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Title: A renewable energy scenario for a new low carbon settlement in Northern Italy: biomass district heating coupled with heat pump and solar photovoltaic system

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Keywords: Wooden Biomass; District Heating; Low-Carbon District; Multi-Energy Systems; Photovoltaic Systems; Heat Pumps

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Abstract: In the framework of the building sector de-carbonization, the case of a new nearly zero-energy district, located in the Milan urban area (Italy), is presented. In particular, the scope of the work is to demonstrate that the proposed energy concept, based on the combination of low-energy building design and high-efficiency technical systems, allows the reduction of the final energy uses. After the evaluation of the energy needs, a low-temperature and small-size wood biomass district thermal plant was designed to be integrated with groundwater heat pumps (GWHP) and solar photovoltaic (PV) systems, taking up the challenge to design an almost full-renewable urban district by means of a Multi-Energy System. The core is a biomass boiler coupled with a small combined heat and power (CHP) unit with a twin-screw steam expander (TSSE). The heat produced by the CHP satisfies a consistent fraction of space heating and domestic hot water (DHW) needs during the winter season. GWHPs coupled with PV satisfy remaining thermal needs in winter and the entire thermal needs in mid-season and in the summer period. The obtained outcomes prove the benefits of the combination of a wood biomass CHP with GWHPs and PV with a significant share of renewable energies.

Esteemed Editor,

We received the invitation for the special issue VSI: SDEWES2019 of Energy journal on behalf of Elsevier international and the organizing committee of the 14th Conference on Sustainable Development of Energy Water and Environmental Systems held in Dubrovnik on October 1 – 6, 2019.

The research aims to increase the scientific knowledge on multi-energy systems as well as the awareness on the combination of different programmable and non-programmable renewable energy sources in advanced energy systems for low-carbon districts.

Our research deals with energy analysis, energy modelling, renewables, biomass integrated energy systems and energy management. All these topics are proper of the multi-disciplinary scope of *Energy*.

The contents and topics treated in the article are mainly appealing to energy scientists, but the approach makes the reading affordable also to a wider audience of other stakeholders of the energy systems and buildings sector, in harmony with the aims of the Journal.

By the way, we had the paper looked at by a native English speaker for a linguistic review.

Sincerely,
The authors

***Declaration of Interest Statement**

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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Authors' replies to Reviewers

Authors are grateful at the reviewers for their useful suggestions to improve the manuscript and the appreciation of the work. Please find hereafter the detailed replies to each issue (text in red).

We kindly note that remarks reported by Reviewer #2 are the same provided in the previous review stage and were totally addressed, thus we assume that there was a mistake in reporting them again.

As a consequence, we address below just comments of Reviewer #5, modifying the manuscript according to his suggestions, as much as possible, even if Reviewer #5 himself specified that he was not involved in the first review of the original manuscript and recognized that previous comments were reasonably addressed by the authors.

Reviewer #5

In particular, the paper does not describe any novel and/or relevant methodology for the optimal integration of the renewable energy sources at play (solar, geothermal, biomass), such as sizing of single components and/or optimization of their operation or control, once the design is defined.

For example, sizing the biomass CHP plant to satisfy the peak heat demand is not always the best option, as has been shown by many other investigators, as it depends, amongst other, on the technology selected and its heat/electricity ratio and part load efficiency, the energy demand pattern, the storage and back up boiler options, the biofuel costs and baseline heat/power costs, etc. As I mention above, there is extensive literature on such optimal sizing of CHP and back-up boilers on the basis of several techno-economic factors.

In the first stage of the research, as clarified in the manuscript and in the References, other energy supply approaches were evaluated (e.g. including natural gas CHP, based only on BIPV and GWHPs, implying connection to near DH networks in operation etc.) and, after an economic, energy and environmental evaluation, the current configuration was selected. The energy sources to be exploited were proposed according to the local availability of renewables and to the willingness of the private investor, who promoted the intervention and the research (see section 3), to avoid as much as possible fossil fuels and to implement a low carbon district.

In particular, the available technical literature was considered to select this specific biomass-fired CHP system, e.g. the references cited in section 2.1, reference [41] and the following further studies:

- Lund et al. [*Lund, R., Østergaard, D. S., Yang, X., & Mathiesen, B. V. (2017). Comparison of low-temperature district heating concepts in a long-term energy system perspective. International Journal of Sustainable Energy Planning and Management, 12, 5-18.*] where five scenarios describing five configurations of DH, with a focus on different temperature levels and technologies, are evaluated and compared in terms of costs and benefits of each;

- Franco et al. [*Franco, A., & Versace, M. (2017). Optimum sizing and operational strategy of CHP plant for district heating based on the use of composite indicators. Energy, 124, 258-271.*] discussed the possible uses of CHP in district heating systems by highlighting the actual issues related to its design, generated by the available support mechanisms, both in sizing and management. The authors proposed guidelines for defining optimal operational strategies of CHP power plants assuming that the capacity of a CHP unit is actually based on a case by case optimization, rather than the adoption of any rule of thumb, due to the technical and economic limitations, and to the several parameters that affect the operation and economy of the system.

As reported in section 4, the size of the biomass system was selected "*to cover a considerable fraction of the space heating and DHW demand in the winter period, where solar energy is scarcely available, according to a synergistic operation with GWHPs"* coupled by BIPV.
The technology and the size of the CHP module have been assessed mainly by considering the hourly profile of the heat needs over the year and the quite low availability of small size CHP technologies in the market (see section 4.1). Moreover, as other studies (e.g. *Taljan, G., Verbič, G., Pantoš, M., Sakulin, M., & Fickert, L. (2012). Optimal sizing of biomass-fired Organic Rankine Cycle CHP system with heat storage. Renewable Energy, 41, 29-38*) point out, generally the installed thermal power of a CHP module should be considerably lower than the peak (1.8 MW for SH and DHW, in the current case study) to obtain desired rates of return on the investment. For these and other reasons explained in the manuscript, the TSSE technology was selected adopting the smallest size available on the market for similar application, resulting in 0.8 MW of thermal power and 0.1 MW of gross electric power. Further evaluations based on CHP of greater sizes demonstrated a less effective global balance than the previous one; this confirmed a sizing criteria aimed not to satisfy the peak heat demand, but rather the lower part of the demand profile (see also Fig. 4). This was therefore the first key point for sizing and managing the overall system referring to winter operation. GWHPs coupled with BIPV were assumed to integrate CHP heat for the winter peek and as back up, avoiding the economic, energy and environmental cost of a natural gas boiler and effectively exploiting the available renewables.
Regarding summer operation, we verified in the first design phase the low cost-effectiveness of a CHP coupled with absorption chillers for space cooling while keeping the existing TSSE for DHW. Thus, we decided to couple the GWHPs with BIPV, dimensioned according to the demand profile, as described in the manuscript and in the following answers. This was therefore the second key point for sizing and managing the overall system.
Regarding mid-seasons operation, our evaluations confirmed that the DHW production through GWHPs powered by BIPV is globally more effective than the operation of the TSSE. This was therefore the third key point for sizing and managing the overall system that includes the important role of the distributed storage systems for controlling the temperature levels along the year.
Based on these criteria, due to the flexibility of the TSSE technology, the CHP was assumed operating thermal driven, according to the space heating and DHW needs of the entire settlement, as explained in the manuscript (section 4 and subsections).

