electrical needs of the buildings and the distribution within the DEN. The amount of the electrical production effectively distributed among buildings has been reported in Fig.10 for the three identified scenarios.

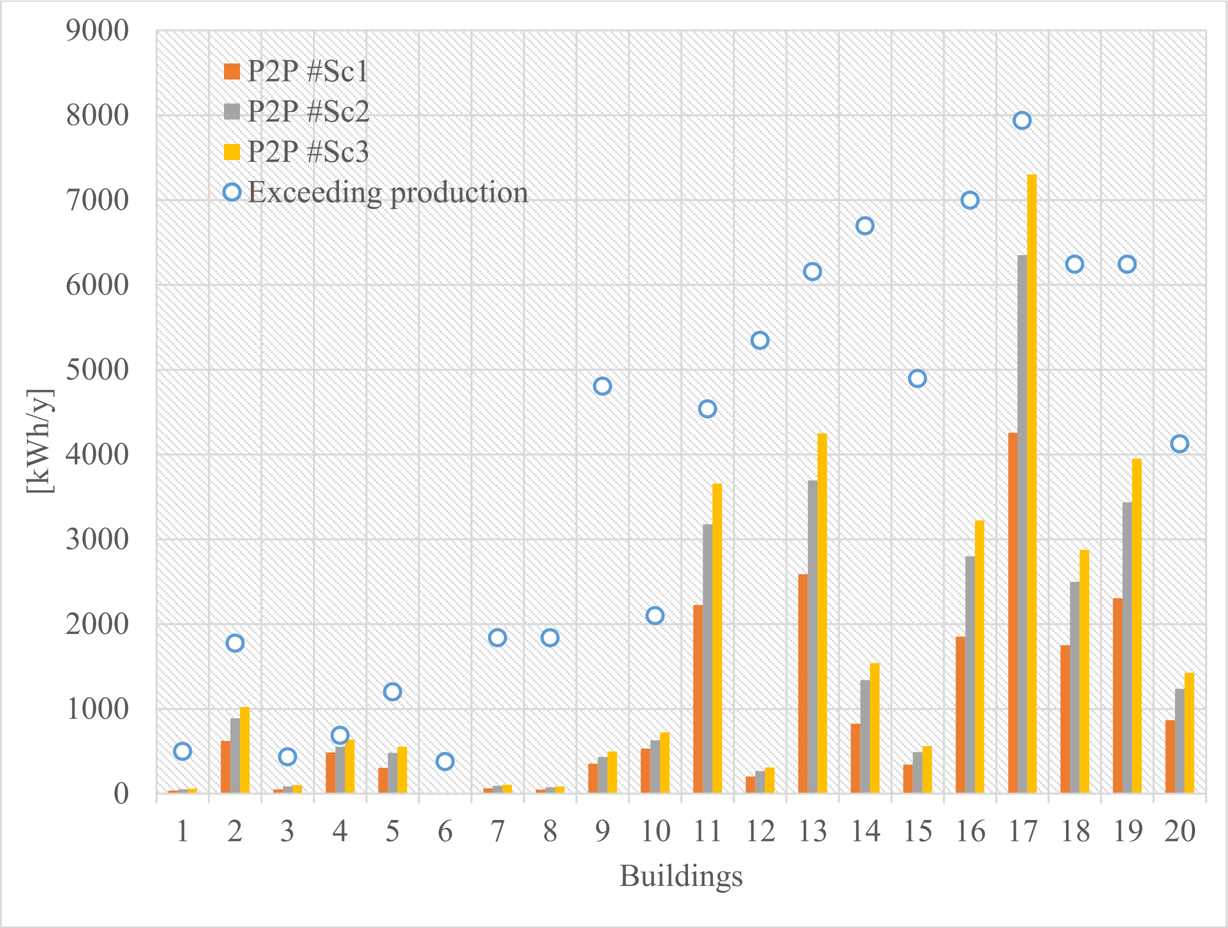


Fig.10 Electricity distribution among buildings of the PED in the three selected scenarios

