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A new concept of a thermal network for the energy resilience in mountain communities powered by renewable sources

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Dear Editor,

please find enclosed the manuscript "**A new concept of a thermal network for the energy resilience in mountain communities powered by renewable sources**" to be submitted to *Sustainable Energy, Grids and Networks*. All listed authors have contributed significantly to the manuscript and consent to their names on the manuscript.

The presented paper has not been and is not intended to be published anywhere else.

Authors: **L. Pompei, F. Nardecchia, F. Bisegna.**

Should You have any question, please do not hesitate to contact me at the e-mail address:

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Hoping that this paper can interest You, I look forward to hearing from you soon.

Thank You very much for Your attention and kindness.

Kind regards,

Laura Pompei

A new concept of a thermal network for the energy resilience in mountain communities powered by renewable sources

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Currently, the technology of the Combined Heat-Power provides about 56% of the heat supply to District Heating in Europe. Many applications of the biomass cogenerators plant/district heating networks were developed, often aimed to improve the electrical energy efficiency supply. Therefore, few works investigated the opportunity to connect more district heating networks, wherein thermal energy is supplied to the end-users. In this framework, this study aims to fulfill this gap, elaborating a new concept of thermal network applied to mountain communities. Two resilient energy system configurations were considered increasing the size of the energy systems components. Moving to the results, Case A (oversizing of the congenerators plants) produces a major amount of electricity for each village (Case A produced 8281 MWh/year compared to 6625 MWh/year of Case B) that can be sold to companies; however, the energy production of Case B (oversizing of both cogenerators and boilers plants) is well balance in accordance with the mountain village's needs. The Pay Back Period (4.39 years) and Profitability Index (4.88%) of Case B were also significantly better than those in Case A. This study gives, therefore, a relevant contribution to the definition of a new thermal network adaptable to a similar landscape.

Keywords: Thermal network, Energy communities' resilience, District heating, biomass Cogeneration plant, renewable energy generation.

Nomenclature

CHP	Combined Heat-Power
DH	District Heating
DHN	District Heating Network
RES	Renewable Energy Sources
DHW	Domestic Hot Water
NPV	Net Present Value (€)
IRR	Internal Rate of Return
PBP	Pay Back Period (years)
PI	Profitability index

O&M   Operation and Maintenance (€/year)
LRMG   Long Run Marginal Cost (€/MWhth)
GSE   Gestore dei Servizi Energetici
IEA   International Energy Agency
ENEA   Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

Subscript

Pth_{loss} Heat losses
$c_{p,W}$ Water-specific heat (kJ/(kg·K)
T_{soil} Soil temperature (°C)
T_{node} Node temperature (°C);
H   Pipe transmittance (kW/(m·K)
x   Pipe length (m)
G   Mass flow rate (kg/s)
ϱ_{water} Water density (kg/m^3)
u   Fluid velocity (m/s)
Q_{load} Total thermal power
Q_{aux} Total thermal power released to the water
$V_{network\ water}$ Water volume

1. Introduction

Population growth and economic development have resulted in considerable increases in global energy consumption over the last few decades, from 3728 Mtoe in 1965 to 12928 Mtoe in 2014 (Aydin 2015). It is estimated that the building sector consumes around 40% of all European energy, a significant contributor to carbon emissions (European Commission 2011, Pompei et al. 2022). Several European directives therefore were developed to reverse this trend, enhancing the use of renewable sources and decreasing the global emissions (Directive 2010; Directive 2012). Moreover, the energy crisis event, started in 1970, was a crucial sign for pushing European countries from fossil fuel usage to the newest independent sources, such as renewable ones (Lund et al. 2014; Buffa et al. 2019; Frederiksen and Werner 2014). To face with the current energy and environmental forceful call, academic researchers together with technologies industries developed strategies for conserving energy related to the thermal insulation, double- and triple-glazed windows, solar shading (Mattoni et al. 2019), efficient HVAC systems (Nardecchia et al. 2022), and the use of renewable and green energy sources. Considered as a promising green alternative solution, the District Heating (DH) network has been developed through the years (Lund et al. 2010). A further advantage of this technology is its inclusion of Renewable Energy Sources (RES) and its corresponding decrease in fossil fuel use (Pompei et al. 2019; Nardecchia et al. 2016). Giving some figures, about 11-12% of the total Europe heat demand in 2017 was supplied by the DH, as the Euroheat&Power (2017) underlined. In literature, the use of CHP plants, especially in Europe, achieved the best position in terms of energy generators for DH systems (Werner 2017), providing about 56% of the heat supply. Moreover, reducing the CO_2 emission and primary energy needs are two attractive qualities of the CHP plant, as suggested (Soltero et al. 2016). The application of the CHP plant to a DH system is widespread in several countries, highlighting their potentialities and weakness (Ravina et al. 2017;

Smith et al. 2013; Sanayea at al. 2020). According to the "World energy Balances: Overview" (2018), by the International Energy Agency (IEA)", biomass (materials and residues of agricultural and forestry origin, secondary products and waste from the agri-food industry, livestock waste and urban waste) was the first source of energy used by humans, and it is still one of the most widespread. Due to being a green alternative to fossil fuels (wood chip—0.015 kg CO_2e/kWh compared to 0.204 kg CO_2e/kWh natural gas), it is used for feeding several energy systems, such as CHP/DH, providing thermal energy to a wider range of stakeholders (Mehregan et al. 2022; Millar et al. 2019). Among the biomass type, the woodchip one is particularly interesting due to the low energy requirements for its production and with very stable burning compared to other solid biofuels (Gonzalez et al. 2015; Toscano et al. 2016). Another aspect that achieved interest is the sizing of biomass CHP plants respect to the building energy demand, being more difficult to evaluate compared to the industrial sector request (Sartor et al. 2014, Manni et al. 2012). In Table 1 a brief summary of some mentioned studies have been presented.

Table 1. Summary of some main studies presented in literature.

Authors	Years	Technology	Research target
Ravina et al.	2017	CHP and DH	Assessment of the environmental impact of a large-scale cogeneration plant for a district heating in Turin, Italy.
Smith et al.	2013	Energy storage combined with CHP	Analysis of eight different commercial building types in Chicago with regard to thermal energy storage options and CHP systems.
Sanaye et al.	2020	CHP	An energy-efficient combined gas engine heating and power system is proposed in order to maximize profit and minimize energy loss.
Millar et al.	2019	CHP and DH	A review of published case studies and recommendations for improving UK District Heating Networks (DHNs).
Mehregan et al.	2022	CHP	Development of a new arrangement of combined heat and power (CHP) system with combination of two prime mover has been investigated using genetic algorithm.
Gonzalez et al.	2015	Biomass CHP	An overview of the different technological alternatives for converting wood chips into electricity and heat related to a micro- and small-scale.
Toscano et al.	2016	Biomass CHP	Investigation of the quality of woodchip, through an evaluation of the most important chemical and physical parameters, demonstrating its goodness even the presence of high ash content.
Sartor et al.	2014	Biomass CHP	Definition of a methodology to assess the average conversion efficiencies over a complete year of operation and to provide reliable estimates for the energy cost forecast.
Manni et al.	2012	Biomass CHP	A pilot project about a district heating system powered by a biomass CHP plant in Perugia (Italy).

This brief overview on the CHP/DH system highlights its spread through the European countries. However, few works in literature investigated the opportunity to connect more district heating networks, feeding by biomass CHP plant, to develop a thermal network (microgrid), wherein thermal energy is supplied to the end-users. In fact, studies on the connection between CHP and microgrid are frequently focused on improving the electrical energy efficiency supply (Hemmati et al. 2021). This research therefore fulfills this gap, through the definition of these contents:

- A theoretical model of a thermal network based on DH and biomass CHP plants (based on steam turbine cycles) will be developed and applied to six mountain communities.
- To ensure energy resilience of these Italian villages, different scenarios of CHP and DH sizing are considered, along with the DH losses. Climate change has increased the intensity and frequency of natural disasters and adverse weather conditions that affect mountain communities' energy systems.
- MATLAB/Simulink was used to develop scenarios for energy systems, analyzing in a dynamic way the main characteristics (e.g. flow distribution, temperature, energy performance) of the models, in accordance with similar applications (Vesterlund et al. 2016).
- Moreover, an economic-financial assessment of the energy and resilient systems was drafted to provide readers with a holistic picture.
- As a final point, sizing energy systems is a challenging task, which this study contributes to by proposing a theoretical model that may be applicable to other countries as well.

The manuscript is organized into five macro-sections. Following the introduction, the methodology paragraph presents the case study as well as the CHP/DH system description. The entire energy microgrid model is exposed in Section 3, showing the main component of this system and the outputs of the simulations. The power of DH/CHP resilient plants were also evaluated. Then, results of the energy network were performed in Section 4. Conclusion and further developments of the presented work were pointed out in the last section.

2. Methodology

The development of a biomass CHP/DH thermal network was carried out with Simulink, a MATLAB tool. An analysis of the main factors related to the building, generation plants, distribution network and the entire thermal network was carried out using simulations (e.g. flow distribution, temperature, energy performance). One community (Sersale village) was selected as the reference case study. The other villages were proportionally defined based on the considerations and calculations applied to Sersale, being also the largest community. According to this, the first step is to develop the thermal and electrical energy demands of the Sersale community, based on the building typologies and thermal characteristics (building materials and energy systems equipment's), as reported in sections 2.1 and 2.3. Both biomass CHP and district heating were sized considering district heating losses at crucial points in the distribution grid. During the second phase, six biomass CHPs/DHs were designed in accordance with the users' energy needs. To evaluate the energy resilience of the six mountain communities in Italy, two thermal energy scenarios were proposed.

2.1Description of the Case study

Six villages of the southern area of Sila Piccola Meridionale, located in the South of Italy, are included in the definition of the thermal network: Sersale, Cerva, Petronà, Andali, Zagarise and Maisano (Table 2). The largest urban centre is Sersale with its 4605 inhabitants, representing the geographical centre of the network’s energy distribution. The other villages are located radially at a maximum distance of 8.6 km.

Table 2: Main information of the mountain communities involved.

	Inhabitants	Surface area	Population density	Altitude	Distance from Sersale
		[km^2]	[In./km^2]	[m]	[km]
Sersale	4605	53.30	86.40	740	0
Cerva	1212	21.37	56.67	860	2
Petronà	2594	45.79	56.11	889	4.3
Andali	728	17.87	40.74	650	3.5
Zagarise	1628	49.33	33.39	581	5.6
Magisano	1230	31.94	37.63	565	8.6

The first step was to create a simulation of both the thermal and electrical requirements of those villages, using Sersale as a reference model. Based on the results obtained for Sersale, the other villager's energy needs will be calculated. There are seven macro-areas of buildings in the Sersale (Figure 1), all of which might have been constructed in the same historical period (Di Pietra et al. 2013).

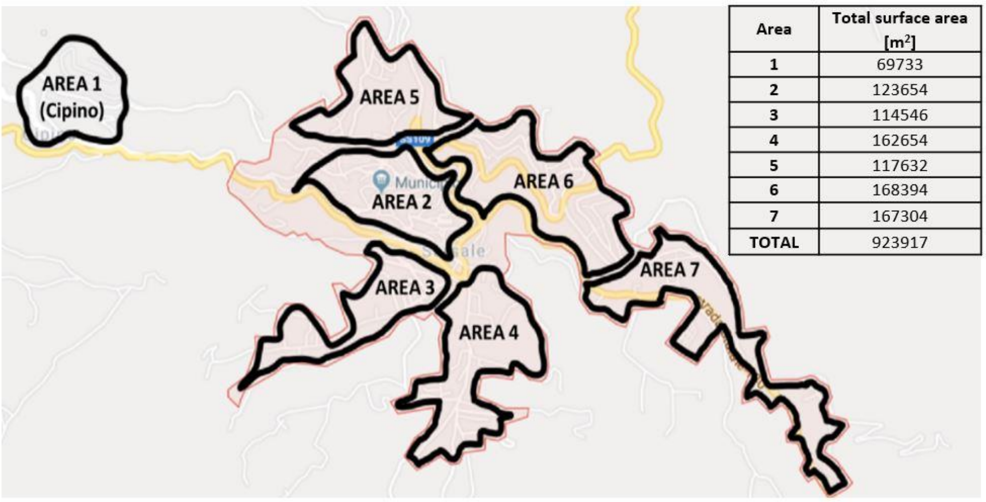


Figure 1: Seven macro-areas of Sersale buildings.

Once the macro-areas have been identified, an approximated method (Cianciolo 2016), named the plot ratio method, was used to quantify the total amount of building distributed in each selected zone. The number of families living in the village is 1681 units with an average of 2.89 components. The non-residential structures were divided into commercial (60% of the non-residential buildings) and office ones (40% of the non-residential buildings). Therefore, three categories of buildings (residential buildings, commercial buildings, offices) and three different stratigraphy’s were identified (Table 3 and Table 4). The total amount of building typology is as follows: 2005 for residential, 110 for commercial use, and 74 for offices. Table 4 reports the number of the same structure per area (see Figure 1) as a result of the materials of the building (see Appendix A). As a result, each macro-area contained buildings with the same envelope (e.g., Area 1 only contains reinforced concrete buildings), except for the old town zone (Area 2), which uses two stratigraphies (Stratigraphy A and B). In accordance with the available data about the context, the same method was used to estimate the distribution of the building type and the structure of the other villages.

Table 3: Geometrical characteristics of three different typologies of users.