Again, sizing the BIPV according to the max installable power is another assumption that should be justified by a specific methodology in order to have scientific relevance, especially *since usually PV sizing is dependent on the demand/generation contemporaneity factor, electric storage options, net metering/feed in options and costs of electricity, again since we know from many other studies that it is not advisable to size based on max installable limits. At least the key factors and relevant literature in optimal sizing of these technologies should be discussed.*

The sizing criteria were added in section 4. In particular, it is based on 3 main assumptions:

1. the presence of the net metering mechanism, which allows to obtain a remuneration for the electricity fed into the grid;
2. the fact that in the analysed context the levelised cost of electricity (LCOE) from PV is approximately the half of the grid price, ensuring a high convenience of PV generation;
3. the presence in the district of additional electric loads not related to heating/cooling/DHW (e.g. electric vehicles charging stations) and of energy storage systems, which maximize instantaneous energy self-consumption.

Also, a comparison with baseload scenarios should be provided, with the quantification of energy and environmental benefits of the proposed solution.

As reported in the answer to the first comment, the performance of the settlement was already preliminarily assessed in a previous research work, according to different possible scenarios, including a baseline solution: the specific reference ([35]) is present in section 3. Among such scenarios, according to the peculiarities of the project (mix of residential and tertiary high performance buildings), to the context (available renewables) and to the project's objectives (willingness to avoid fossil fuels and to implement energy networks) the solution assessed in the present paper was selected as the best option, since it maximizes the share of renewables and minimizes the global cost (investment cost + running costs).

The district heating modelling is not described, while the profitability of the proposed system is highly dependent on the energy demand intensity, length of the heating/cooling network, and also temperature levels should be justified and are dependent on the heat distribution losses, HP seasonal COP, building energy efficiency and their heating systems.

The answers to the previous comments and the revisions included in the updated version of the manuscript (see section 4.2, 4.3 and 4.4 for the calculation of the COP and EER) may also explain the details here requested.

In addition, in the revised version of the manuscript (section 4) the heat density was presented in relation to the winter operation (in order find benchmarks in the technical literature on DH), demonstrating the appropriateness of the district system. Moreover, the particular design conditions of the case study should be taken into account about profitability and global effectiveness (e.g. the construction of concrete technical tunnels are included in the overall costs for the realization of the settlement).

Furthermore, it can be stated that the low temperature along the network, the innovative technology and the compactness of the grid allow a strong reduction of the heat distribution losses. However, since the heat distribution was not simulated, thermal losses were set around 10% of the gross heat produced according to a conservative approach (section 4.1).

The considerations reported above are in accordance to contributions available in technical literature, e.g. the cited references [16], [32], [37] and also according to Nord et al. [*Nord, N., Nielsen, E. K. L., Kauko, H., & Tereshchenko, T. (2018). Challenges and potentials for low-temperature district heating implementation in Norway. Energy, 151, 889-902*]. The authors compared eight district heating scenarios in order to assess the impact of different heat densities and operative temperature levels on network heat losses and pumping energy consumption.

Also, the possibility to integrate DHW heating and air conditioning in summer to increase COP is interesting, but it is not quantified nor properly described in the results.

A specific assessment on such topic was added at the end of section 4 and the obtained COPs were added. In detail, the average COP for DHW preparation during the typical summer day resulted equal to 5.6, which is significantly higher than that of the mid-season day, equal to 3.9. This demonstrates that the connection in series of the GWHPs providing space cooling to those providing DHW allows a consistent heat recovery, increasing the overall efficiency of the system.

The results only report the share of renewable energy with the assumed configuration, but the reader is left with further questions: What would be the optimal system configuration? What the actual benefits of the proposed systems in comparison to the alternatives?

As stated in the previous answer, such comparative analysis was carried out in a previous research work, that is cited in section 3, ref. 35.

The proposed case study neglects the opportunities offered by the recent Italian legislation, of the energy communities, where energy could be exchanged among the prosumers, while the paper explicitly says that this is not possible. It would be important to discuss these and why they were not considered given the case study is in Italy.

The sizing of the system started in 2016, when the concept of “energy community” had not yet been formalized. Authors are aware of the opportunities introduced by the recent legislation about energy communities, that is currently being implemented in Italy. However we prefer not to take in consideration such option in the paper, since there are still some points that must be clarified by the regulatory framework and also some limitations (e.g. maximum size of PV systems equal to 200 kW, incompatibility with the net metering mechanism, etc.). For sure, it could represent an additional advantage for the proposed scenario, further increasing the RES self-consumption.
In any case we agree with the reviewer about the need to mention such topic and a specific sentence was added at the end of the manuscript (see section 6).

In closing, I add that I was not involved in the review of the original manuscript and I do recognize that 3 other reviewers submitted comments that have been reasonably addressed by the authors. I would therefore suggest further major revisions to make the paper more *scientifically sound and evaluate how well the author have responded to the comments in the next round.*

Authors thank the reviewer for the useful comments; indeed, it is the second stage of the review process, and the comments of other 3 reviewers were already successfully addressed. Thus, we did our best to integrate new recommendations, consistently with previous suggestions and without significantly change the structure of the paper.

The Authors

A renewable energy scenario for a new low carbon settlement in Northern Italy: biomass district heating coupled with heat pump and solar photovoltaic system

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ABSTRACT

In the framework of the building sector de-carbonization, the case of a new nearly zero-energy district, located in the Milan urban area (Italy), is presented. In particular, the scope of the work is to demonstrate that the proposed energy concept, based on the combination of low-energy building design and high-efficiency technical systems, allows the reduction of the final energy uses. After the evaluation of the energy needs, a low-temperature and small-size wood biomass district thermal plant was designed to be integrated with groundwater heat pumps (GWHP) and solar photovoltaic (PV) systems, taking up the challenge to design an almost full-renewable urban district by means of a Multi-Energy System. The core is a biomass boiler coupled with a small combined heat and power (CHP) unit with a twin-screw steam expander (TSSE). The heat produced by the CHP satisfies a consistent fraction of space heating and domestic hot water (DHW) needs during the winter season. GWHPs coupled with PV satisfy remaining thermal needs in winter and the entire thermal needs in mid-season and in the summer period. The obtained outcomes prove the benefits of the combination of a wood biomass CHP with GWHPs and PV with a significant share of renewable energies.