The blue dots of Fig.10 characterize the exceeding production for each building, calculated as in Eq. (2) and representing the residual amount of electrical energy that a building can distribute within the district after the satisfaction of its demand. On average, the surplus of each building is positive: this does not imply that they are always configured to distribute energy; indeed, depending on the actual values of the surplus during the entire year, the balance may be also negative, i.e. indicating the need to receive electricity to meet the demand. As a general observation arising from Fig.9, the higher is the permitted distance for the distribution, the higher is the amount of electricity distributed among buildings in a peer-to-peer configuration in the DEN. Indeed, enlarging the spatial boundary within electricity exchanges may occur, it is reasonable to have a more interconnected DEN and, therefore, higher amounts of electricity flows contributing to the satisfaction of the electrical demand of the PED. Around 26.36% of the exceeding production is distributed in #Sc1, 38.22% in #Sc2, and, finally, 43.95% in #Sc3. Building 17 (residential) has the largest share of electrical distribution in all the three chosen scenarios. Indeed, especially for #Sc3, almost all exceeding production is distributed to other buildings, enhancing the self-sufficiency of the area. Similar results, although less relevant for the magnitude of distribution, are achieved from building 3, 4, and 11. There are still some buildings, e.g. 7, 8, 12, and 15, that do not efficiently distribute their exceeding production. Reasons could be recognized for example in a limited spatial configuration of the buildings (mutual distance not sufficient to cover the established metrical criterion) or in other distributors closer to the buildings. A detail of the distribution performances of the PED for the best scenario, #Sc3, is reported in Fig.11.

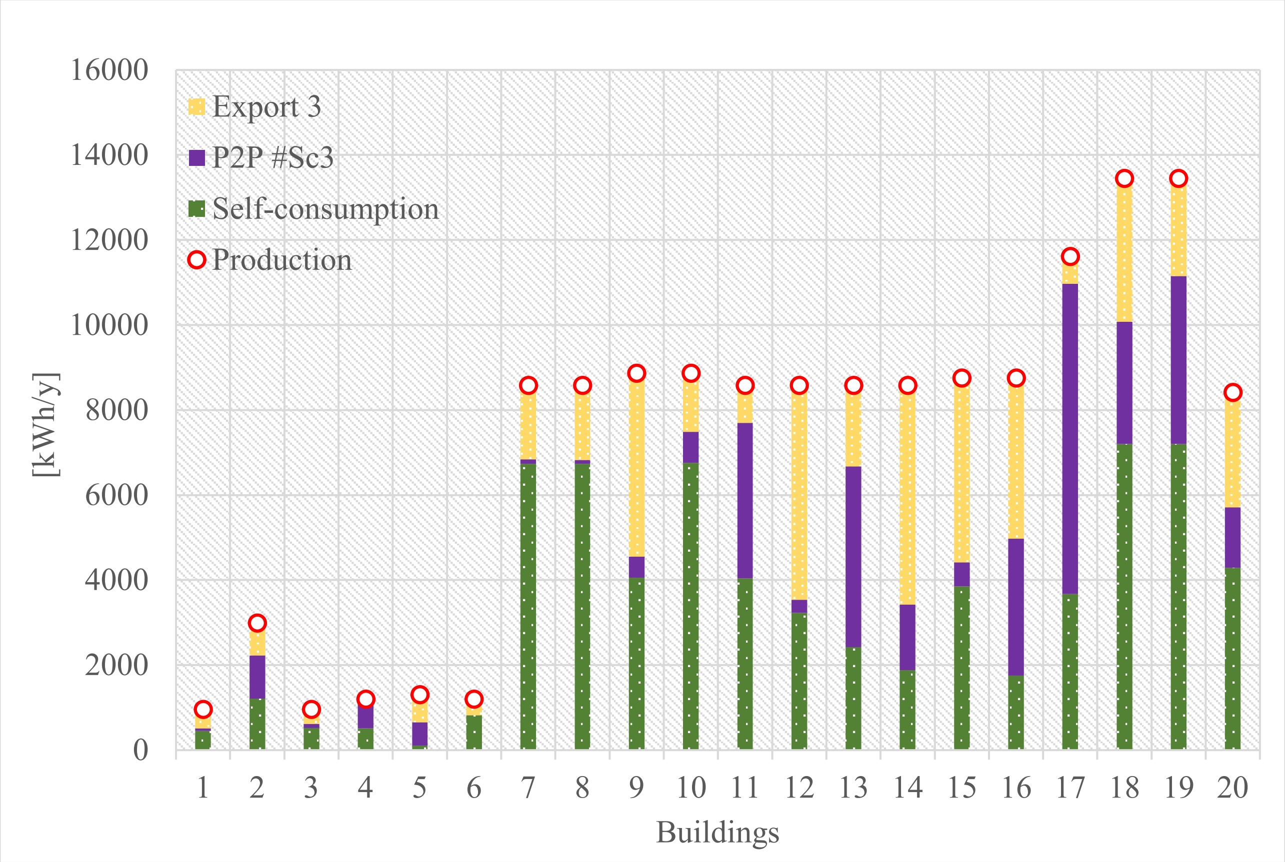
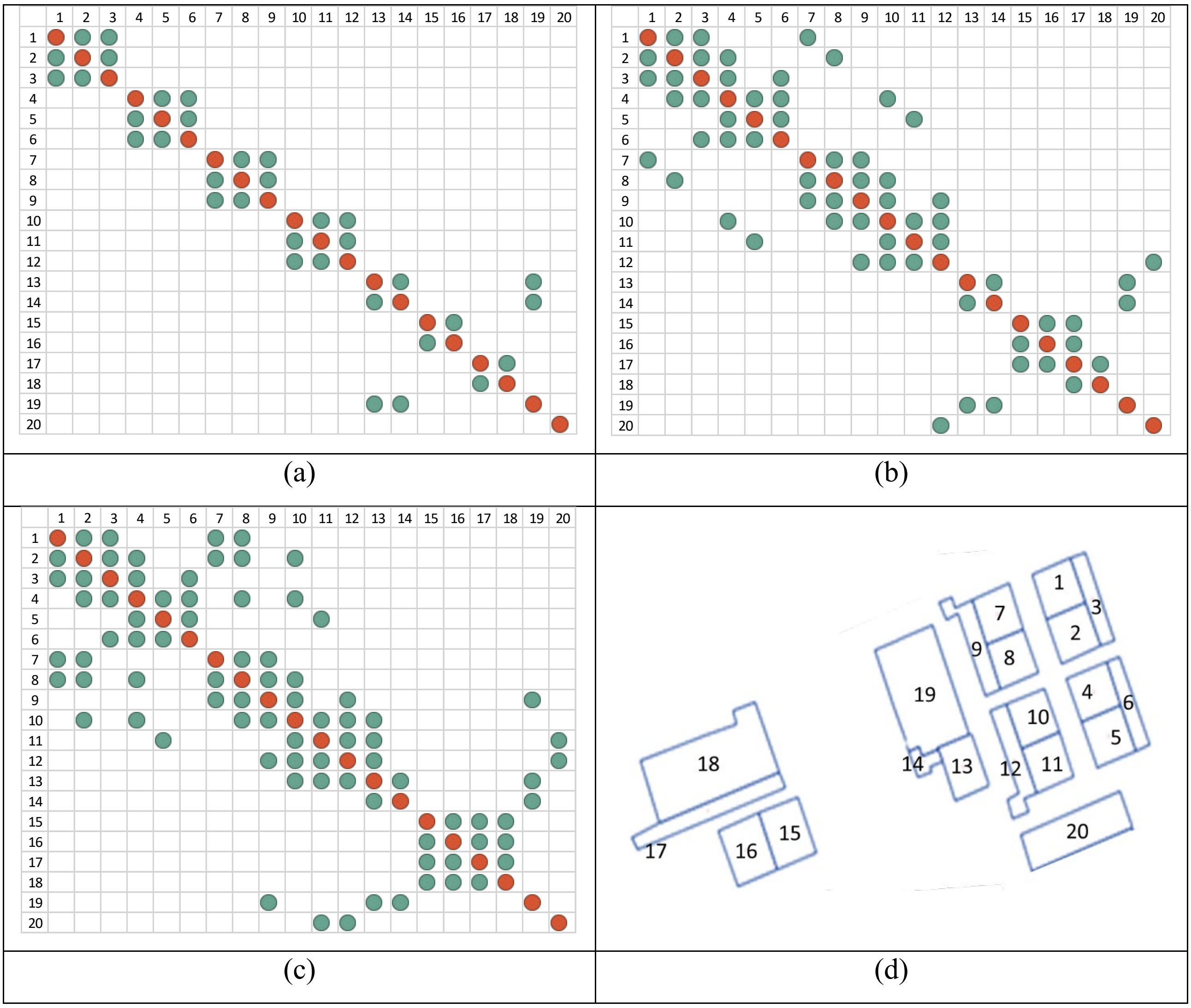