		Residential building	Commercial building	Office building
Height	[m]	6	4	9
Length	[m]	10	10	10
Width	[m]	5	10	8
Nr of floors	-	2	1	3
Total useful surface	[m^2]	100	100	240
Volume	[m^3]	300	400	720

Table 4: Stratigraphy for the buildings belonging to the different macro-areas.

	Nr of buildings		
Area	Stratigraphy A	Stratigraphy B	Stratigraphy C
1	0	0	93
2	449	449	0
3	0	137	0
4	0	360	0
5	0	0	103
6	0	411	0
7	0	0	186
TOTAL	449	1357	382
	21%	62%	17%

2.2Energy generation system

The wood biomass availability of the case study, the Sila Piccola Meridionale, suggests the installation of a CHP biomass plant-based on a steam turbine cycle, operated according to a back-pressure configuration. The choice for the back-pressure steam turbine arrangement derives from technical considerations (Sartor et al. 2014). Moreover, the combination of internal combustion engines and gas turbines is a suitable technological scheme for small and medium CHP (power lower than 2 MW, as this case study). This technical system is generally operated with the bypass of steam at the exit of the turbine rather than with steam extraction. Furthermore, the low electric efficiency of a back-pressure steam cogeneration plant, which represents its main drawback, is justified in this study by the high thermal demand load of those mountain villages. The low value of the cogeneration ratio, characterizing this type of plant, indeed does not represent an issue for a DHN application.

2.3Calculation of the energy requirements

The total energy demand of the six villages, starting with Sersale, was calculated using Simulink software.For the weather data, the "Neural weather generator", a climate condition simulator developed by ENEA (Di Pietra et al. 2013), was used, basing on the techniques of Soft-computing. The model provides data about temperature, humidity, and solar radiation. According to this, the results of the environmental temperature trend over the year (8760 hours) are shown in Figure 2.

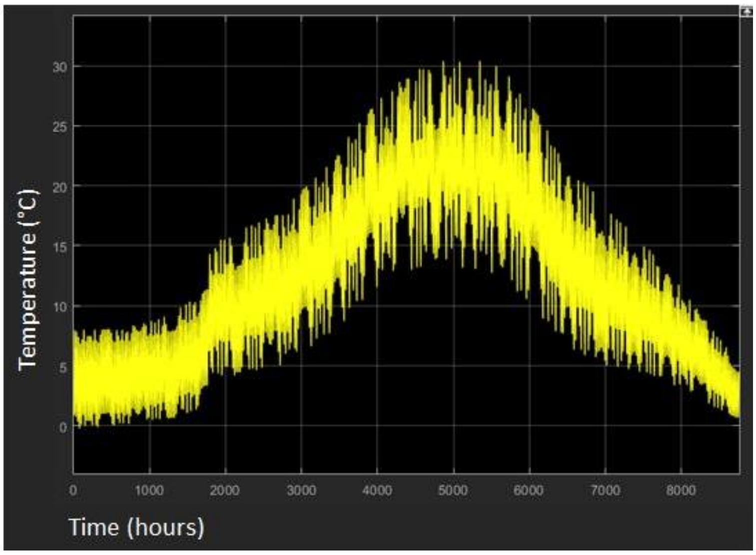


Figure 2: Environmental temperature trend during the year [°C]

Sersale's maximum temperature during the summer months is about 30 °C, while in the winter, it can drop as low as 0 °C.The model also provides a daily temperature trends. Among the thermal and electric loads and internal gains, data from regulations were used, being difficult to manage that information of six communities.

Presence of people. The residential buildings are occupied by a single family of three. In the evenings and at night, a building can accommodate up to three occupants; during the day, though, only one is estimated. In non-residential buildings, the average occupancy is calculated according to UNI 10339. This average value is 17 for commercial buildings and 13 for offices. For commercial buildings, supposed as a department store of 100 m^2, the working hours are from 9 am to 8 pm, from Monday to Saturday; conversely, from 9 am to 1 pm on Sunday. The total number of employers is set to 6, the cleaners to 2 and the costumers to 30. Moving to the office, they are organized on three floors of 80 m^2 each: 70% of the total useful surface is effectively occupied, while 30% is constituted by corridors and other common areas. Also, for this case, 17 employers are estimated, assuming a 10 m^2 available for a person. Regarding the working hours, the schedule involved Monday to Friday (from 8 am to 1 pm and 2 pm to 5 pm) and Saturday morning (from 8 am to 1 pm) (Figure 3).

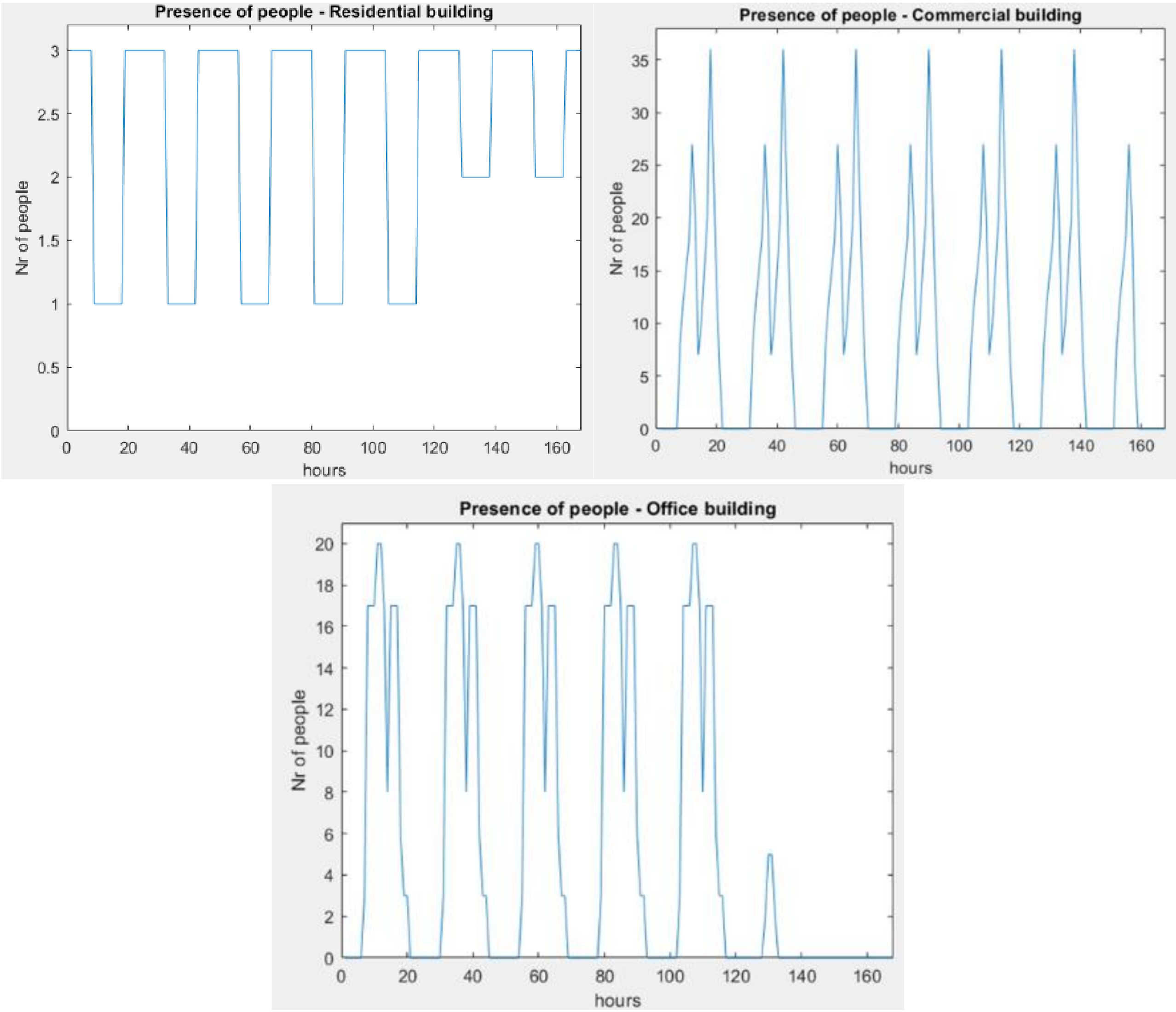


Figure 3: Weekly hourly profile of working hours [Nr of people/hours].

Ventilation rate. Table 5 shows the calculation of the air renewals needed for the external air inlet to ensure an external air inlet value, following the UNI 10339 standard.

Table 5: Calculation of air renewals needed in the different types of buildings according to UNI 10339.

Type of building	Useful surface	Volume	Crowding index	N° of people	Flow rate of external air	Flow rate of external air	Air renewal
	[m²]	[m³]	[people/m²]	-	[m³/(h*person)]	[m³/h]	[1/h]
Residential	100	300	0.04	4	39.6	158	0.5
Commercial	100	400	0.25	25	32.4	810	2.0
Offices	240	720	0.06	14	39.6	570	0.8

As reported in Table 5, the "Air renewal" column is used when the building is occupied or when the plant is operating. However, when the plant is off, the air renewal values are assumed to be 0.2 for residential buildings and 0.1 for non-residential ones, which takes into account the infiltration of the building envelope (Figure 4).

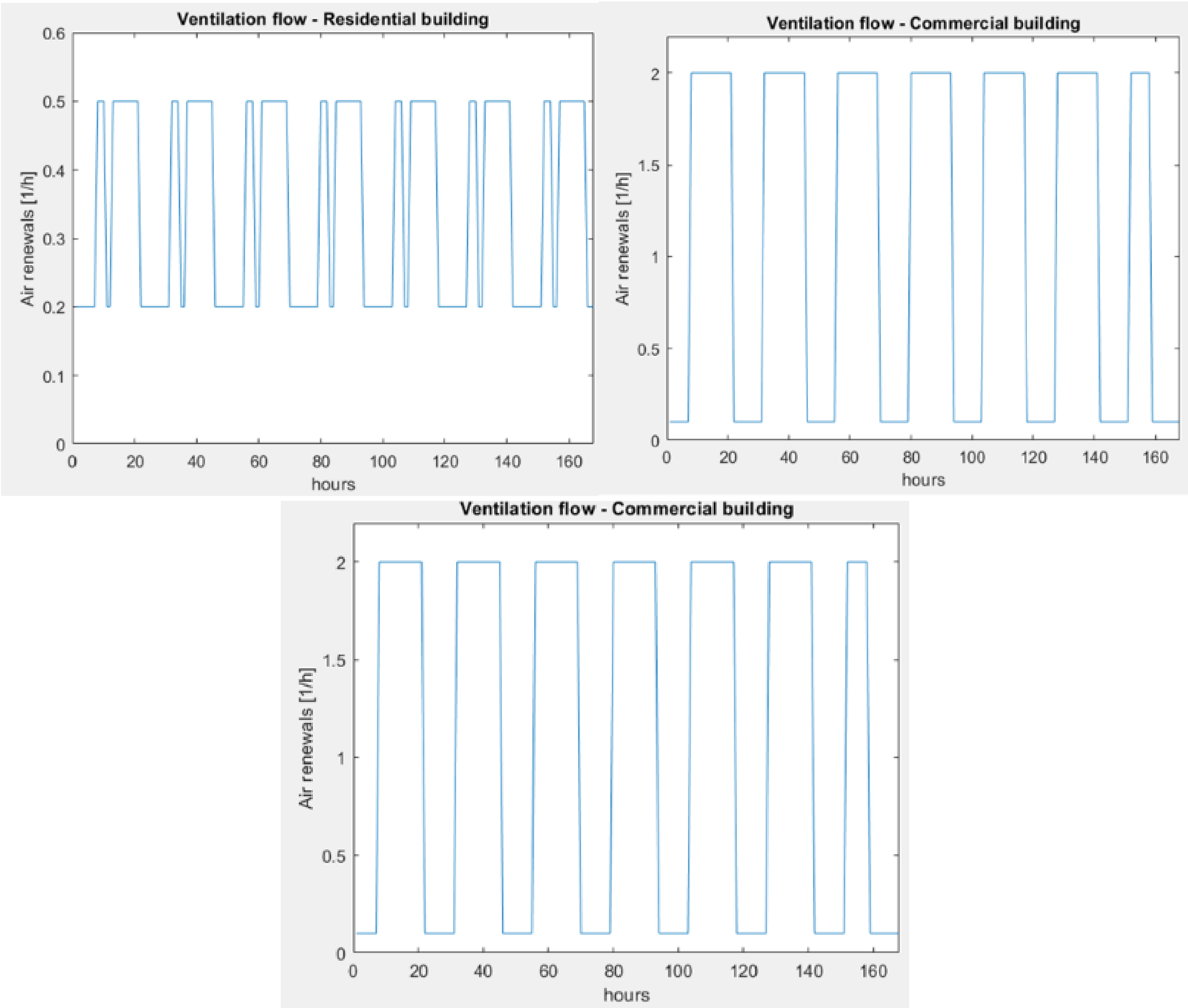


Figure 4: Weekly hourly profile of air renewals interesting the building [1/h].

Internal heat gains. The internal gains (people occupancy, the lighting systems, devices, etc) contribute to increasing the indoor temperature of buildings. In accordance with Standard UNI/TS 11300-1, values of the global thermal internal loads (due to the occupancy of people and electric devices) are provided per floor unit, (i.e. in W/m^2), depending on the type of structures. For residential and office buildings, these values are set for weekdays and weekends, respectively; while the hourly profile for commercial buildings can be calculated from industry standards (UNI/TS 11300-1), as shown in Figure 5.