KEYWORDS

Wooden Biomass; District Heating; Low-Carbon District; Multi-Energy Systems; Photovoltaic Systems; Heat Pumps.

ACRONYMS AND ABBREVIATIONS

BDHP – Biomass District Heating Plants
BIPV – Building-Integrated Photovoltaic
CHP – Combined Heat and Power
COP – Coefficient Of Performance
DH – District Heating
DHS – District Heating System
DHW – Domestic Hot Water
EER – Energy Efficiency Ratio
GSHP – Ground Source Heat Pump
GWHP – Groundwater Heat Pump
HP – Heat Pump

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LCOE - Levelized Cost of Electricity
LHD – Linear Heat Density
MES – Multi-Energy System
ORC – Organic Ranking Cycle
PE – Primary Energy
PM – Particulate Matter
PV – Photovoltaic
RES – Renewable Energy Sources
~~S/V – Surface to Volume Ratio~~
TSSE – Twin-Screw Steam Expander
ULT – Ultra-Low Temperature
~~WWR – Windows to Wall Ratio~~

1. INTRODUCTION

Nearly 40% of global energy-related CO_2 emissions are attributable to buildings and about two-third of this fraction is directly related to operational emissions [1]. The revised Energy Performance of Buildings Directive (EPBD 2018/844/EU) [2], amending the previous EPBD (2010/31/EU) [3], is aimed to increase the rate of building renovation and strengthen the energy requirements for new buildings, towards a more energy-efficient and smarter building sector. These aims are even more urgent in northern Italy where atmospheric emissions of pollutants and a number obsolete and low-efficiency domestic combustion systems are still in operation.

Nevertheless, the total electrification of the building sector, even if combined to the energy efficiency improvement, implies a huge increase of building-related electricity consumptions and peak power demand, which may overload the power grid [4], requiring strategies for load matching [5], load shifting [6] and peak demand reduction [7]. In this context, thermal and electric networks for smart districts or cities have a key role, allowing the interconnection of distributed energy resources (renewables, combined heat and power generators, etc.), storage systems, and loads (electrical and thermal), balancing the supply and demand locally. Such Multi-Energy Systems (MES) are able to couple weather dependant renewable energy sources with non-weather dependant ones (like biomass), reducing thus the use of storage technologies and increasing, at the same time, the reliability of the whole system [8]. Several examples of MES applied to buildings already proved the convenience of such strategy both in terms of energy consumption and in the reduction of the impact on the national grid [9]. In fact, in MES the production peak by RES will be entirely absorbed by electric systems and used to directly cover energy needs for heating/cooling/DHW of buildings or stored in the thermal/electric storage systems. In such regard, solutions at the district and urban level should consider bi-directional energy streams among buildings and electrical grids and thermal networks at different temperature levels [10]. However, the MES application is still limited, so the present work aims to increase the scientific knowledge on such topics as well as the awareness of the feasibility of advanced energy systems.

2. EVOLUTION OF DISTRICT HEATING SYSTEMS

District Heating Systems (DHS) have undergone an evolution and technological maturation [11] that placed them in an important position in the modern European carbon emissions mitigation challenges [12]. Referring to the European context, approximately 6,000 different systems can be found with a global distribution network's trench length of almost 200,000 km [13]. Several review studies carried out ~~in relation to~~concerning the European context provided a precious effort in the definition and classification of DHS evolution. A recognised classification identifies five different district heating (DH) generations. Following this scheme, the first and second generations were mainly fuelled by coal steam boilers and some examples of CHP and hot water on the users' side were directly heated up with steam or with pressurized high-temperature water (over 100°C). Following the technological evolution of emission systems in buildings (i.e. radiators, gradually working at lower temperature 70°C), and the reduction in the heat demand of buildings, the 3rd generation is characterized by reduced distribution temperatures (80-90°C) of water and is equipped with control and management technologies. First examples of large-scale CHP and integration between fossil and renewable fuels were shown up ~~Lund et al.~~ [14]. The evolution toward the recent 4th and 5th generations has been characterized by a further lowering of the distribution temperatures, higher energy efficiencies and integration with RES. The classification in different generations is ~~in fact~~ combined with another one based on the temperature levels, identifying high temperature, low temperature and ultra-low temperature systems. Indeed the adoption of low-temperature DH networks offers potential savings compared to high-temperature DH due to heat loss reduction and lower pumping energy demand [15]. The 5th generation of DHS presents the possibility to satisfy both heating and cooling demand for different buildings connected to the same grid [16]. The new generation DHS implies the integration of different energy sources, often RES or waste heat. This can be achieved for instance through the decentralization of heat pumps (HP), operating at low temperatures, which are able to meet the heating, cooling and DHW demand of each building, stabilize the power grid and facilitate the integration of different RES [17]. In addition, this configuration may enhance the exploitation of local RES, as PV systems installed on roofs or, in particular cases, wind farms, producing heat in combination with local CHP systems [18]. Further, the heat pump COP has increased thanks to lower operating temperatures [19]. The integration of different RES as biomass, PV and geothermal with heat pumps and solar thermal storage in MES has become attractive for district heating networks [20]. Hast et al. [21] studied the adoption of thermal energy storage in a CHP based DH plant, showing that large heat storage coupled with heat pumps helps to produce more renewable electricity and increase revenues, reducing impacts of electricity price fluctuation. Moreover, the integration of energy storage systems (ESS) with CHP based DH is very effective with more fluctuating thermal loads and higher RES penetration [22].

2.1. Weather dependant and non-weather dependant sources integration at district level ~~along~~across Europe: significant case studies

The feasibility and the benefits deriving from coupling weather dependant (e.g. solar) and non-weather dependant (e.g. biomass) renewable sources [23] are demonstrated through a large number of systems currently in operation. In Slough (United Kingdom), these concepts were applied in the development of mini DHS, where different renewable heat technologies are integrated with PV tiles and thermal storage [24]. The 10 single-family houses are supplied by 165 metres of pipes where water for heating purpose is kept at 55°C through the combined use of a biomass boiler, solar thermal collectors and heat pumps. DHW is provided at 43°C by instantaneous heat exchangers. Unless heat losses amounted to 28%, the system is able to cover 100% of the demand for heating and DHW from RES, representing a successful example of sustainable technology integration.