Fig.11 Distribution performances of the PED for #Sc3

Here an overview is presented to evaluate the different contributions in which electricity production has been split from each building. In particular, Fig.11 illustrates the values of electricity production and the amount of electricity that is used from the building for self-consumption, the amount exchanged (considering the operative conditions of #Sc3) and the amount exported to the main power grid, i.e. the amount that has been produced by PVs, yet it has not been used either from the building itself or from other buildings of the district. As can be observed, a large amount of PV production serves for the satisfaction of the electrical demand of the building in which they are installed. The amount of electricity distributed highly depends on two main issues: on the spatial location of the buildings (indeed, not only buildings are connected in a peer-to-peer configuration) and on the timely balance between surplus (i.e. the residual production after the satisfaction of the demand) and other demands of connected buildings. Therefore, the rate of distributed electricity varies from building to building and for the different selected spatial boundaries. Exceeding production that is not self-consumed and that no longer be distributed to connected buildings is then released to the main power grid and reported in Fig.10 as “exported”. Building 17 is confirmed to be the most impacting actor within the PED from the distribution perspective. Other good performances are achieved from the residential buildings 11, 13, 14, and 16 and all the three commercial buildings (18, 19, and 20). In these cases, however, the share of electrical production devoted to self-consumption remains significant. Other buildings, such as 3, 7, and 8, instead, spend the higher amount of production for their own needs. It is interesting to have a look at all the possible bi-directional connections established for the three scenarios, as reported in Fig.12.