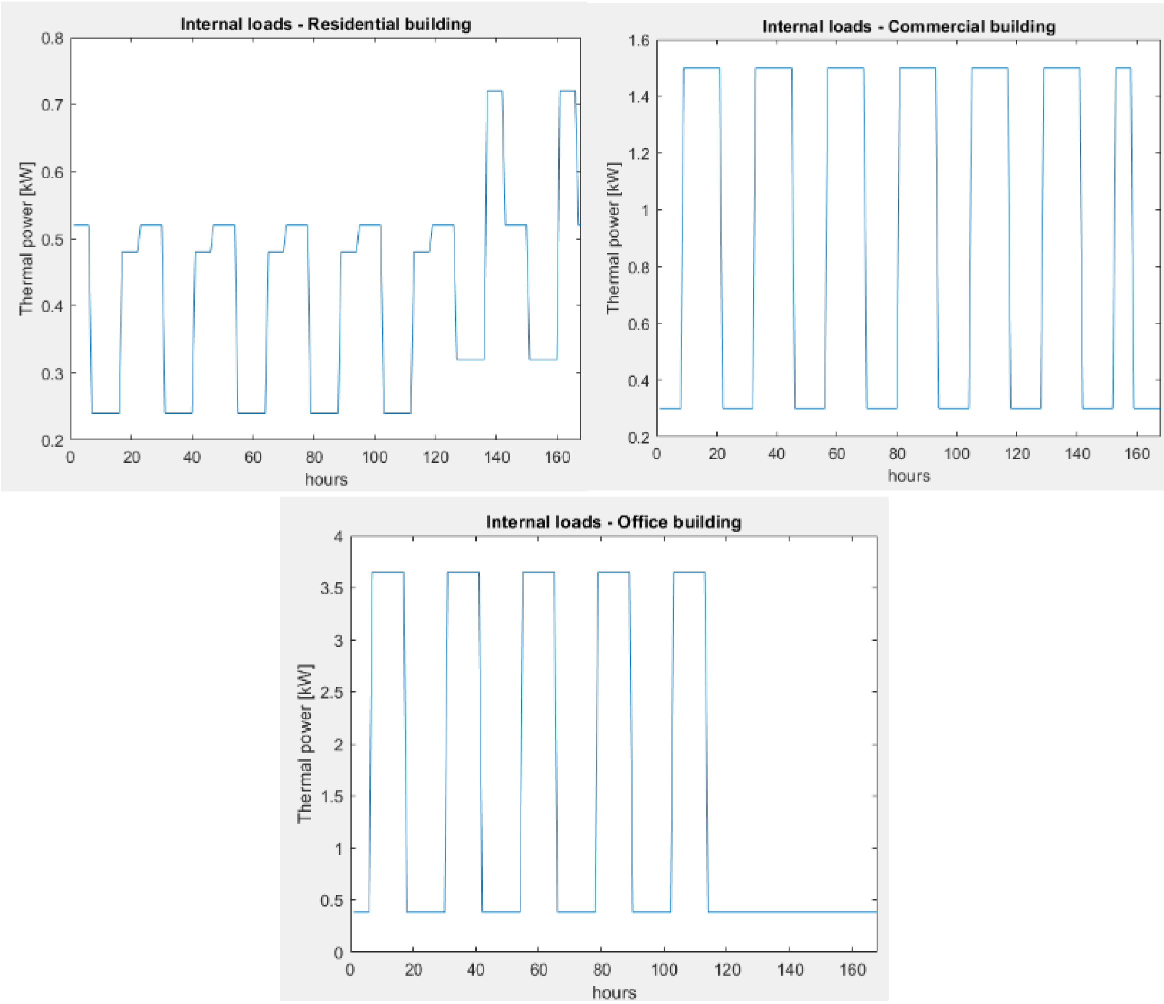
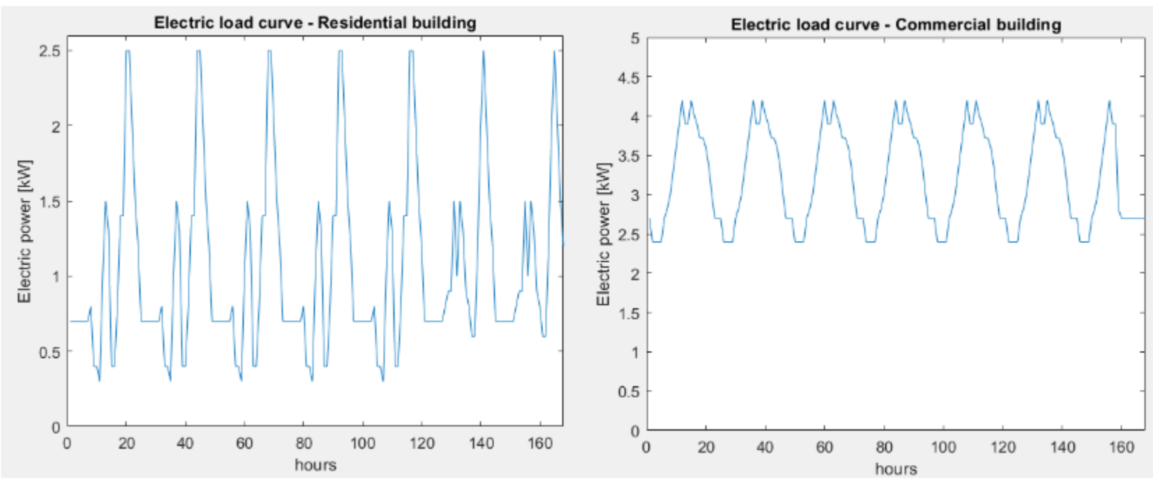


Figure 5: Weekly hourly profile of the thermal power produced by internal sources in the building [kW].

Electric load curves. The building electric power needs of a typical day presents two peaks, one at 1 pm and another at 9 pm, following the maximum electric demand. The electric load profile in the commercial buildings is in line with "Electric load patterns for residential, commercial, and industrial usage" (UNI/TS 11300-2). To obtain this curve, the value of the installed electric power capacity was estimated equal to 6 kW. Knowing the electrical system power installed in the store, the electric load curve for the offices is 4.5 kW. Finally, it was assumed that the electrical energy consumption of non-residential buildings slightly decreases during lunchtime (Figure 6).



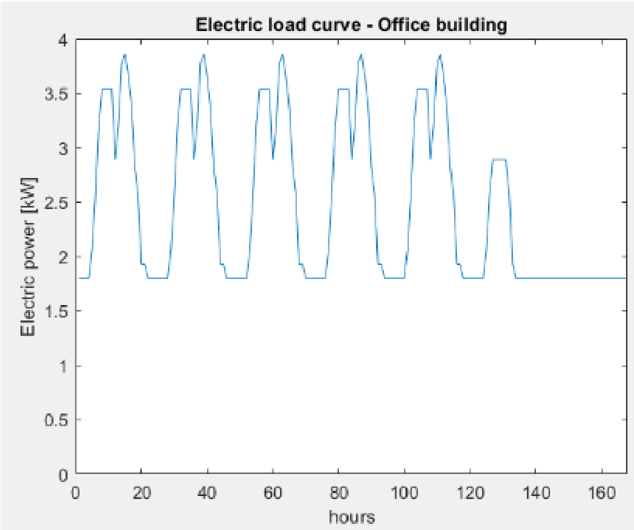
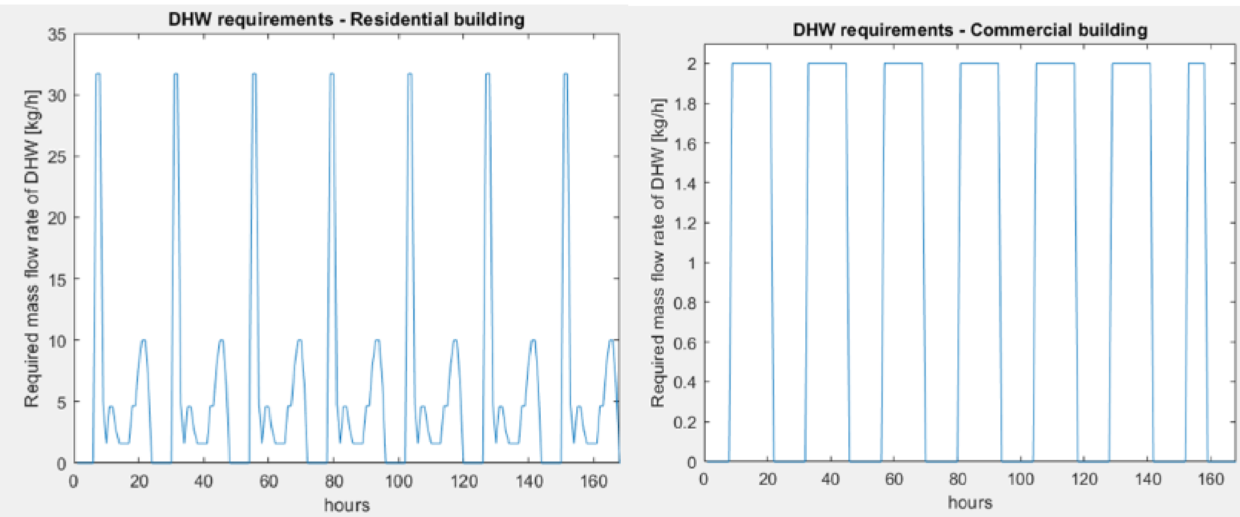


Figure 6: Weekly hourly electric power requirements of the building [kW].

Domestic Hot Water requirements. To define the thermal energy needed for the Domestic Hot Water (DHW), the flow rates of water required, and its temperature (inlet and outlet) were elaborated based on technical data (Figure 7). The thermal power $P_{th\ DHW}$ indeed is given by Equation 1 (UNI/TS 11300-2):

$$P_{th\ DHW} = \varrho \cdot \dot{V} \cdot c_{p,W} \cdot (T_{W\ out} - T_{W\ in}) \tag{1}$$

where: ρ is the water density equal to 1000 kg/m^3; $\dot{V}$ is the required volumetric flow rate of water in terms of m^3/s; $c_{p,w}$ is the specific heat of water, equal to 4.186 kJ/(kg·K); $T_{w\ out}$ and $T_{w\ in}$ are respectively the temperature at which the water must be heated and the cold water intake temperature, assumed equal to 40 °C and 15 °C, according to the Standard (UNI/TS 11300-2).
In the residential building case, the hourly trend of the water volume required during a day by the occupants is calculated according to UNI-EN/16247 guidelines. For the non-residential use, the daily values are provided by the Standard UNI EN 11300-2. For both commercial buildings and offices, the daily required volume of DHW is equal to 0.2 l/(day·m^2).



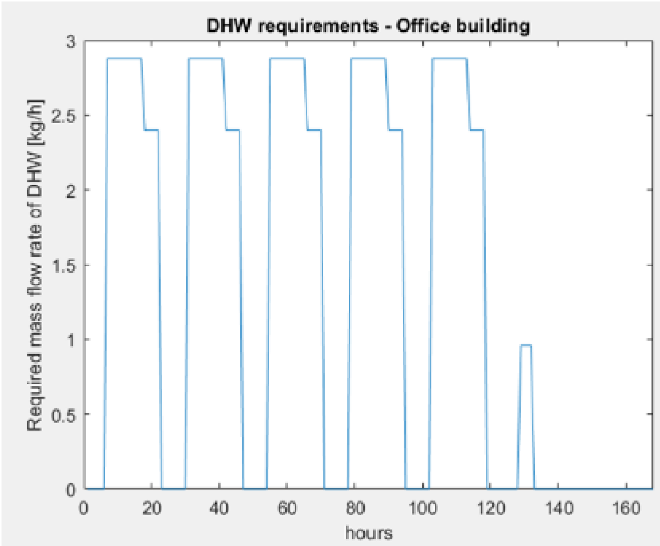


Figure 7: Weekly hourly profile of DHW mass flow rate required by the building users [kg/h].

2.4 The models of CHP biomass plant and the DH network

In this paragraph, the DH and the biomass CHP plant of Sersale village, were modelled (Figure 8). The inputs of the district heating networks are listed below:

- The values of the mains water mass flow rates delivered to the macro-areas of the village (kg/s);
- Temperatures of the network water stream at the exit of each block of costumers (°C);
- The total electric and thermal power requirements of the macro-areas of Sersale (kW);

These parameters play an essential role in the simulations to evaluate:

- The total mass flow rate (kg/s) of mains water which is extracted from the network accumulator in order to feed the buildings, is equal to the sum of the flow rates fore-calculated;
- The temperature at which the water of the network reaches the delivery in nodes the different macro areas (°C);
- The fluid temperature of the return network (°C);
- The total heat losses occurring along with the delivery network and along with the return network as well as their sum (kW);
- The network efficiency;
- The total electric and thermal power requirements of Sersale’s buildings, connected to the DHN system (kW);
- The thermal power extracted from the network accumulator during the operation of the system to meet the customer's demand (Q load, network accumulator, kW).