In Ludwigsburg (Germany) [25], a gas-fired CHP was integrated with a ground source heat pump (GSHP) and decentralized thermal storage. Particular attention was given to the sizing and management of heat generators and to the optimization of storages' charge strategy.

The housing area of Zum Feldlager in Kassel (Germany) [26] represents another interesting example of a low carbon district where geothermal heat is integrated with solar energy. With the adopted configuration, about 80% of heating and DHW energy needs are supplied by a

low-temperature district heating grid powered by RES. A centralized GSHP feeds the network with water at 40°C, while decentralized heat exchangers, solar collectors and thermal storages allow covering the DHW demand. Moreover, considering the Italian context, even if just few 4th generation systems are in operation, it worth to mention the case of 3 pilot projects that have been recently started coupling ultra-low temperature (ULT) networks, geothermal heat sources and HPs in substations. These systems are located in three small cities of the Province of Brescia, in Northern Italy. The first is in operation since 2018 and integrates geothermal heat and waste heat from the local industry. This DHS operates by a ULT network at 13°C. The second is in operation since 2014 and is equipped by a small ULT network providing heat to a school campus. The network is powered by a geothermal system exploiting groundwater and distribute heat to two substations equipped with HPs. The last is in operation since 2013 and consists in an ULT open-loop working at 12/8 °C in winter and 15/17 °C in summer supplied by a 90 kW GSHP coupled with a PV system of 20 kWp [27].
Within the RELaTED project [28], four case studies of multi-renewable sources district heating and cooling systems are implemented, with the aim to introduce innovative solutions for the design of decentralized ULT networks.

2.2. District heating systems in the Italian context: barriers and constraints

Despite the significant cases mentioned above, the diffusion of efficient DHS promoted at European level and the described evolution of the current existing plants toward multi-generative systems and low-temperature heating supply is still hampered by existing barriers related to the regulatory, administrative and economic difficulties. In particular, in Italy DH has been so far hindered by inappropriate energy policies and financial supporting scheme. According to 2019 annual report of AIRU ~~[29]~~[29], the national association of DH in Italy, 341 high-temperature DHS are in operation providing mostly space heating and Domestic Hot Water (DHW) services to 358 Mm^3 in terms of buildings volume for users in 198 cities along a total network length of 4,446 km.
As mentioned, these DHS are mainly fuelled by fossil fuels and characterised by high-temperature levels. Despite an important diffusion of such technologies and a fast growth of the sector between 2000 and 2013, most of the recent developments regard few extensions of existing networks, highlighting the stagnation of the sector and the difficulty to promote investments on new and advanced systems (i.e. 4th and 5th generation DH). This trend is in contrast to the directive 2012/27/CE ~~[30]~~[30], member states have been demanded to draft a potential evaluation and an associated policy strategy for the development of the DH sector ~~[29,31].~~[29,31]. Also concerning the one hundred Biomass District Heating Plants (BDHP), that currently satisfy only the 2-3% of the total Italian building heating demand with a total installed power of 614 MW$_t$ [32], only few examples can be categorized as 4th generation (Figure 1). Instead, the mentioned technical literature demonstrates that the integration of wood biomass in advanced 4th and 5th generation DHS can be a viable and pivotal solution toward de-carbonization, especially in 100% renewable new districts and even in urban contexts, which could benefit from higher linear heat density (LHD) of the grids and from the local availability of biomass by-products such as pruning from urban green areas. On the contrary, an unfavourable market of pellet and wood chip may limit the penetration of biomass-based technologies [33]. For this reason, the implementation of a well-designed biomass supply-chain is fundamental to ensure sustainable management from the economic and environmental point of view.

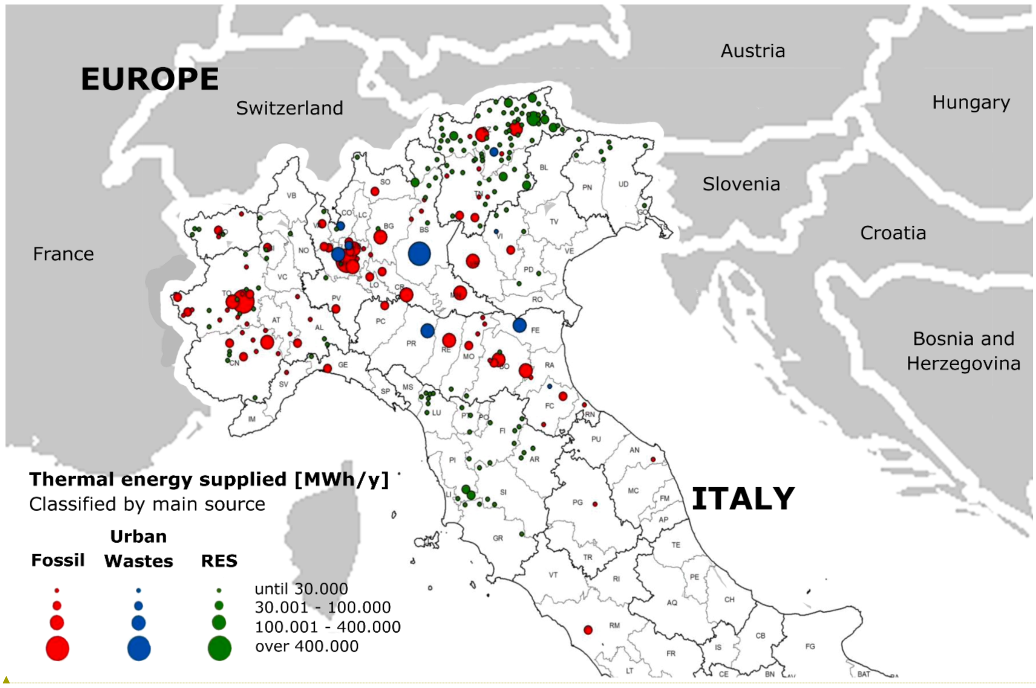

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Figure 1. Map of the Italian municipalities served by DHS, classified by the main energy source adopted (more than 50% of the primary energy adopted is provided by that source), adapted from [31].

Another barrier to the penetration of biomass DHS is related to air quality issues since the particulate matter (PM) emissions have become even more important in flat areas of northern Italy. This theme is much debated and represents a non-technical barrier versus biomass combustion. Oppositions to biomass combustion are justified if obsolete and low efficient domestic technologies are adopted, while they are inapposite in the case of BDHP that are always equipped with proper components and sections aimed at emissions control and abatement.