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(a)

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(b)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
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3	🟢	🟢	🔴	🟢		🟢														
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5				🟢	🔴	🟢					🟢									
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20											🟢	🟢								🔴

(c)

(d)

Fig.12 Electricity exchanges for (a) #Sc1 = 100 m, (b) #Sc2 = 150 m, and (c) #Sc3 = 200 m, and (d) buildings' labels

All electrical connections have been reported in Fig.12(a), (b), and (c), depending on the chosen scenario, i.e. on the permitted distance of connection among the buildings of the PED. Fig.12(d) shows a schematic map of the PED with the labeling of the edifices. The representation chosen for Fig.12 recalls the matricial form of Eq. (3), whilst symmetry is due to the bidirectionality of the connections for the peer-to-peer distribution within the DEN. Indeed, if a building i is connected to a building j, it is equally considered that the building j is linked to the building i for the electricity exchange. It is worth noting that, beyond the connections of Fig.12, the optimization model considers the connections with the centralized layer GRID, mathematically expressed as in the matrix of Eq. (4), having each building of the PED the right to maintain the role of consumers [5]. Comparing the three scenarios, it is clear how increasing the distance of connection permits to reach a higher number of buildings and, therefore, to enhance the distribution performances of the PED.

After considering the distribution performances of the PED, it is equally important to estimate the export to the grid, reported in Fig.13.