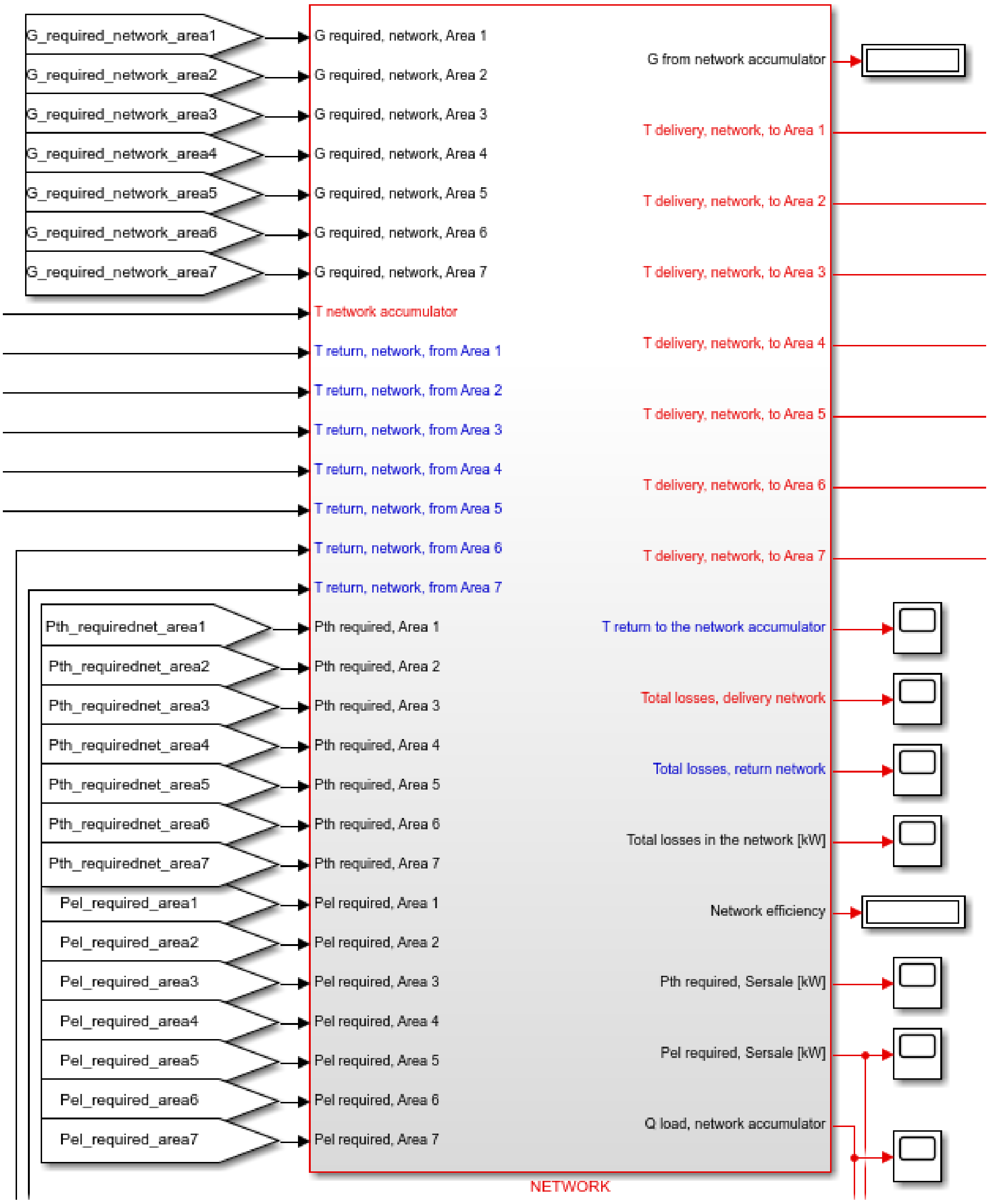


Figure 8: "Network" block.

Using two Matlab functions that estimate the temperature difference between the water and the soil surroundings the insulated pipes of the DHN plant, the heat losses are calculated as follows (Equation 2) (Sartor et al. 2014):

$$Pth_{loss} = G \cdot c_{p,W} \cdot \Delta T \tag{2}$$

Where G is the mass flow rate of water flowing through the pipe of the DHN (kg/s), $c_{p,W}$ is the water-specific heat (kJ/(kg·K)) and ΔT is the difference between the water temperatures at two different consecutive nodes (°C) at the extremes of the pipe. A Simulink block calculates the network water required by the individual user. This block assumed the mass flow rate constant during the network operation; while the water temperatures, in correspondence of specific nodes of the DHN, will change over time.

Finally, the thermal level of mains water located in each node to the delivery network is provided by Equation 3 (Sartor et al. 2014).

$$T(x,t) = T_{soil} + (T_{node} - T_{soil})e^{\frac{-2\cdot\pi\cdot H}{G\cdot c_{p,w}}x}$$

(3)

where: T_{soil} is the soil temperature equal to 15 °C; T_{node} is the temperature of the node that forerun the one for which the temperature has to be calculated (°C); H is the pipe transmittance (kW/(m·K)); x is the length of the concerned pipe in meters, (i.e. the distance between the two considered nodes). In correspondence with the return network nodes, the water reaches an average thermal level of the water temperatures mixing at that point, weighted with their mass flow rates, as expressed in Equation 4 (Sartor et al. 2014).

$$T_{node} = \frac{\sum_i T_i \cdot G_i}{\sum_i G_i}$$

(4)

The heat losses assessment was defined for both the delivery and return networks. The evaluation of thermal losses ensured the over-sizing of the generation system and guaranteed an adequate temperature value of the heat transfer fluid when this reaches the thermal needs of the users.

More in detail, the heat losses and temperature drop of the network water were studied, as shown in Figures 9-10. The graph shows the time trend of the total heat losses (taking in account the heat exchange with both the supply network and the return network) and the annual temperature trend of the network's heat storage tank (Figures 9-10).

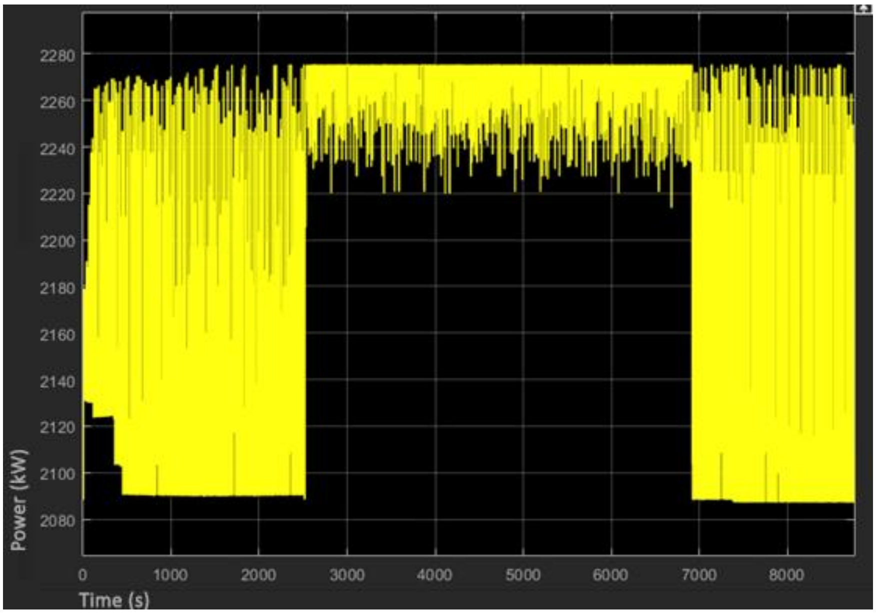


Figure 9: Total heat losses along the network during the year [kW]

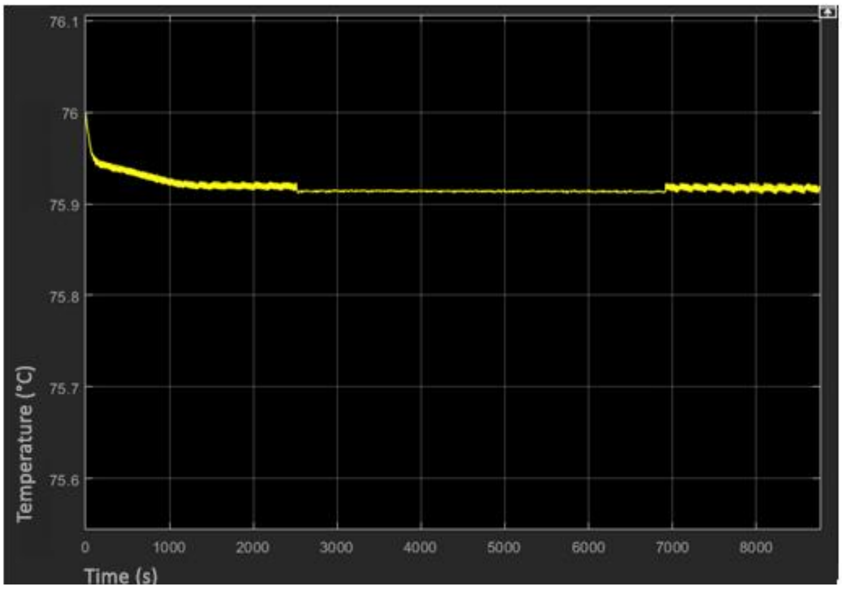


Figure 10: Temperature of water inside the network accumulator during the year [°C]

If the water flow is assumed to be constant, the heat losses along the network are almost constant throughout the year at a value of 2.1-2.28 MW, which has a significant weight in the annual energy balance. In addition, the heat losses are responsible for the decrease in water temperature, which falls to the values shown in Figure 11 at the delivery nodes to the macro-areas. Figure 12 shows instead the evolution of the water temperature due to the heat exchange in the substations of the consumers.

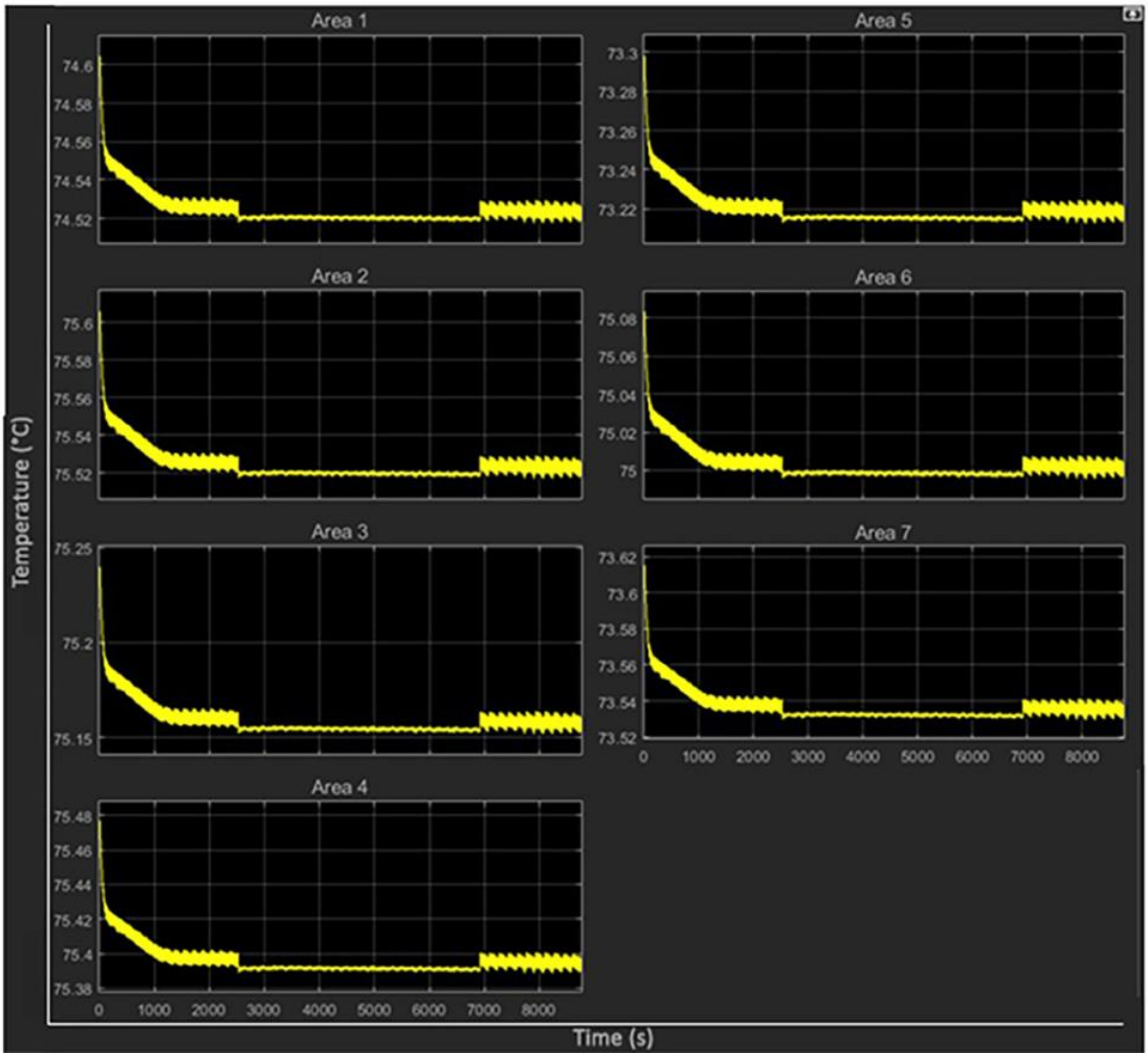


Figure 11: Temperature of network water at the nodes of delivery to the macro-areas during the year [°C].