The study here presented lies exactly in this framework, presenting the design of a new district near Milan, in northern Italy, where weather dependant and non-weather dependant RES are integrated into an innovative multi-source network for providing heating, cooling and DHW.

3. CASE STUDY

According to the new definition of Smart City, based on a network of efficient buildings able to provide and consume energy on-site, a new neighbourhood called “Milano 4 You” is currently under development in the Milan urban area. In detail, the district is designed according to sustainability concepts, which can be considered an interesting example due to the adopted technologies in the planning phase.

Site	Milan
Latitude	45°
Heating Degree-Days	2645
Cooling Degree-Days	343
Max. temp. – July [°C]	31.9

Min. temp. – December [°C]	-6.9
Max. monthly global irradiation on the horizontal plane – July [kWh/m^2 month]	187
Min. monthly global irradiation on the horizontal plane – December [kWh/m^2 month]	27

Table 1. Representative parameters of the reference climatic context elaborated through Meteonorm Software [34].

The ~~performances~~performance of the settlement ~~were~~was already preliminarily ~~presented~~assessed in a previous research work, according to different possible scenarios [35]. ~~However, in the present paper the solution of~~Among them, according to the peculiarities of the project (mix of residential and tertiary high-performance buildings), to the context (available renewables) and to the project's objectives (willingness to avoid fossil fuels and to implement energy networks) the following solution was selected and assessed in detail.

It considers a generation plant able to integrate different RES, consisting of a small-size wooden biomass CHP system coupled with electric heat pumps and building-integrated photovoltaic (BIPV) systems~~, is assessed in detail.~~. Moreover, the reference data about buildings' energy demand has been updated according to the design novelties still in progress. ~~The dynamic energy~~Dynamic simulations~~ of the whole neighbourhood~~ have been performed in EnergyPlus [36] to estimate the energy needs of the buildings, considering two reference buildings that well represent the residential and non-residential destinations of the "Milano 4 You" district. The main features of the reference buildings are reported in Table 2.

According to the summarized boundary conditions, the energy demand of the two buildings has been calculated. The results were then extended to the total heated/cooled net floor area equal to 89,090 m^2 (64,490 m^2 residential and 24,600 m^2 non-residential).

	residential building	***non-residential building***
Surface/Volume [-]	*0.40*	*0.22*
Windows to wall ratio [%]	20%	30%
U opaque [W/m^{2}K]	0.2	0.18 (average)
U glazed [W/m^{2}K]	1.1	1.2
g [-]	0.8	0.52
Heating setpoint [°C]	20	20
Cooling setpoint [°C]	26	26
Infiltration [Vol/hr]	0.52	0.56 during occupation (8am to 8pm);
Internal gain [W/m^2]	2,3 W/m^2 (occupancy profile provided by SIA2024-2015)	6 W/m^2 (8am to 8pm);
Lighting	-	4 W/m^2 (Dimmerable)
Daylighting set point	-	300 lux on the work plan
Shutter	-	Venetian blinds
DHW demand	ASHRAE standards	-

Table 2. Main features of the reference buildings.

The total annual energy ~~demand~~need for heating, cooling and DHW are equal to 1,350 MWh, 3,300 MWh and 1,600 MWh, respectively. According to preliminary results of the design phase, a thermal power peak of about 1.8 MW is experienced during the heating season (Space heating and DHW). Therefore, the selection of a proper CHP size was hindered by the low availability of such low size solutions on the market.

The annual electric consumption of appliances in non-residential buildings amounts to 540 MWh.

It must be noted that electricity demand for home appliances was not considered in the analysis since, according to the current Italian regulation in force during the preliminary design of the settlement, it must be supplied by individual ~~POD~~PODs (Points of Delivery) and cannot be provided by a district generation system.

4. METHOD FOR THE HYBRID DISTRICT HEATING SYSTEM DESIGN

~~The~~According to the energy concept based on a network for thermal purposes, the configuration designed is mainly constituted by two water loops. As already introduced, the main generation system consists of a biomass boiler combined with a small CHP unit, able to satisfy ~~the~~ most of the space heating and DHW needs during its operation period in the heating season. Energy is provided to a water loop, maintained at 55°C, which is connected to the buildings by means of substations (the district heating system units that connect the network and internal building heating systems) with heat exchangers connected to buildings' distribution systems and DHW storages. ~~The~~Since the CHP is thermal driven, but not sized on the winter peak, the remaining part of thermal energy demand, not covered by the CHP during the winter, and the whole thermal need for DHW in mid-seasons, is provided by decentralized water-to-water heat pumps connected with a low-temperature district groundwater loop ~~with a length of approximately 1 km.~~. The length of both networks is approximately 1 km. Considering only the heat provided by the CHP during the winter season (space heating and DHW), the heat density of the network amount to 2.1 MWh/m, in line with the reality of district heating systems in operation in Italy [32]. In addition, a heat density of 1.5 MWh/m is reported as minimum threshold for DHS feasibility, attesting the appropriateness and the efficiency of the network design [37].

In the summer period, the entire cooling demand is covered by GWHPs which may indeed take advantage of the heat discharged by GWHPs for DHW connected in series to the same groundwater loop. Electricity needs ~~for the~~of heat pumps and ~~for~~ the electric appliances ~~of~~in office buildings are covered by the CHP electric output (during its operation period), by photovoltaic systems integrated on the roofs and by the grid, as the last option. The scheme of the energy supply concept is shown in Figure 2.

The BIPV systems are sized ~~in order~~ to cover a substantial part (80-100%) of the electricity demand of the heat pumps in the mid-seasons and in the cooling period and – more in general – to maximize the exploitation of solar energy. Such sizing criteria is based on 3 main assumptions:

1. the presence of the net metering mechanism, which allows to obtain a remuneration for the electricity fed into the grid;
2. the fact that in the analysed context the levelized cost of electricity (LCOE) from PV is approximately half of the grid price, ensuring a high convenience of PV generation;
3. the presence in the district of additional electric loads not related to heating/cooling/DHW (e.g. electric vehicles charging stations) and of energy storage systems, which maximize instantaneous energy self-consumption.

More in detail, it was considered that all the available surface of the buildings' roofs is covered with PV systems with a total peak power of 1660 kW$_p$. The size of the biomass system, which has a nominal thermal power of 800 kW and an electric power of 100 kW, was instead selected ~~in order~~ to cover a considerable fraction of the space heating and DHW demand in the winter period, where solar energy is scarcely available, according to a synergistic operation with GWHPs that is subsequently explained in detail. ~~Heat~~The selected heat pumps have a maximum power of 200 kW$_t$ each for ~~domestic~~residential buildings and 500 kW$_t$ for office buildings.