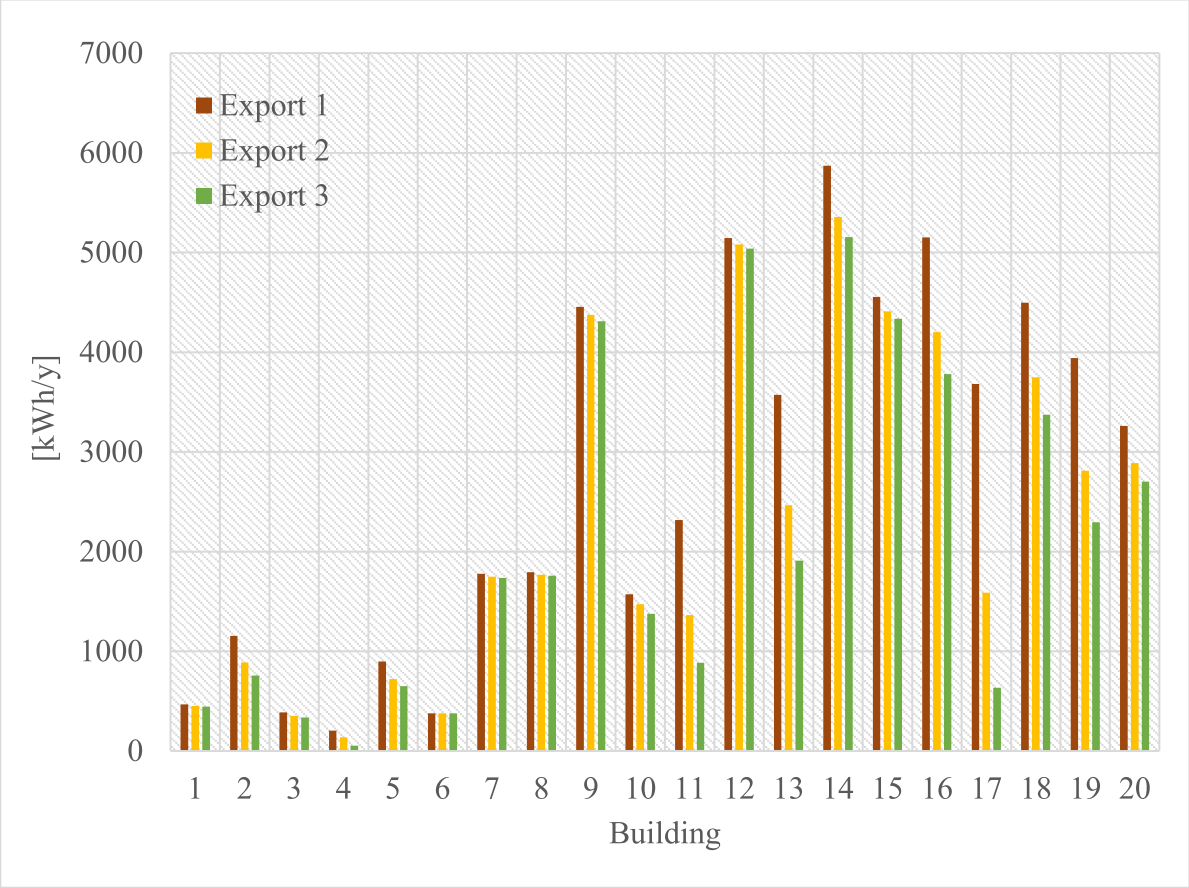

Fig.13 Electrical export of buildings for the three scenarios

As can be observed, there is a significant amount of electricity that is exported to the GRID. These amounts of electricity can be valorized in various ways for the benefit of the PED itself. For instance, part of this exceeding production can be stored in batteries to account for the typical mismatch between production and demand, intrinsically characterizing intermittent renewable sources, like solar energy. It can be used to promote electrical mobility, e.g. considering the investment in public electrical buses for the neighborhood. Or, it can be addressed for social equality, ensuring secure access to electricity for heating and cooking purposes for underserved persons and low-income families near the PED, following the social inclusiveness recommended by the United Nations with the indications of the Agenda 2030 and the Sustainable Development Goals [41].

Concerning the environmental performances of the PED, the carbon dioxide (CO_2) emissions reduction has been calculated for both the DEN and the BDHN and reported in Table 2. A comparison has been made between the traditional and centralized configurations and the designed decentralized networks in Italy. For the electricity sector, a value of 0.492 $kgCO_2eq/kWh$ has been used; when wood biomass is combusted, it releases 0.133 $kgCO_2eq/kWh$, which should be compared to the emission rate of natural gas for heat production is estimated to be 0.224 $kgCO_2eq/kWh$ [42].

Table 2. CO_2 emission avoided

	#Sc1	**#Sc2**	**#Sc3**
ΔCO_2 – DEN	62 %	71 %	73 %
ΔCO_2 – BDHN	55 %		

A minimum percentage of 62% carbon reduction can be recorded if planning the infrastructure of the DEN among buildings. This reduction becomes more significant at varying the simulation scenarios, i.e. at increasing the distance among connected buildings, reaching a significant percentage of emissions reduction equal to the 73% for the #Sc3, in which all buildings within 200 m are connected to the DEN. However, as can be seen, the beneficial impact of providing a high interconnected district, in terms of peer-to-peer distribution does not increase linearly at increasing the distance of connection among buildings. In this sense, further analyses should be carried on to establish if a more complex distribution infrastructure can be considered cost-effective, particularly compared to the cost of realization and the attractiveness of the investment for buildings.

The dimensioning of the BDHN starts with the choice of the biomass boiler, a 209 kW Stoker Burner boiler, with 80% of peak load, fueled with wood pellets, and having an efficiency of 93% [43]. Due to their diffusion in the Sicilian territory, oak pellets have been selected. They are characterized by less than 7% moisture content, 0.5% ash, and a calorific value of 5,4 kWh/kg, certified EN Plus A1, as declared by the supplier [44]. Here, pellets have been selected due to their higher energy performances and needing less space for the storage site. They are of cylindrical forms, with lengths between 5 and 40 mm, and labelled ENplus, a certification that follows the European Standard EN ISO 17225-2 [45], having, therefore, higher control and quality if compared to chips. For this demand, the annual biomass requirement would be 70 $tons$ (110 m^3) of pellets. Thus, a storage room of about $6x5x3\ m^3$ that would be fed with biomass up to a maximum height of 2 m twice a year would be a suitable option. The dimensions of the buffer tank for the water storage for this case would be 6250 l [46]. To prevent the changes in the volume of the fluid inside the closed circuit, associated with temperature variations, an expansion deposit is used. The dimensions of this deposit are calculated under the indications of UNI 10412-1 [47]. In this case study, a 500 l deposit would be necessary. The design day heat demand and the boiler capacity are reported in Fig.15, plotted as the green dotted line and the blue line, respectively. The orange line at the bottom represents the minimum output below which the boiler has to be switched off. As can be observed, the boiler size is sufficient to meet the demand, also considering that the thermal storage will be used when the demand exceeds the capacity of the boiler.