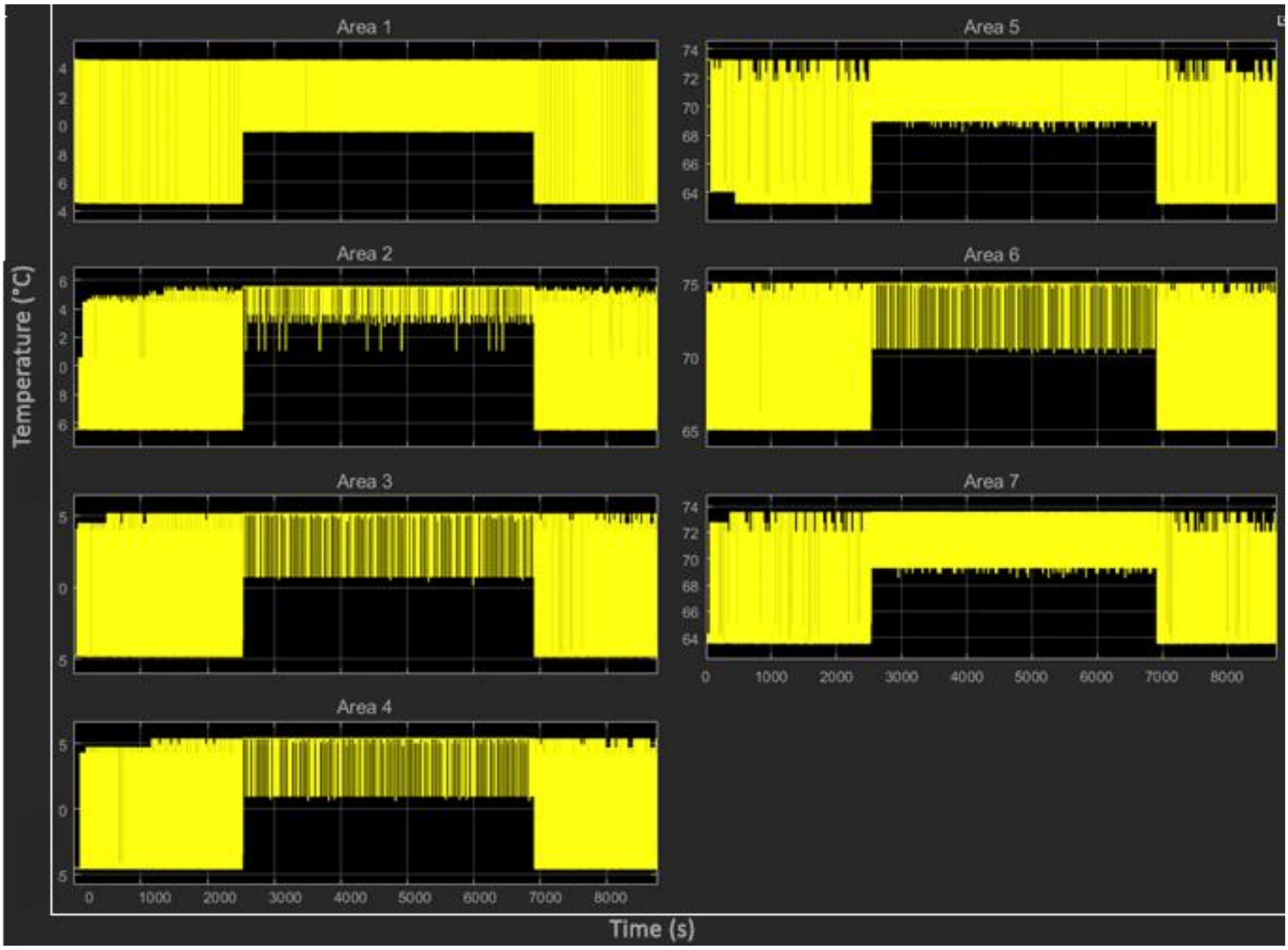


Figure 12: Temperature of network water at the nodes of return from the macro-areas during the year [°C].

Figure 13 showed the variation of the water temperature reinjected in the storage tank, oscillating between 65 and 75 °C during the winter season and between 72 and 75 °C during the summer one.

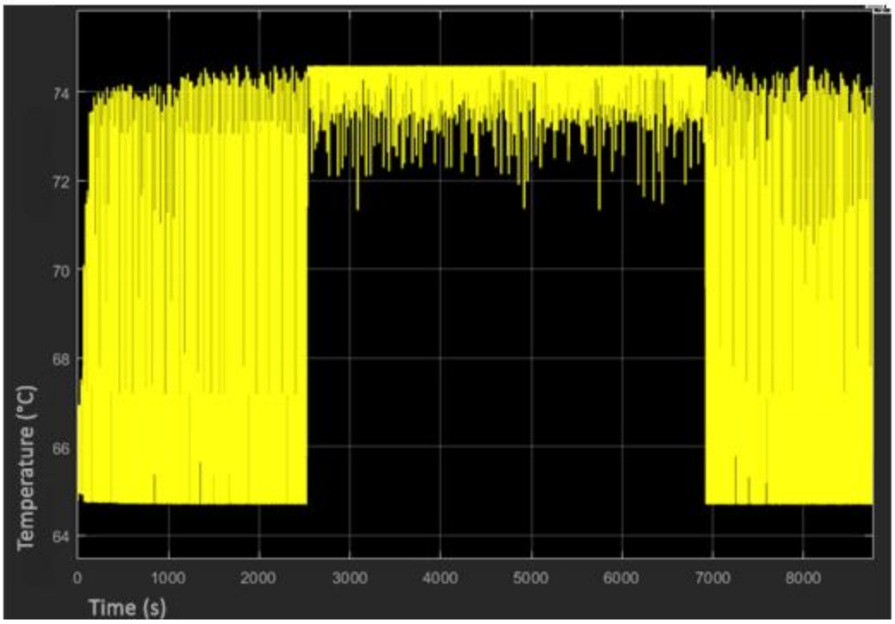


Figure 13: Temperature of network water reinjected in the network accumulator during the year [°C]

It is interesting to evaluate the magnitude of heat losses occurring in a 1 km pipe and the associated water temperature drop. Heat losses of 114 kW/km and a temperature drop of 0.067 °C/km were determined (although both vary slightly with time), which is consistent with the established value of 0.1 °C/km for small district heating networks (Mazza et al. 2006).
The network efficiency is also calculated. According to the simulation, it is 0.74, which means that the total heat losses in the DH system account for 26% of the total heat energy distributed through the pipelines. This value is slightly higher than the 16% recommended by the GSE (Gestore dei Servizi Energetici) guidelines [34], which indicates the current average heat losses of Italian DH systems. Other sources indicate a greater percentage of losses (up to 20%), reaching the maximum value of 25% for networks in mountainous areas (GSE 2016). The dimensioning of the pipes of the DHN is a crucial point to consider, and therefore it might be necessary to lay them along a rather wide road.
The simulated network has an indirectly branched configuration, which offers economic advantages in the realization phase or in the future expansion in the area. Figure 14 shows only the backbones and the secondary network with branches to the areas. Additional branches were not considered. It is also assumed that the direct connection between the users and the network is through the branches and not through the sub-branches, otherwise the amount of data would be difficult to handle.

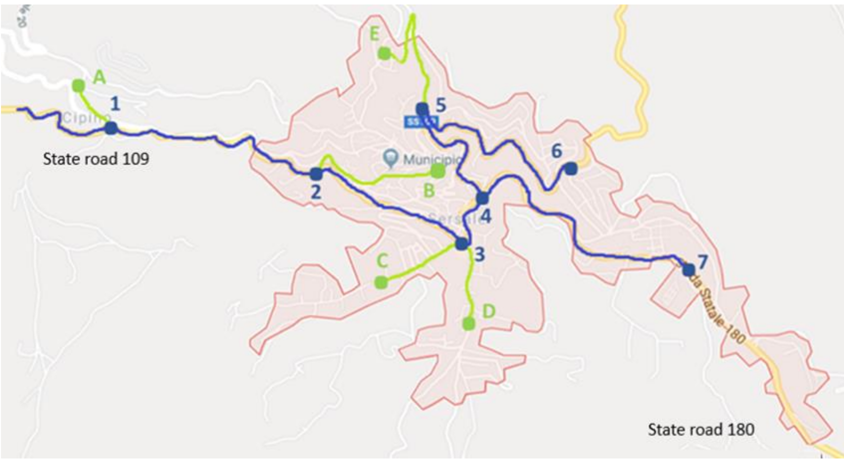


Figure 14: Path of the main pipelines (blue) and the secondary branches (green) of the DHN.

Points A, B, C, D, E identify the different areas, as shown in Figure 14. The roads (identification name, carriageway width, and maximum height difference), the length data of pipelines and their ramifications are essential for the pipeline sizing (Table 6).

Table 6: Main information about the track of DH network pipes.

	Extremes	Length	Width of the carriageway	Max difference in level	Notes
		[m]	[m]	[m]	
MAIN PIPES	0 – 1	4000	6 ÷ 7	98	0-1 upward path
	1 – 2	850	6 ÷ 7	45	1-2 descending path
	2 – 3	600	6 ÷ 7	28	2-3 descending path
	3 – 4	200	6 ÷ 7	10	3-4 descending path
	4 – 5	500	6 ÷ 7	39	4-5 descending path

	5 -6	900	6 ÷ 7	6	Max intermediate peak at 782 m over the sea level
	4 – 7	1000	6 ÷ 7	92	6-7 descending path
	TOTAL DELIVERY NETWORK	8050			
BRANCHES	1- A	270	6	128	1-A upward path
	2 – B	500	5 ÷ 6	15	Max intermediate peak at 790 m over the sea level
	3 – C	350	5 ÷ 6	27	3-C descending path
	3 – D	300	4 ÷ 5	27	3-D descending path
	5 – E	600	5 ÷ 6	74	5-E upward path
	TOTAL DELIVERY NETWORK	2020			
TOTAL DELIVERY AND RETURN NETWORK		20140			

The definition of the total surface area of Sersale covered by the DH and the required pipeline's length allows the computation of the surface and mass flow rates of water required of the DH network (Table 7).

Table 7: Mass flow rates of water required to the DHN by the macro-areas of the village

Macro-area	Mass flow rate [kg/s]
Area 1	6.491
Area 2	200.922
Area 3	27.036
Area 4	71.196
Area 5	7.681
Area 6	80.902
Area 7	13.944

Simulink provides the following results: the annual trend of the electrical power required by the three building categories, the thermal power required according to the building's heat balance, and the effective thermal load. From the Simulink simulations, the district heating distribution network must be able to provide a total mass flow of water of 408 kg/s, and a total thermal energy of 41100 MWh/year (see Figure 15). Note that the maximum power that must be guaranteed is corresponds to about 17 MW in winter and 5.5 MW in summer.

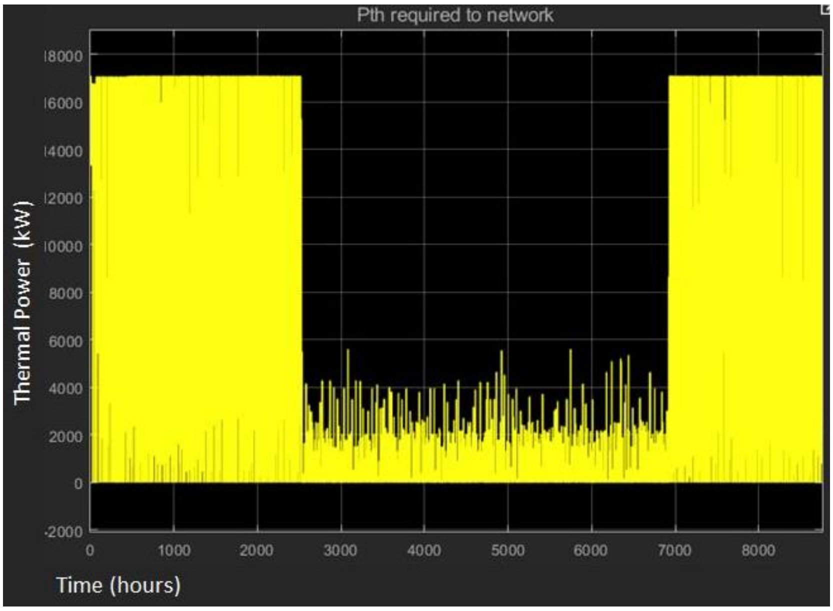


Figure 15: Total thermal power required to the DHN by the macro-areas of the village during the year [kW].

The diameter of the pipes is calculated for each section of the network using the following expression (Equation 5) (Sartor et al. 2014):

$$D = \sqrt{\frac{4 \cdot G}{\varrho_{water} \cdot \pi \cdot u}} \cdot 1000$$

(5)

where: G is the mass flow rate of water flowing through the pipe of the DH network (kg/s); ϱ_{water} is the water density (kg/m^3); u is the fluid velocity, (2.5 m/s for speed along the backbones and 1.5 m/s for speed along the branches).

Therefore, the chosen technology consists of steel pipes with plastic sheath whose thermal insulation is made of rigid polyurethane foam. The geometrical and thermal characteristics of the DH pipes are shown in Table 8.

Table 8: Geometrical and thermal characteristics of the DHN pipes selected from a commercial catalogue.