The DHW is prepared by mean of distributed heat exchangers installed in storage systems located in substations on the users' side secondary network, allowing to implement optimized charging profiles, maximizing the output of the CHP in the winter: storage tanks are heated when the space heating demand is low (thus using CHP energy); similarly, in summer and mid-seasons, storage tanks are heated when there is high PV generation.

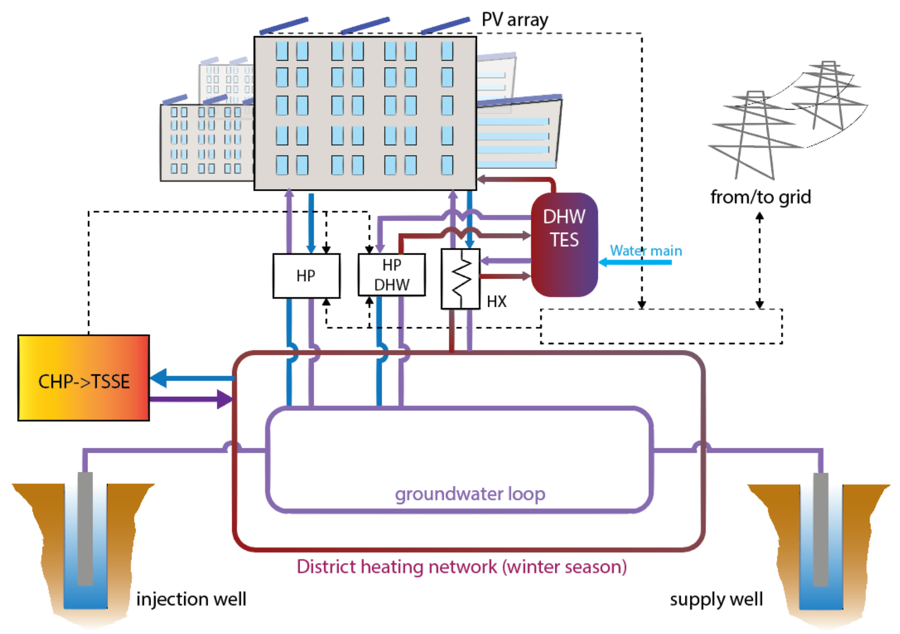

Figure 2. Scheme of the energy supply concept/strategy of the district.

4.1. Biomass CHP unit

The adoption of a CHP unit with a Twin-Screw Steam Expander (TSSE) was selected as the most feasible technology for energy conversion of wood biomass, according to techno-economic considerations. Stirling engines and pyrolysis-gasification coupled with gas cycles (gas turbine) were excluded because the experiences documented so far on a commercial scale are still too limited. Further, also conventional steam cycles are not proper at size lower than 1 electric MW and Organic Rankine Cycles (ORC), based on the same principle of steam turbines but using an organic working fluid, are in general expensive and characterised by complex and binding maintenance ~~[37]. Therefore, another available CHP technology was explored for the present application, the mentioned TSSE since it is more compact, cost-effective, robust and simple. According to the information provided by companies involved in this sector, TSSE systems, able to harness saturated process steam and generate electricity, have been experimented in Europe and in Italy in different cases with sizes between 75 and 200 kW of~~[38]. Therefore, another available CHP technology was explored for the present application, the mentioned TSSE since it is more compact, robust and simple. Moreover, as

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reported by [39], TSSE technology has proven to be a particularly cost-effective and reliable CHP solution when coupled with biomass boilers serving district heating networks. According to the information provided by companies involved in this sector, TSSE systems, able to harness saturated process steam and generate electricity, have been experimented in Europe and in Italy in different cases with sizes between 100 and 200 kW of net electric power.

The main components of the selected CHP system can be grouped in the following sections (as also shown in Figure 3): biomass storage section, combustion and steam generation section, TSSE section and treatment and expulsion of the flue gas.

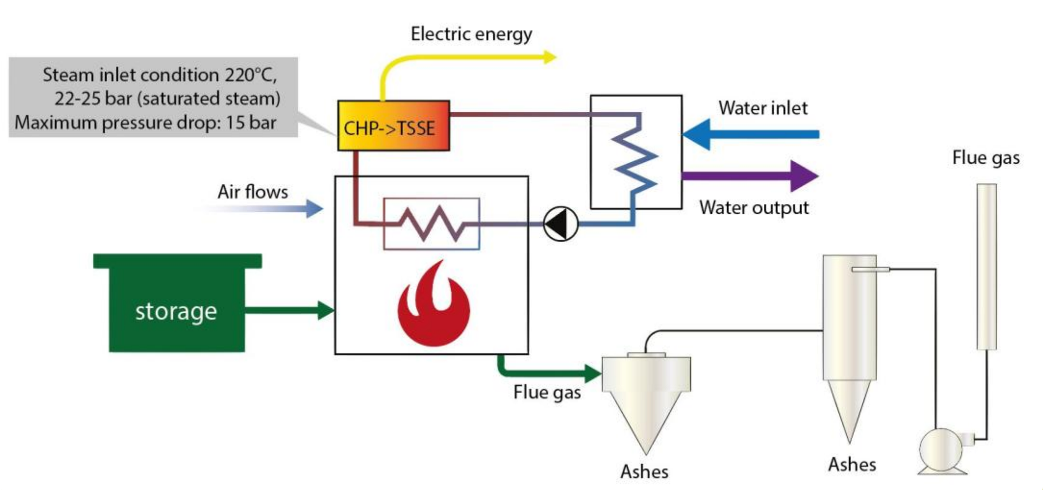

Figure 3. Scheme of the thermal power station with main components.

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TSSE systems are characterized by an optimal thermal performance, while it allows producing electricity with gross yields in the order of 10%. These systems are able to generate electricity by fully adapting to the boundary conditions ~~[38]. In particular, TSSE systems can provide tailored outputs from 70~~[40]. In particular, TSSE systems can provide tailored outputs from 75 to 630 kW of electric power and maintain stable performance even at partial load, according to the technical information provided by the manufacturers.