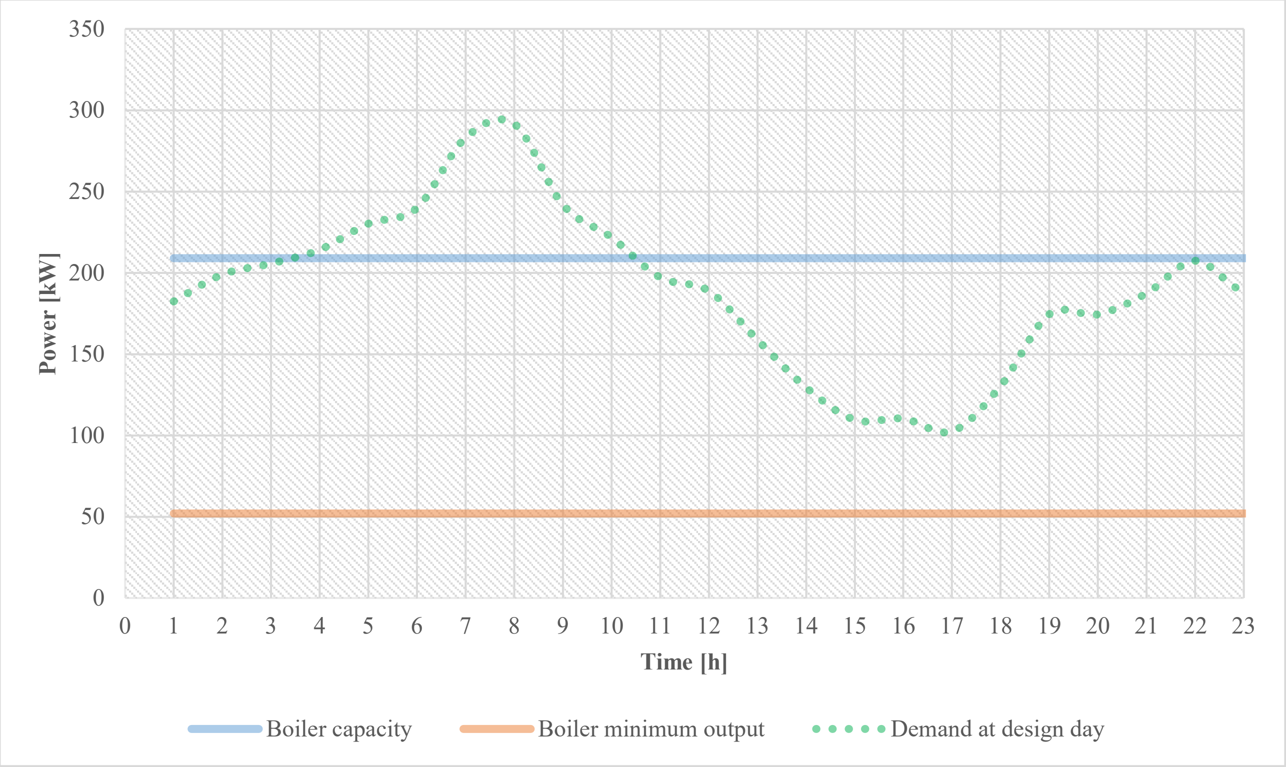

Fig.15 Heating demand profile and boiler capacity

4. CONCLUSION

This paper proposed an optimization model for the definition of the optimal design and operation of distributed energy networks arising among buildings of urban areas aiming at targeting the transition to Positive Energy District and coupled with biomass district heating. The model is applied to a small neighborhood in Southern Italy, counting twenty buildings connected to both the electrical and thermal centralized grids. PV panels installed on buildings and biomass district heating have been proposed to facilitate the path towards autonomous and sustainable urban areas. As recommended by the European Union Strategy, buildings are now able not only to consume and produce electricity that is managed by the main grid but also to interact within their neighborhood and exchange electricity with other interconnected buildings in a peer-to-peer configuration under the agreement of constituting an energy community and pointing to a net positive energy balance between production and demand. Results allow inferring that the proposed autonomous networks (both thermal and electrical) can be successfully implemented to reach the self-sufficiency of the area and to target the positive balance required by the district to be recognized as a PED. In particular:

- the proposed decentralized configuration can help in significantly reducing the electricity import from the main grid and fosters the distribution among buildings. Around 44% of the electrical energy of the district derives from the renewable production of the area
- significant emissions reduction can be achieved for both the thermal and electrical sides; in particular, for the electrical network a minimum reduction of 62% can be targeted and for the thermal network a net decrease of more than 55%.

As can be seen, there is still a significant amount of electricity that is imported from the grid, despite the insertion of PV panels and the distribution among connected buildings, due to the characteristic intermittency of the solar source. In this sense, the integration of electrical energy storage may be a solution for avoiding large exports to the grid. Other ways could be the usage of electrical energy to cover cooling demands, for mobility, or as an incentive for families with low-income (contributing to decreasing the energy bills).

As a last consideration, it is worth pointing out that these results have been achieved for a district of a Mediterranean area, characterized by significant electricity production from solar sources and by a limited thermal load. Therefore, it is reasonable to consider the outcomes of this research comparable for areas of South Italy or, generally, for regions with similar climate conditions.