	Extremes	Lenght	Mass flow rate	Chosen D	Insulation thickness	Conductivity
		[m]	[kg/s]	[mm]	[mm]	[W/mK]
MAIN PIPES	0-1	4000	408.17	456	101	0.277
	1 - 2	850	401.68	452	86	0.344
	2 - 3	600	200.68	320	72	0.268
	3 - 4	200	102.54	229	64	0.251
	4 - 5	500	88.59	212	64	0.251
	5 -6	900	80.91	203	48	0.251
	4 - 7	1000	13.95	84	36	0.186
BRANCHES	1- A	270	6.49	74	36	0.186
	2 - B	500	201.00	413	87	0.344
	3 - C	350	27.04	152	41	0.239

	3 - D	300	71.10	246	64	0.251
	5 - E	600	7.68	81	36	0.186

The total electricity demand of the users in the village is calculated using two summation operators in Simulink. The results of the sums are then integrated to obtain the global energy demand.

The biomass cogeneration plants are based on steam turbine technology. The cogeneration of the plant is realized by introducing a heat exchanger behind the turbine. This component can recover the condensation heat of the expanded steam to heat the water in the distribution network, realizing a back-pressure configuration of the steam turbine plant.

The Simulink simulation aims to quantify and obtain the hourly trend of the following parameters throughout the year:

- The useful thermal power generated by the biomass CHP plant and the boiler and its sum (kW);
- the useful electric power generated by the steam power plant (kW);
- Total useful thermal and electrical energy (kWh/year).

The Simulink model of the plants requires the definition of the following parameters (Figure 16): the operating planof the plant; the environmental temperature (°C); the temperature of the water stored in the network storage (°C); the electricity demandof the users that could be supplied by the plant (kW). n the energy model, different blocks are defined described by several thermophysical equations. These have the objective of determiningthe transformations of the working fluids such as the thermophysical states at the inlet and outlet of each plant component as well as the thermal power exchanges.

Also, the total amount of woodchips needed to operate the CHP plant and the integrative boiler is calculated (tons per year).

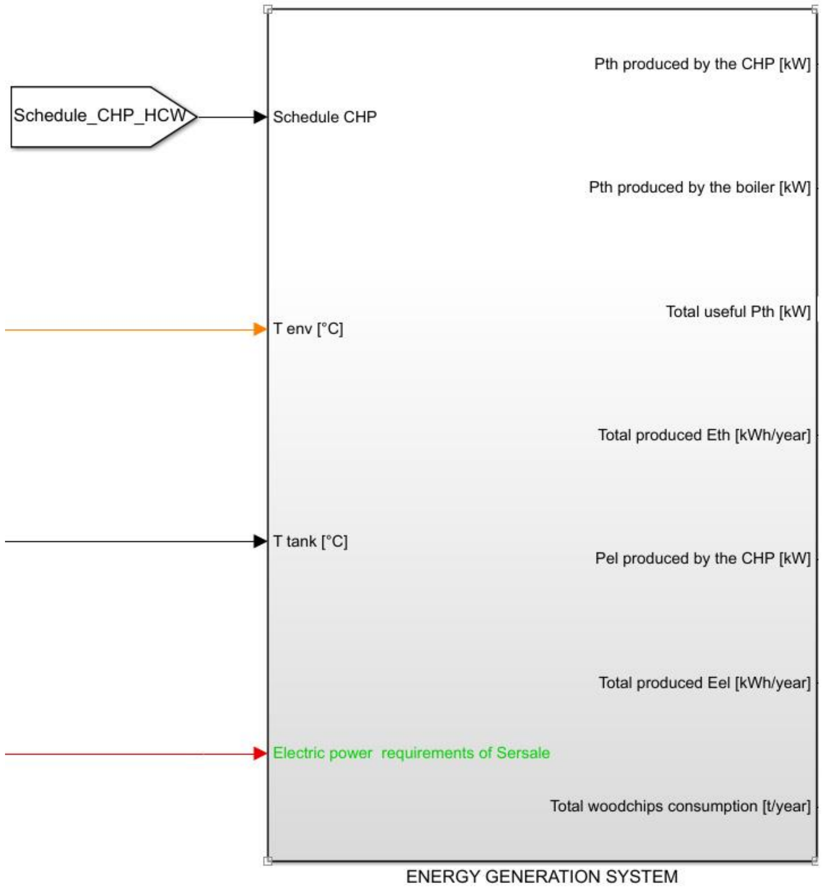


Figure 16: “Energy generation system” block.

Therefore, the nominal electrical power of the plant was set at 2.5 MW, taking into account he needs of the village, which is a maximum of about 2.4 MW. In this way, the simultaneous operation of the two power plants would be able to cover the peaks of the electricity demand of the village.

The electrical efficiency of the biomass cogeneration plant is 0.13, a value that corresponds to the data in the literature (Vio 2009), where the electrical efficiency of different CHP plants is presented as a function of several parameters.

On the other hand, an auxiliary boiler is essential to cover the peaks of the thermal power electricity demand. The boiler chosen for this study has a nominal thermal capacity of about 29 MWh/year and a nominal efficiency of 0.85. The energy production of the whole power generation system is shown in Table 9, together with the woodchip consumption.

Table 9: Energy production and fuel consumption of the energy generation system.

Produced electric energy	[MWh/year]	6625
Produced thermal energy (CHP)	[MWh/year]	22470
Produced thermal energy (Boiler)	[MWh/year]	29540
Total Produced thermal energy	[MWh/year]	52010
Cogeneration ratio	-	0.29
Woodchip’s consumption (CHP plant)	[t/year]	14880
Woodchip’s consumption (Boiler)	[t/year]	10220
Total woodchips consumption	[t/year]	25100

3. Resilient thermal network

Simulations were performed to demonstrate the resilience of the entire thermal network applied to six mountain communities. Equation 6 [22] describes the dynamic behavior of the energy system proposed, providing the time trend of the temperature of the water circulating in the networks.

$$\frac{dT_{network\ water}}{dt} = \frac{Q_{aux} - Q_{load}}{c_{p,w} \cdot \varrho_w \cdot V_{network\ water}} \quad (6)$$

where Q_{load} represents the total thermal power requirements of the urban centres , taking into account the heat losses of the network; Q_{aux} is the total thermal power released to the water of the network after the CHP plants and boilers activation; $V_{network\ water}$ is the volume of water.
The model developed in Simulink is composed by the following subsystems:

- "Weather data" and "Profiles and schedules" blocks: these two blocks collect data of climate conditions and operative schedules of the CHP plants.
- "Calculation of energy requirements of the villages": the outputs from the subsystem are the annual electric power profiles required by each village and the trend of the thermal power requested by the users of the DH network. The load curves were derived for every single village and then combined to obtain the entire thermal network.
- Six "Energy generation system" blocks: each block represents the group of the CHP plant and the auxiliary boiler installed in the villages.
- "Global network" block: the distribution network, which supplies the six villages, is simulated as a physical water storage tank.

It is well-known that the energy power plants may be subject to faults, malfunctions, or necessary maintenance operations which may cause their shutdown (Sharifi and Yamagata 2016). The network, therefore, is resilient if it manages to maintain the operation even during black out, completing its task of fulfil the customers' heat and electricity requests. Two resilient scenarios were elaborated in case a failure event of at least one plant occurs. The blackout circumstance involving more than one system was excluded from this study because they are not considered realistic. The description of both scenarios is reported below:

- Case A: if a plant goes off, the demand of energy production is higher for the remaining CHP plants. This is the need to satisfy the increased thermal load request from the network. It is assumed that the electrical and thermal production is divided among the remaining cogeneration plants, so the oversizing regards only the cogeneration systems, while the boilers keep unchanged its dimensions.
- Case B: both CHP plants and boilers were oversized compared to the base case, wherein no plant shutdown is expected.

4. Results and Discussion Results of the thermal network

Table 10 collects the main results obtained, wherein the maximum value of the thermal power required by the village users is combined with the power lost for heat dispersion along the pipelines.

The user's needs are responsible for a total of 6 MW of electric power and more than 47 MW of thermal power during the winter. The annual energy requirements were listed for the different urban centres, together with the total amount of the thermal network.

Table 10: Power and energy requirements of the villages and the entire network.

	Max electric power required	Max thermal power required	Required electric energy	Required thermal energy
	[kW]	[kW]	[MWh/year]	[MWh/year]
Sersale	2400	19172	11360	40480
Cerva	527	4267	2303	12580
Petronà	1300	10000	6393	29320
Andali	600	4758	2806	13880
Zagarise	745	5870	3204	17960
Magisano	450	2790	2637	8687
TOTAL (Simultaneous)	6018	46776	28703	122907

From the maximum thermal power value, it is possible to calculate the total mass flow rate of water circulating in the village network, considering the water temperature variation equal to 10 °C.

Base case: biomass CHP sizing

The first simulation is carried out sizing the biomass CHP plants according to the electric energy demand of the single villages, as was already done for Sersale. Moreover, an electric load tracking was included, allowing to better manage the cogenerator functioning. The auxiliary boilers were introduced to satisfy the peaks of the thermal power requirements. Main results were synthesized in Table 11.

Table 11: Energy production by the CHP plants and boilers of the thermal network – Base case.

	Produced electric energy	Produced thermal energy (CHP)	Produced thermal energy (Boiler)	Total Produced thermal energy	Cogenerati on ratio
	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	-
Sersale	6625	22470	29540	52010	0.29
Cerva	2153	6851	5579	12430	0.31
Petronà	4969	15920	13130	29050	0.31
Andali	2153	6851	5251	12100	0.31
Zagarise	3312	10540	9190	19730	0.31
Magisano	2153	6851	4923	11770	0.31

Table 12 reported the annual woodchip consumption per each mountain village. Although the biomass is not a 100% green source, it is a sustainable alternative compared to common fossil fuels in terms of emissions savings (Elsayed et al. 2003). Giving a couple of figures, the energy systems of Sersale consumes the major amount of biomass and allows to save around 11000 ton of the CO_2 emissions.

Table 12: Fuel consumption of the CHP plants and boilers– Case BASE (Elsayed et al. 2003).

	Woodchip consumption [t/year]	Annual total CO_2 emissions

				[t saved c.f. gas]
	CHP plant	Boiler	TOTAL	
Sersale	14880	10220	25100	11442.20
Cerva	4835	1931	6766	2734.60
Petronà	11160	4543	15700	6391.00
Andali	4835	1817	6652	2662.00
Zagarise	7439	3180	10620	4340.60
Magisano	4835	1703	6539	2589.40

Case A: oversizing of the biomass CHP plants

To calculate the required oversizing of the cogenerators, six different operating conditions of the thermal network were performed. This situation occurred in case the energy generation systems of the villages switched off one by one. Each case was considered individually, pointing out the sizes of the CHP plants which should be adopted to face the lack of heat production (highlighted in grey in Table 13).

Table 13: Max power produced by CHP and boiler for all scenarios - CASE A.

Scenario	1	2	3	4	5	6
	Max P_{th} produced by CHP+boiler	Max P_{th} produced by CHP+boiler	Max P_{th} produced by CHP+boiler	Max P_{th} produced by CHP+boiler	Max P_{th} produced by CHP+boiler	Max P_{th} produced by CHP+boiler
	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
Sersale	0	17850	20060	17850	20060	17850
Cerva	10520	0	8317	6155	7190	6155
Petronà	15060	11740	0	11740	11740	11740
Andali	10450	6025	8237	0	6025	6025
Zagarise	13860	9437	9437	9437	0	9437
Magisano	8187	5975	7081	5975	7081	0

It can be noted that the sizes of the CHP plants identified for the scenarios 2, 4, and 6 are equal since the involved villages showed similar heat generation capacity also in case all the plants were on (Table 13). These sizes are the smallest compared to the case of Sersale, Petronà and Zagarise shutdown plants (scenarios 1, 3 and 5). Thus, it would be more important to deal with an energy shutdown in these villages because they host the largest energy-generating systems. As soon as the new thermal network configuration was determined, it was checked if the new sizes could adequately distribute heat. To avoid heat exchangers producing excess heat that disrupts the network, a bypass of the turbine's steam must be planned for CHP plants. The oversizing of the CHP plants provides an excess of electricity production that could be selling to other companies (national or private). Based on the following operating conditions, a higher cogeneration ratio was obtained (Table 14). Moving to the woodchip analysis, Table 15 shows the consumption and the fossil fuel emissions saved per year (Elsayed et al. 2003).

Table 14: Energy production by the CHP plants and boilers of the thermal network– Case A.

	Produced electric energy	Produced thermal energy (CHP)	Produced thermal energy (Boiler)	Total Produced thermal energy	Cogeneration ratio
	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	-
Sersale	8281	13270	29540	42810	0.62
Cerva	6625	10620	5579	16190	0.62
Petronà	8281	13270	13130	26400	0.62
Andali	6625	10.539	5251	15790	0.68
Zagarise	8281	13270	9190	22460	0.62
Magisano	4969	7908	5087	12990	0.63

Table 15: Fuel consumption of the CHP plants and boilers– Case A (Elsayed et al. 2003).

	Woodchip consumption [t/year]			Annual total CO_2 emissions [t saved c.f. gas]
	CHP plant	Boiler	TOTAL	
Sersale	18600	10220	28820	9418.20
Cerva	14880	1931	16810	3561.80
Petronà	18600	4543	23140	5808.00
Andali	14880	1817	16690	3473.80
Zagarise	18600	3180	21780	4941.20
Magisano	11160	1760	12920	2857.80

Case B: oversizing of the biomass CHP plants and auxiliary boilers

An alternative resilient configuration of energy systems is then developed based on what has been learned from Case A, named Case B, where both cogenerators and auxiliary boilers have been expanded in size (Tables 16 and Table 17).