As already introduced, for the present case study, the size of the TSSE has been selected among market alternatives, according to the global needs of space heating and DHW of the district, based on an energy supply strategy that includes heat pumps and BIPV systems, with the aim to design a full-renewable district. ~~More in detail, the selected size refers, in nominal conditions, to input biomass~~Aware of the complexity of a proper selection of the size and operation mode of a CHP system, as described e.g. in [41], in the present case the minimum size available on the market of TSSE has been selected. It refers, in nominal conditions, to input biomass power of 1 MW, a gross electric power output of 100 kW and a net thermal power output of 800 kW, respectively. The electricity consumption for auxiliaries leads to an available electric net power of 85 kW.

According to the electric to thermal ratio of the selected TSSE (about 1 to 8), the operative mode is thermal driven, i.e. it follows the heating needs in winter. As it will be described in the following sections, the selected size allows to increase energy efficiency, primary energy and greenhouse gases savings and economic effectiveness, according also to [41]. Back up boilers are not envisaged in this case, since the presence of GWHPs allow the robustness and redundancy of the overall system. From the electric point of view, there are two main loads in the district (electricity for HP operations and for electric appliances in the office buildings) and three sources (CHP, BIPV and the national grid). According to the main design criteria, such elements are matched ~~in order~~ to minimize the electricity interchanged with the national grid. Furthermore, given the small number of monitored 4th and 5th generation networks, it is not possible to provide a typical range of heat losses along with the network. However, in line with the ranges of values (5-15%) provided by [16], a constant average value of 10% has been conservatively assumed for heat losses along with the distribution network for the whole operating period of the CHP. This value is also in accordance with [32], where a range of 10-15% of heat loss is reported for the most efficient 3rd generation DHS. Actual monitoring results that will be collected during the first year of district operation will be used to determine the heat losses in each condition.

4.2. Reference days

The performance of the abovementioned system has been evaluated in three reference days, which were selected as representative of the 3 different typical load conditions, as it follows:

- winter day, where significant space heating thermal loads are present (min/max external temperatures 0°C/5°C), together with DHW loads;
- summer day, where significant space cooling thermal loads are present (min/max external temperatures 18°C/34°C), together with DHW loads;
- mid-season day, where there are no space heating/cooling loads (min/max external temperatures 8°C/13.5°C) and just DHW loads are present.

These days are representative of the winter, mid and summer season, respectively. They have been selected because the first is the day with the average heating demand during the coldest months, the second has the average cooling demand in the hottest month and the last is a typical day during the mid-season, where DHW is the unique thermal load.

4.3. Control strategy in the winter season

The 3 different load conditions are handled with 3 different control strategies. During the winter season, the CHP module operates to cover thermal needs, i.e. space heating and DHW. Most ~~part~~ of the heat demand is covered by the CHP module’s thermal output while the remaining one is satisfied by the GWHPs, powered by the electricity output of the CHP module. Therefore, electricity produced by the CHP is assumed to be fully exploited for the operation of the GWHPs and auxiliaries.

Taking into account the nominal performance of the TSSE (85 kW net electric power and 800 kW net thermal power) and the ~~weighted~~ nominal COP of the GWHPs in the specific operating conditions~~ (groundwater at 15°C and supply water at 35°C for SH and 55°C for DHW),~~, the maximum heat power available results 1,225 kW, calculated by Equation 1 as it follows:

$$Q'_{max,CHP}[kW] = Q'_{FL\_CHP}[kW] + \left(E'_{FL\_CHP} \times COP\right)[kW] \qquad (1)$$

Where:

$Q'_{max,CHP}[kW]$ is the maximum thermal power provided by CHP and GWHPs powered just by electricity from CHP;

$Q'_{FL\_CHP}[kW]$ is the thermal power provided by CHP in operation at full load;

$E'_{FL\_CHP}[kW]$ is the electric power provided by CHP in operation at full load;

COP is the ~~maximum~~ coefficient of performance of the GWHPs in winter operation~~, set equal to 5~~.

According to the dynamic simulation of the energy behaviour of the buildings included in the settlement, the thermal power peak in winter is 1,790 kW. During the typical winter day, the ~~hourly~~thermal needs (space heating ~~needs~~+ DHW) range from ~~177~~549 kWh to 1,~~256~~399 kWh. This ~~peak value~~last is ~~very close to~~higher than the maximum heat that can be provided as a sum of cogenerated heat and heat provided by GWHPs powered by cogenerated electricity. Therefore, in some hours, when the thermal needs are equal or higher than 1,225 kWh per hour, the CHP works at full load (Equation 2), while in others, when the thermal needs are lower than ~~1225~~1,225 kWh per hour, it works at partial load (Equation 3). Thanks to the configuration of the supply system, the thermal needs exceeding 1,225 kWh per hour are provided by the GWHPs powered by BIPV electricity, when available, or by electricity from the national grid (Equation 2).

$$Q_{users\_W}[kWh] = Q_{FL\_CHP}[kWh] + \left[\left(E_{FL\_CHP} + E_{BIPV} + E_{N\_Grid}\right) \times COP\right][kWh] \qquad (2)$$

~~$Q_{users}[kWh]$~~

$$Q_{users\_W}[kWh] = Q_{PL\_CHP}[kWh] + \left(E_{PL\_CHP} \times COP\right)[kWh] \qquad (3)$$

Where:

Q_{users_W} are the buildings thermal needs in winter;
Q_{FL_CHP} is the heat provided by CHP in operation at full load;
Q_{PL_CHP} is the heat provided by CHP in operation at partial load;
E_{FL_CHP} is the electricity provided by CHP in operation at full load;
E_{PL_CHP} is the electricity provided by CHP in operation at partial load;
E_{BIPV} is the electricity provided to the GWHPs by BIPV;
E_{N_Grid} is the electricity provided to the GWHPs from the national grid;
COP is the coefficient of performance of the GWHPs in winter operation.

The COP of the GWHPs has been evaluated considering the operating temperature levels (i.e. groundwater at 15°C and supply water at 35°C for space heating and 55°C for DHW) and the specific curve of performance of a commercial GWHP with the assumed sizes. A weighted COP has been calculated as described in Equation (4), resulting in a value of 5 in winter conditions.

$$COP = \frac{Q_{SH}}{(Q_{SH}+Q_{DHW})} \times COP_{SH} + \frac{Q_{DHW}}{(Q_{SH}+Q_{DHW})} \times COP_{DHW} \qquad (4)$$

Where:

Q_{SH} is the heat demand for space heating of all the buildings;
Q_{DHW} is the heat demand for DHW of all the buildings;
COP_{SH} is the GWHPs COP for space heating (output temperature: 35°C);
COP_{DHW} is the GWHPs COP for DHW preparation (output temperature: 55°C);

The CHP module’s size and control logic have been designed in a way to maximize the exploitation of the cogenerated heat and thus minimize heat dissipation. On average, during the typical winter day, the CHP operation is at 82% of its full load. Further, also considering the consumption of electric appliances in commercial buildings, excess PV electricity and electricity from the national grid can be minimized.