ACKNOWLEDGMENT

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REFERENCES

[1] Masson-Delmotte V et al. (eds.). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: 2021

[2] United Nations. Paris Agreement. 2015

[3] Dobravec V, Matak N, Sakulin C, Krajačić G. Multilevel governance energy planning and policy: a view on local energy initiatives. Energy, Sustainability and Society 2021;11:2. https://doi.org/10.1186/s13705-020-00277-y

[4] E. U. Commission. “A Framework Strategy for a Resilient Energy Union with a Forward-Looking,” Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank

[5] European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). Official Journal of the European Union 2018

[6] European Union. Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast). Official Journal of the European Union

[7] Gazzetta Ufficiale della Repubblica Italian (in Italian). Decreto Legge 31 dicembre 2020, n. 183 (c.d. Decreto “Mille Proroghe”)

[8] European Union. Recovery plan for Europe, NextGenerationEU (NGEU). 2020

[9] Implementation Working Group (IWG) 3.2 S-SP information system. Implementation Working Group (IWG) on positive energy districts and neighbourhoods for sustainable urban development (PED) or IWG 3.2. 2018

[10] JPI Urban Europe. “Positive Energy Districts and Neighbourhoods for Sustainable Urban Development” Programme

[11] JPI Urban Europe / SET Plan Action 3.2. Whi te Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods. Austria: 2020

[12] JPI Urban Europe. Announcement: Projects awarded funding in Positive Energy Districts (PEDs) pilot call. Https://Jpi-UrbaneuropeEu/News/Announcement-Projects-Selected-for-Funding-in-the-First-Pilot-Call-on-Positive-Energy-Districts-Peds/ 2020

[13] IEA EBC - Energy in Buildings and Communities Programme. IEA EBC - Annex 83 - Positive Energy Districts

[14] Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 2014;65:1–17. https://doi.org/10.1016/j.energy.2013.10.041

[15] Gabrielli P, Gazzani M, Martelli E, Mazzotti M. Optimal design of multi-energy systems with seasonal storage. Applied Energy 2018;219:408–24. https://doi.org/10.1016/j.apenergy.2017.07.142

[16] Mavromatidis G, Petkov I. MANGO: A novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems. Applied Energy 2021;288:116585. https://doi.org/10.1016/j.apenergy.2021.116585

[17] Kour J, Shukla A. Enhanced energy harvesting from rooftop PV array using Block Swap algorithm. Energy Conversion and Management 2021;247. https://doi.org/10.1016/j.enconman.2021.114691

[18] Tonellato G, Heidari A, Pereira J, Carnieletto L, Flourentzou F, de Carli M, et al. Optimal design and operation of a building energy hub: A comparison of exergy-based and energy-based optimization in Swiss and Italian case studies. Energy Conversion and Management 2021;242. https://doi.org/10.1016/j.enconman.2021.114316

[19] Kılkış Ş. A nearly net-zero exergy district as a model for smarter energy systems in the context of urban metabolism. Journal of Sustainable Development of Energy, Water and Environment Systems 2017;5:101–26. https://doi.org/10.13044/j.sdewes.d5.0136

[20] Karami M, Madlener R. Business models for peer-to-peer energy trading in Germany based on households' beliefs and preferences. Applied Energy 2022;306:118053. https://doi.org/10.1016/j.apenergy.2021.118053

[21] Fichera A, Frasca M, Palermo V, Volpe R. An optimization tool for the assessment of urban energy scenarios. Energy 2018;156. https://doi.org/10.1016/j.energy.2018.05.114

[22] Fichera A, Pluchino A, Volpe R. From self-consumption to decentralized distribution among prosumers: A model including technological, operational and spatial issues. Energy Conversion and Management 2020;217. https://doi.org/10.1016/j.enconman.2020.112932

[23] Wagner O, Venjakob M, Schröder J. The growing impact of decentralised actors in power generation: A comparative analysis of the energy transition in germany and japan. Journal of Sustainable Development of Energy, Water and Environment Systems 2021;9. https://doi.org/10.13044/j.sdewes.d8.0334

[24] Penttinen P, Vimpari J, Kontu K, Junnila S. How to promote local district heat production through real estate investments. Journal of Sustainable Development of Energy, Water and Environment Systems 2021;9. https://doi.org/10.13044/j.sdewes.d8.0343

[25] Hammar T, Levihn F. Time-dependent climate impact of biomass use in a fourth generation district heating system, including BECCS. Biomass and Bioenergy 2020;138:105606. https://doi.org/10.1016/j.biombioe.2020.105606

[26] Terreros O, Spreitzhofer J, Basciotti D, Schmidt RR, Esterl T, Pober M, et al. Electricity market options for heat pumps in rural district heating networks in Austria. Energy 2020;196:116875. https://doi.org/10.1016/j.energy.2019.116875