Table 16: Max power produced by CHP and boiler for all scenarios - Case B.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	max p_{th} produced by chp+boiler	max p_{th} produced by chp+boiler	max p_{th} produced by chp+boiler	max p_{th} produced by chp+boiler	max p_{th} produced by chp+boiler	max p_{th} produced by chp+boiler
	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
Sersale	0	17850	17850	17850	17850	17850
Cerva	9617	0	7419	5854	7419	5854
Petronà	12850	10640	0	10640	10640	10640
Andali	9637	5876	7425	0	5876	5876
Zagarise	11850	7425	9637	7425	0	7425
Magisano	9637	5876	6540	5876	5876	0

Sizes chosen for the CHP plant correspond to worst-case scenario (Scenario 1, when the largest power plant of Sersale is switched off). However, those sizes are lower compared to case A. As a

result of the increased production capacity of auxiliary boilers in this configuration, it is possible to deal with possible failure events better than in Case A. In line with this, the new configurations of the boilers were planned to cover both the thermal peaks and the shutdown of the smallest villages plants (Cerva, Andali or Magisano). Once the boilers were modified, the size of the cogenerators were increased to balance the other three possible scenarios (Sersale, Petronà, or Zagarise black-out).
By following this criterion, the oversizing of the auxiliary boilers was aimed to supply the energy demand of the less critical scenarios. The total electric and thermal energy production yearly trend of network is shown in Table 17. Ultimately, Table 18 reported the values of the woodchip consumptions and the advantages in terms of emissions savings (Elsayed et al. 2003).

Table 17: Energy production by the CHP plants and boilers of the micro-grid – Case B.

	Produced electric energy	Produced thermal energy (CHP)	Produced thermal energy (Boiler)	Total Produced thermal energy	Cogeneration ratio
	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	-
Sersale	6625	11060	29540	40600	0.60
Cerva	4969	7391	9846	17240	0.67
Petronà	6625	12290	13130	25420	0.54
Andali	4969	7391	9846	17240	0.67
Zagarise	6625	9913	9846	19760	0.67
Magisano	4969	7391	9846	17240	0.67

Table 18: Fuel consumption of the CHP plants and boilers– Case B (Elsayed et al. 2003).

	Woodchip consumption [t/year]			Annual total CO_2 emissions [t saved c.f. gas]
	CHP plant	Boiler	TOTAL	
Sersale	14880	10220	25100	8932.00
Cerva	11160	3407	14570	3792.80
Petronà	14880	4543	19420	5592.40
Andali	11160	3407	14570	3792.80
Zagarise	3407	3407	18280	4347.20
Magisano	11160	3407	14570	3792.80

As for the economic and financial evaluation, Table 19 shows the main parameters and values obtained for both resilient cases, considering that woodchip is purchased by users (see Appendix B for more details).

Table 19: Investment and running costs for the thermal network – Case A and Case B.

CASE A		**Sersale**	**Cerva**	**Petronà**	**Andali**	**Zagarise**	**Magisano**	**TOTAL**
Total investment	€	5418965	2885985	4129488	2859547	3786543	2247315	21327844
Total running costs	€/year	1317152	743837	1035428	737899	967842	573204	5375362

(purchased woodchips)								
NPV (Net Present Value)	€	11729283	5401603	7900294	5520570	6772909	4215281	41539940
IRR (Internal Rate of Return)	-	12%	10%	11%	10%	10%	10%	11%
PBP (Pay Back Period)	years	8.15	8.98	8.85	8.80	9.25	8.97	8.75
PI (Profitability index)	-	2.16	1.87	1.91	1.93	1.79	1.88	1.95
CASE B		**Sersale**	**Cerva**	**Petronà**	**Andali**	**Zagarise**	**Magisano**	**TOTAL**
Total investment	€	4827152	2598724	3560946	2598724	3222840	2598724	19407111
Total running costs (purchased woodchips)	€/year	739712	340108	462716	340108	397013	340108	2619765
NPV	€	22080631	12161589	19230838	12332827	16580094	12259587	94645566
IRR	-	22%	24%	24%	24%	23%	24%	23%
PBP	years	4.63	4.54	4.03	4.49	4.20	4.51	4.39
PI	-	4.57	4.68	5.40	4.75	5.14	4.72	4.88

The Net Present Value (NPV) shows its highest value for the micro-grid configuration assumed for case B. Because of the high economic revenues derived from the sale of electricity and heat, it is the best choice to slightly oversize steam turbines and boilers (Case B) to guarantee a greater resilience of the thermal network. This fact is also attested by other financial indices such as the Internal Rate of Return (23%) and the Profitability Index (4.88). Furthermore, case B requires the least number of years to recover the initial investment outlay (about 4÷5 years). The higher economic profit associated with oversized energy generation systems leads to this value of PBP (4.39 years) even though each village's total investment for its plant is higher for case B than for the reference one. In terms of financial perspective, Case A appears to be the worst-case scenario.
Summarizing, the comparison of the two elaborated scenarios leads to list the following considerations:

- As expected, Case A generates the most electric power since its cogenerators are the largest.
- Using only cogeneration for the other energy systems configurations, Case A shows a higher thermal production.
- The increased dimensions of the auxiliary boilers allow covering the thermal peaks and the energy demands of the smallest communities shutdown plants. In this way, the size of CHP plant is smaller than Case A, providing lower costs in terms of the maintenance and cost of the energy generator.
- As Table 19 showed, Case B is more affordable, due to the lower cost of the investment and running cost. Among these, the running cost related to the woodchip of Case B demonstrates relevant savings, more than half respect to 5 million €/year obtained for Case A.

- PBP of Case B (4.39 years) demonstrates its profitability compared to Case A (8.75 years).

5. Conclusion

This work aims to develop a new thermal network, exploiting the local renewable sources (woodchip) and guaranteeing the energy resilience of mountain communities. Knowing the impact of bad weather conditions in mountain villages, the study of resilient energy systems is still an urgent issue. District heating was planned for six Italian communities using biomass CHP plants as energy generators. According to the literature, few works investigated the potentialities of a thermal grid (network) composed of biomass CHP plant and district heating. Relevant studies were often focused on the electrical energy improvements of the CHP/DH systems, not exploring the thermal contribution.
In line with this, simulations were performed using MATLAB/Simulink tool, able to create and model a dynamic energy/environmental system. The entire thermal network was developed starting from Sersale, the biggest community, calculating its thermal and electrical requirements. Then, two resilient energy configurations (Case A and Case B) were investigated, increasing the size of the biomass CHP plant and the CHP/boilers, respectively. Results pointed out:

- the relevant role of the auxiliary boiler ensures the thermal needs of the users (around the 46 MW), even for the no-resilient energy configuration (Base Case).
- Although the woodchip is not 100% a green energy source, it can reduce emissions compared to fossil fuel, e.g. Sersale (Case B) obtained an annual total CO_2 emissions of 8932 toe saved (compared to gas).
- Although Case A produces a major amount of electricity (Sersale for Case A produced 8281 MWh/year v.s. 6625 MWh/year Case B) that can be sold to companies, the energy production (thermal and electrical) of Case B is well balance in accordance with the mountain village's needs.
- Based on the economic and financial results of Case B (oversizing both the CHP and boilers), the PBP (4.39 years), IRR (23%), and PI (4.88%) were significantly better than those in Case A.

Last but not least, designers and experts could take advantage of the proposed theoretical model of biomass CHP and DH to adapt it to another mountain country, investigating the benefit of biomass CHP plant and DH to supply thermal needs to users. Since this study analyzed the resilience of a new concept of thermal network, the reliability of each energy system and its components can be investigated as further step in the future research.

Bibliography

Aydin G (2015). Regression Models for Forecasting Global Oil Production. *Petroleum Science and Technology*, 1532-2459, ISSN: 1091-6466.
Buffa S, Cozzini M, D'Antoni M, Baratieri M, Fedrizzi R. (2019). 5th generation district heating and cooling systems: A review of existing. *Renewable and Sustainable Energy Reviews*,104, 504–522.

Cianciolo M (2016). Studio di fattibilità di una rete di teleriscaldamento/teleraffrescamento a Termini Imerese, thesis project of, Politecnico di Milano, 2015/2016 academic year.

Di Pietra B, Pazzola L, Puglisi G, Zanghirella F (2013). Metodologia di valutazione avanzata delle prestazioni di reti energetiche termiche, Ricerca di Sistema Elettrico ENEA, Report RdS/PAR2013/052.

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Brussels: Official Journal of the European Union; 2010.

Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency Brussels: Official Journal of the European Union; 2012.

Elsayed MA, Matthews R, Mortimer ND (2003). Life cycle analysis data from: Carbon and energy balances for a range of biofuels options. Study for DTI URN 03/836.

Euroheat & Power. Country by Country Survey. Brussels; 2017.

European Commission. Joint Research Centre, and European Technology Platform on Renewable Heating and Cooling (RHC-Platform), 2020–2030–2050, common vision for the renewable heating and cooling sector in

Europe: European technology platform on renewable heating and cooling. Luxembourg: EUR-OP; 2011.

F. Nardecchia, S. Minniti, F. Bisegna, L. Gugliermetti G., Puglisi. An alternative tool for the energy evaluation and the management of thermal networks: The exergy analysis. 16th International Conference on Environment and Electrical Engineering, EEEIC 2016; Florence; Italy; 7 June 2016 through 10 June 2016; Category numberCFP1651I-CDR; Code 123530.

Frederiksen S. and Werner S (2014). District heating and cooling. Lund: Studentlitteratur.

Gestore dei Servizi Energetici (GSE), December 2016.Valutazione del potenziale nazionale e regionale di applicazione della cogenerazione ad alto rendimento e del teleriscaldamento efficiente.

Gonzalez A., Riba JR, Puig R, Navarro P (2015). Review of micro- and small-scale technologies to produce electricity and heat from Mediterranean forests' wood chips. *Renew Sustain Energy Rev*;43:143-55.

Hemmati M, Mirzaei MA, Abapour M, Zare K, Mohammadivatloo B, Mehrjerdi H, Marzband M (2021). Economic-environmental analysis of combined heat and power-based reconfigurable microgrid integrated with multiple energy storage and demand response program. *Sustainable Cities and Society 69*, 102790.

Indagine conoscitiva sul settore del teleriscaldamento (IC46), Autorità Garante della Concorrenza e del Mercato.

Lund H, Möller B, Mathiesen BV, Dyrelund A (2010). The role of district heating in future renewable energy systems. *Energy*, 35(3), 1381-1390.

Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F,. Mathiesen BV (2014). 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. *Energy*, 68, 1-11.

Manni M, Petrozzi A, Nicolini A, Cotana F. (2012). District heating thermal plant fed by biomass residues in a rural area of Central Italy. IOP Conf. Ser.: Mater. Sci. Eng., 609 062012.

Mattoni B, Mangione A, Pompei L, Bisegna F, Domenico I, Spinelli F, Zinzi M 82019). An alternative method for the assessment of the typical lighting energy numeric indicator for different outdoor illuminance conditions”, Building Simulation Conference Proceedings, 2, pp. 1224–1230.

Mehregan M, Abbasi M, Majid Hashemian S (2022). Technical, economic and environmental analyses of combined heat and power (CHP) system with hybrid prime mover and optimization using genetic algorithm. *Sustainable Energy Technologies and Assessments*, 49, 101697.

Millar MA, Burnside N M, Yu Z (2019). District Heating Challenges for the UK. *Energies*, 12, 310; doi:10.3390/en12020310.

Nardecchia F, Pompei L, Bisegna F (2022). Environmental parameters assessment of a new diffuser for air cooling/heating system: Measurements and numerical validation. *Building Simulation*, 15, 6, 1111 – 1132.

Pompei L, Blaso L, Fumagalli S, Bisegna F (2022). The impact of key parameters on the energy requirements for artificial lighting in Italian buildings based on standard EN 15193-1:2017. *Energy and Buildings*, 263, 112025.

Pompei L, Nardecchia F., Mattoni B, Gugliermetti L, Bisegna F (2019). Combining the exergy and energy analysis for the assessment of district heating powered by renewable sources. International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe, (Genoa) - (978-172810652-6).

Ravina M, Panepinto D, Zanetti M.C, Genon G (2017). Environmental analysis of a potential district heating network powered by a large-scale cogeneration plant. *Environ Sci Pollut Res*, 24:13424–13436 DOI 10.1007/s11356-017-8863-2.

Sanayea S, Khakpaay N, Chitsazb A (2020). Thermo-economic and environmental multi-objective optimization of a novel arranged biomass-fueled gas engine and backpressure steam turbine combined system for pulp and paper mills. *Sustainable Energy Technologies and Assessments 40*, 100778.

Sartor k, Quoilin S, Dewallef P (2014). Simulation and optimization of a CHP biomass plant and district heating network. Applied Energy, 2014, 130 474–483.

Sharifi A and Y. Yamagata Y (2016). Principles and criteria for assessing urban energy resilience: A literature review. *Renewable and Sustainable Energy Reviews*, 60,1654–1677.

Smith D.A, Mago Pedro J, Nelson F (2013). Benefits of thermal energy storage option combined with CHP system for different commercial building types. *Sustainable Energy Technologies and Assessments* 1, 3–12.

Soltero VM, Chacartegui R, Ortiz C, Velazquez R (2016). Evaluation of the potential of natural gas district heating cogeneration in Spain as a tool for decarbonisation of the economy. *Energy*, 115, 3, 1513-1532, https://doi.org/10.1016/j.energy.2016.06.038

Teleriscaldamento: tecnologie, vantaggi e aspetti normativi, AEES (Agenzia per l'Energia e lo Sviluppo Sostenibile di Modena), Mariagrazia Mazza, Marcello Antinucci, Mauro Brolis, March 2006.

Toscano G, Duca D, Foppa Pedretti E, Pizzi A, Rossini G, Mengarelli C, Mancini M. Investigation of woodchip quality: Relationship between the most important chemical and physical parameters, Energy, 2016, 106, 38-44.

UNI 10339: Impianti aeraulici ai fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura.

UNI CEI EN 16247-1:2012: Energy audits - Part 1: General requirements.

UNI/TS 11300-1: Evaluation of energy need for space heating and cooling.

UNI/TS 11300-2: Evaluation of primary energy need and of system efficiencies for space heating, domestic hot water production, ventilation and lighting for non-residential buildings.

Vesterlund M, Toffolo A, Dahl J (2016). Simulation and analysis of a meshed district heating network. Energy *Conversion and Management*, 122, 63-73, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2016.05.060.

Vio M (2009). Impianti di cogenerazione, Editoriale Delfino.

Werner S (2017). International review of district heating and cooling. *Energy*, 137:617-31. https://doi.org/10.1016/j.energy.2017.04.045

World energy balances: Overview, International Energy Agency (IEA), 2018 edition.

Appendix A

Buildings stratigraphy's.

- Stratigraphy A

External wall (Stratigraphy A)				
Layer	Thickness [cm]	Thermal conductivity [W/(m·K)]	Thermal resistance [(m²·K)/W]	Frontal mass [kg/m²]
Internal superficial resistance	-	-	0.13	-
Internal plaster	2	0.70	0.03	16
Stone blocks	70	2.40	0.29	
External plaster	2	0.70	0.03	16
External superficial resistance	-	-	0.04	-
Thermal transmittance	**1.951**	**W/(m²·K)**		

Slab covering (Stratigraphy A)				
Layer	Thickness [cm]	Thermal conductivity [W/(m·K)]	Thermal resistance [(m²·K)/W]	Frontal mass [kg/m²]
Plaster	2	0.70	0.03	16
Garret	22	0.66	0.33	396
Expanded clay	5	0.27	0.19	45
Screed	3	1.40	0.02	12
Concrete structure	3	1.40	0.02	60
Thermal transmittance	**1.322**	**W/(m²·K)**		

Ground floor (Stratigraphy A)				
Layer	Thickness [cm]	Thermal conductivity [W/(m·K)]	Thermal resistance [(m²·K)/W]	Frontal mass [kg/m²]
Cobblestones	18	0.70	0.26	270
Garret	18	0.60	0.30	324
Clay	6	0.12	0.50	27
Screed	3	0.90	0.03	54
Tile	2	1.00	0.02	46
Thermal transmittance	**0.806**	**W/(m²·K)**		

Single glass window (Stratigraphy A)		
Type of glass	Untreated single glass of 4 mm, thermal cond. 1 W/(mK)	
Transmittance of glass	5.747	W/(m²·K)
Emissivity of glass	0.85	-
Type of frame	Frame of softwood, density 500 kg/m³	

Transmittance of frame	2.03	W/(m²·K)
Frame ratio	0.24	-
Thermal transmittance	**4.855**	**W/(m²·K)**

- Stratigraphy B

External wall (Stratigraphy B)				
Layer	Thickness	Thermal conductivity	Thermal resistance	Frontal mass
	[cm]	[W/(m·K)]	[(m²·K)/W]	[kg/m²]
Plaster	2	1.40	0.01	40
Pot bricks	8	0.90	0.09	160
Air chamber	20	0.03	0.16	0.206
Bricks	12	0.72	0.17	216
Thermal transmittance	**1.169**	**W/(m²·K)**		

Slab covering (Stratigraphy B)				
Layer	Thickness	Thermal conductivity	Thermal resistance	Frontal mass
	[cm]	[W/(m·K)]	[(m²·K)/W]	[kg/m²]
Plaster	3	0.70	0.04	24
Garret	18	0.60	0.30	324
Semi-rigid panels	3	0.05	0.65	0.48
Screed	3	1.40	0.02	12
Concrete surface	3	1.40	0.02	60
Thermal transmittance	**0.828**	**W/(m²·K)**		

Ground floor (Stratigraphy B)				
Layer	Thickness	Thermal conductivity	Thermal resistance	Frontal mass
	[cm]	[W/(m·K)]	[(m²·K)/W]	[kg/m²]
Cobblestones	18	0.70	0.26	270
Garret	30	0.73	0.41	540
Semi-rigid panels	5	0.05	1.09	0.8
Screed	3	0.90	0.03	54
Tile	2	1.00	0.02	46
Thermal transmittance	**0.516**	**W/(m²·K)**		

Single glass window (Stratigraphy B)		
Type of glass	Untreated single glass of 4 mm, thermal cond. 1 W/(mK)	
Transmittance of glass	5.747	W/(m²·K)
Emissivity of glass	0.85	-
Type of frame	Frame of softwood, density 500 kg/m³	
Transmittance of frame	2.03	W/(m²·K)
Frame ratio	0.24	-

Thermal transmittance		**4.855**	**W/(m²·K)**

- Stratigraphy C

External wall (Stratigraphy C)				
Layer	Thickness	Thermal conductivity	Thermal resistance	Frontal mass
	[cm]	[W/(m·K)]	[(m²·K)/W]	[kg/m²]
Lime and plaster	1	0.70	0.01	14
Concrete with natural aggregates - closed structure (mv2400)	30	1.91	0.16	720
Extruded expanded polystyrene	8	0.03	2.48	4
Lime or lime and cement grout	1	0.90	0.01	18
Thermal transmittance	**0.352**	**W/(m²·K)**		

Slab covering (Stratigraphy C)				
Layer	Thickness	Thermal conductivity	Thermal resistance	Frontal mass
	[cm]	[W/(m·K)]	[(m²·K)/W]	[kg/m²]
Insulation	9	0.04	2.31	
Lightweight aggregate concrete	4	0.25	0.16	
Cement and bricks	24	0.49	0.49	
Plaster	1	0.70	0.01	24
Thermal transmittance	**0.32**	**W/(m²·K)**		

Ground floor (Stratigraphy C)				
Layer	Thickness	Thermal conductivity	Thermal resistance	Frontal mass
	[cm]	[W/(m·K)]	[(m²·K)/W]	[kg/m²]
Pavement	1.5	1.47	0.01	46
Cement grout	3	0.70	0.04	18
Aggregate concrete	10	1.16	0.08	
Gravel	30	1.20	0.25	
Thermal transmittance	**0.3879**	**W/(m²·K)**		

Double glass window (Stratigraphy C)		
Type of glass	Superficially treated double glass of 4 mm with a gap filled with argon of 16 mm	
Transmittance of glass	1.14	W/(m²·K)
Emissivity of glass	0.1	-
Type of frame	Frame of PVC with empty three-chamber profile	
Transmittance of frame	2	W/(m²·K)
Frame ratio	0.24	-
Thermal transmittance	**1.622**	**W/(m²·K)**

Appendix B

- Economical and financial evaluation

CASE A (Purchased woodchips)			Sersale	Cerva	Petronà	Andali	Zagarise	Magisano	TOTAL
Cogenerator	Investment	€	2500000	2000000	2500000	2000000	2500000	1500000	13000000
	TOTAL COST OF INVESTMENT	€	2500000	2000000	2500000	2000000	2500000	1500000	13000000
	O&M	€/year	57967	46375	57967	46375	57967	34783	301434
	Fuel	€/year	557912	446294	557912	446294	557912	334765	2901088
	TOTAL RUNNING COSTS	€/year	615879	492669	615879	492669	615879	369548	3202522
Boiler	Investment	€	1530000	289000	680000	272000	476000	263500	3510500
	TOTAL COST OF INVESTMENT	€	1530000	289000	680000	272000	476000	263500	3510500
	O&M	€/year	88620	16737	39390	15753	27570	15261	203331
	Fuel	€/year	306618	57918	136235	54512	95382	52809	703474
	TOTAL RUNNING COSTS	€/year	395238	74655	175625	70265	122952	68070	906805
Network tank	Investment	€	160000	56000	120000	56000	80000	56000	528000
Distribution network	Pipes	€	231174	87475	142560	85266	121284	70173	737932
	Users substations	€	282546	106913	174240	104214	148236	85767	901916
	Auxiliaries	€	222612	84235	137280	82108	116792	67574	710601
	TOTAL COST OF INVESTMENT	€	736332	278623	454080	271588	386312	223514	2350449
	Pumping	€/year	68496	25918	42240	25264	35936	20792	218646
	O&M	€/year	93540	35395	57684	34501	49075	28394	298589
	TOTAL RUNNING COSTS	€/year	162036	61313	99924	59765	85011	49186	517235
Fees for experts		€	492633	262362	375408	259959	344231	204301	1938895
Salaries for workers		€/year	144000	115200	144000	115200	144000	86400	748800
TOTAL INVESTMENT		€	5418965	2885985	4129488	2859547	3786543	2247315	21327844
TOTAL RUNNING COSTS		€/year	1317152	743837	1035428	737899	967842	573204	5375362

CASE B (Purchased woodchips)			Sersale	Cerva	Petronà	Andali	Zagarise	Magisano	TOTAL
Cogenerator	Investment	€	2000000	1500000	2000000	1500000	2000000	1500000	10500000
	TOTAL COST OF INVESTMENT	€	2000000	1500000	2000000	1500000	2000000	1500000	10500000
	O&M	€/year	46375	34783	46375	34783	46375	34783	243474
	Fuel	€/year	446	335	446	335	102	335	1999
	TOTAL RUNNING COSTS	€/year	46821	35118	46821	35118	46477	35118	245473

Boiler	Investment	€	1530000	510000	680000	510000	510000	510000	4250000
	TOTAL COST OF INVESTMENT	€	1530000	510000	680000	510000	510000	510000	4250000
	O&M	€/year	88620	29538	39390	29538	29538	29538	246162
	Fuel	€/year	306600	102210	136290	102210	102210	102210	851730
	TOTAL RUNNING COSTS	€/year	395220	131748	175680	131748	131748	131748	1097892
Network tank	Investment	€	160000	56000	120000	56000	80000	56000	528000
Distribution network	Pipes	€	219240	93080	137268	93080	106699	93080	742446
	Users substations	€	267960	113764	167772	113764	130409	113764	907434
	Auxiliaries	€	211120	89632	132184	89632	102747	89632	714948
	TOTAL COST OF INVESTMENT	€	698320	296476	437224	296476	339855	296476	2364828
	Pumping	€/year	64960	27579	40672	27579	31614	27579	219984
	O&M	€/year	88711	37663	55543	37663	43173	37663	300416
	TOTAL RUNNING COSTS	€/year	153671	65242	96215	65242	74788	65242	520400
Fees for experts		€	438832	236248	323722	236248	292985	236248	1764283
Salaries for workers		€/year	144000	108000	144000	108000	144000	108000	756000
TOTAL INVESTMENT		€	4827152	2598724	3560946	2598724	3222840	2598724	19407111
TOTAL RUNNING COSTS		€/year	739712	340108	462716	340108	397013	340108	2619765

CASE A (Purchased woodchips)			**Sersale**	**Cerva**	**Petronà**	**Andali**	**Zagarise**	**Magisano**
Electric energy	Marginal cost for investment	€/MWhel	7.01	6.62	6.73	6.61	6.66	6.65
	Marginal cost for O&M	€/MWhel	12.19	12.19	12.19	12.19	12.19	12.19
	Marginal cost for fuel	€/MWhel	67.87	67.87	67.87	67.87	67.87	67.87
	LRMG	€/MWhel	87.07	86.69	86.80	86.68	86.73	86.72
		€/kWhel	0.0871	0.0867	0.0868	0.0867	0.0867	0.0867
Thermal energy	Marginal cost for investment	€/MWhth	6.70	6.77	6.78	6.81	6.76	6.83
	Marginal cost for O&M	€/MWhth	11.68	13.56	12.73	13.65	13.21	13.32
	Marginal cost for fuel	€/MWhth	13.54	20.47	16.69	20.89	18.68	19.17
	LRMG	€/MWhth	31.91	40.81	36.20	41.35	38.65	39.32
		€/kWhth	0.0319	0.0408	0.0362	0.0413	0.0386	0.0393

CASE B (Purchased woochips)			**Sersale**	**Cerva**	**Petronà**	**Andali**	**Zagarise**	**Magisano**
Electric energy	Marginal cost for investment	€/MWhel	7.14	6.77	6.80	6.77	6.71	6.77
	Marginal cost for O&M	€/MWhel	14.37	14.37	14.37	14.37	14.37	14.37
	Marginal cost for fuel	€/MWhel	67.87	67.87	67.87	67.87	67.87	67.87
	LRMG	€/MWhel	89.38	89.02	89.04	89.02	88.95	89.02
		€/kWhel	0.0894	0.0890	0.0890	0.0890	0.0890	0.0890
Thermal energy	Marginal cost for investment	€/MWhth	6.54	7.00	6.26	7.00	7.03	7.00

	Marginal cost for O&M	€/MWhth	11.77	13.13	12.83	13.13	13.64	13.13
	Marginal cost for fuel	€/MWhth	13.01	15.49	15.84	15.19	16.89	15.49
	LRMG	€/MWhth	31.33	35.63	34.93	35.32	37.57	35.63
		€/kWhth	0.0313	0.0356	0.0349	0.0353	0.0376	0.0356

Declaration of interests

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

AUTHORSHIP STATEMENT

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All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in Sustainable Energy, Grids and Networks.

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