[27] Aste N, Caputo P, del Pero C, Ferla G, Huerto-Cardenas HE, Leonforte F, et al. A renewable energy scenario for a new low carbon settlement in northern Italy: Biomass district heating coupled with heat pump and solar photovoltaic system. Energy 2020;206:118091. https://doi.org/10.1016/j.energy.2020.118091

[28] Sebestyén TT, Pavičević M, Dorotić H, Krajačić G. The establishment of a micro-scale heat market using a biomass-fired district heating system. Energy, Sustainability and Society 2020;10:25. https://doi.org/10.1186/s13705-020-00257-2

[29] Doračić B, Pavičević M, Pukšec T, Quoilin S, Duić N. Utilizing excess heat through a wholesale day ahead heat market – The DARKO model. Energy Conversion and Management 2021;235. https://doi.org/10.1016/j.enconman.2021.114025

[30] Dorotić H, Pukšec T, Duić N. Multi-objective optimization of district heating and cooling systems for a one-year time horizon. Energy 2019;169:319–28. https://doi.org/10.1016/j.energy.2018.11.149

[31] Yılmaz Balaman Ş, Selim H. Sustainable design of renewable energy supply chains integrated with district heating systems: A fuzzy optimization approach. Journal of Cleaner Production 2016;133:863–85. https://doi.org/10.1016/j.jclepro.2016.06.001

[32] Jayarathna L, Kent G, O'Hara I, Hobson P. A Geographical Information System based framework to identify optimal location and size of biomass energy plants using single or multiple biomass types. Applied Energy 2020;275:115398. https://doi.org/10.1016/j.apenergy.2020.115398

[33] Sánchez-García S, Athanassiadis D, Martínez-Alonso C, Tolosana E, Majada J, Canga E. A GIS methodology for optimal location of a wood-fired power plant: Quantification of available woodfuel,

supply chain costs and GHG emissions. Journal of Cleaner Production 2017;157:201–12. https://doi.org/10.1016/j.jclepro.2017.04.058

[34] https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Regional-Trends. IRENA, International Renewable Energy Agency 2021

[35] UNI. UNI/TS 11300:2019 Prestazioni energetiche degli edifici (in Italian). 2019

[36] Fichera A, Frasca M, Palermo V, Volpe R. Application of the Complex Network Theory in Urban Environments. A Case Study in Catania. Energy Procedia, vol. 101, 2016. https://doi.org/10.1016/j.egypro.2016.11.044

[37] Cellura M, Fichera A, Guarino F, Volpe R. Sustainable Development Goals and Performance Measurement of Positive Energy District: A Methodological Approach. Smart Innovation, Systems and Technologies 2022;263:519–27. https://doi.org/10.1007/978-981-16-6269-0_43

[38] Huld T. Estimating Solar Radiation and Photovoltaic System Performance, the PVGIS Approach. AFRETEP 1ST Regional Workshop 2011

[39] World Bank Group. Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector 2021

[40] Carbon Trust. Biomass sizing tool. www.carbontrust.co.uk/emergingtechnologies/current-focus-areas/biomass/pages/biomass-tool.aspx. Last Access: November 2021

[41] ASHRAE. ANSI/ASHRAE/IES Standard 90.1-2019 Energy Standard for Buildings Except Low-Rise Residential Buildings. 2019

[42] Sorknæs P, Østergaard PA, Thellufsen JZ, Lund H, Nielsen S, Djørup S, et al. The benefits of 4th generation district heating in a 100% renewable energy system. Energy 2020;213:119030. https://doi.org/10.1016/j.energy.2020.119030

[43] MathWorks. MATLAB R2021a 2021

[44] United Nations, Department of Economic and Social Affairs, UNDESA. The 2030 Agenda for Sustainable Development and the 17 Sustainable Development Goals (SDGs). Https://SdgsUnOrg/Goals

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

[46] https://www.heitzmann.ch/fileadmin/user_upload/Bilder/PDF/Broschueren_Italienisch/brochure-caldaia-a-cippato-hargassner-heitzmann.pdf. Caldaie a cipparo 6- 330 kW HARGASSNER (in Italian)

[47] https://www.etnapellet.net/. Etnapellet, Sicilian wood (in Italian)

[48] International Organization for Standardization. EN ISO 17225-2:2021, Solid biofuels - Fuel specifications and classes - Part 2: Graded wood pellets

[49] UNI EI di N. UNI 9182:2014 Titolo: Impianti di alimentazione e distribuzione d'acqua fredda e calda - Progettazione, installazione e collaudo (in Italian)

[50] UNI EI di N. UNI 10412-1:2006 Titolo : Impianti di riscaldamento ad acqua calda - Requisiti di sicurezza - Parte 1: Requisiti specifici per impianti con generatori di calore alimentati da combustibili liquidi, gassosi, solidi polverizzati o con generatori di calore elettrici (in Italian)