4.4. Control strategy in mid-seasons and summer

During mid-seasons, when DHW is the only thermal need, the CHP unit is switched off and DHW is provided as follows (Equation ~~4~~5).

$$Q_{DHW}[kWh] = \left[\left(E_{BIPV} + E_{N\_Grid}\right) \times COP\right][kWh]$$ (~~4~~5)

Where:

Q_{DHW} are the DHW thermal needs at the users' side;
E_{BIPV} is the electricity provided to the GWHPs by BIPV;
E_{N_Grid} is the electricity provided to the GWHPs from the national grid;
COP is the average coefficient of performance of the GWHPs in mid-season operation.

In this case, the COP of the GWHPs has been evaluated considering as operating temperature levels groundwater at 15°C and supply water at 55°C for DHW, resulting in a value of 3.9.
As already mentioned, the presence of DHW storage tanks allows the optimization of the charging strategy when there is high PV production, improving the load-matching between DHW needs and BIPV electricity generation. Also, in this case, the global balance takes into account the consumption of electric appliances in commercial buildings.
In summer, i.e. when cooling and DHW needs occur, the CHP unit is kept switched off and thermal needs are provided as follows (Equation ~~5~~6 and 7).

$$Q_{users\_S}[kWh] = \left[\left(E_{BIPV} + E_{N\_Grid}\right) \times EER\right][kWh]$$ (6)

$$Q_{DHW\_S}[kWh] = \left[\left(E_{BIPV} + E_{N\_Grid}\right) \times COP\right][kWh]$$ (~~5~~7)

Where:

Q_{users_S} are the buildings thermal needs for space cooling in summer;
Q_{DHW_S} are the DHW thermal needs at the users' side in summer;
E_{BIPV} is the electricity provided to the GWHPs by BIPV;
E_{N_Grid} is the electricity provided to the GWHPs from the national grid;
EER is the energy efficiency ratio of the GWHPs in summer operation.
COP is the coefficient of performance of the GWHPs in summer operation.

~~In the summer period,~~Analogously to winter operation, the EER of the GWHPs has been evaluated considering the operating temperature levels, i.e. groundwater at 15°C and supply water at 7°C for space cooling, resulting in a value of 7.1. For DWH production instead, the hourly COP was calculated based on the temperature difference between 55°C (DHW production) and the specific hourly discharging temperature of heat pumps dedicated to space cooling. In detail, the average COP for DHW preparation during the typical summer day resulted equal to 5.6, which is significantly higher than that of the mid-season day, equal to 3.9. This demonstrates that the connection in series of the GWHPs providing space cooling to those providing DHW allows a consistent heat recovery, increasing the overall efficiency of the system. In some conditions, where there is a good balance between cooling and DWH load, the groundwater loop can be also hydraulically isolated from wells with a significant additional energy saving.

5. RESULTS AND DISCUSSION

As introduced, in this phase of the research detailed energy simulations have been carried out in 3 reference days. The main obtained results are reported and commented hereafter.

In detail, in the reference winter day, the 62% of the total thermal energy demand (space heating and DWH) is covered by the CHP output, while the remaining 38% is supplied by the GWHPs; the 68% of the electricity needed from the latter to cover the thermal energy demand is represented by the CHP electric output. In total, just 17% of the daily electricity demand (GWHPs and electric needs in office buildings) is taken from the national grid, thus the remaining part is provided by the CHP supply and the PV supply. Lastly, the amount of electricity sold to the grid is equal to 16.5% of the PV daily generation.

In brief, the obtained results confirm the effectiveness of the control strategy described in the previous section, because the proposed configuration and operation logic ensures the total hourly self-consumption of the thermal and electrical production of the CHP unit while minimizing the electricity interchange with the grid.

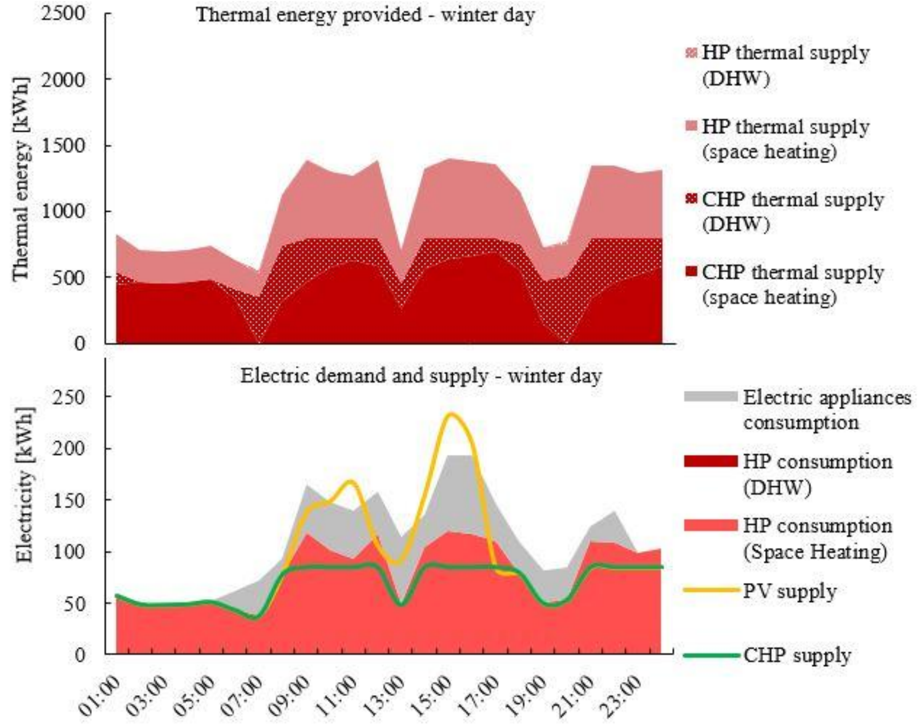

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Figure 4. Thermal and electric results for the reference winter day.

In the reference mid-season day instead, the low thermal load (just DHW) and the adopted strategy to charge the DHW storages in the central hours of the day, allow the full coverage by using just the GWHPs, which are mainly powered by PV energy. ~~In fact, just~~Just 13.5% of the daily electricity demand (GWHP and electric needs in office buildings) is taken from the national grid, while the electricity sold to the grid is equal to 27% of the PV daily generation. The results are represented in Figure 5.

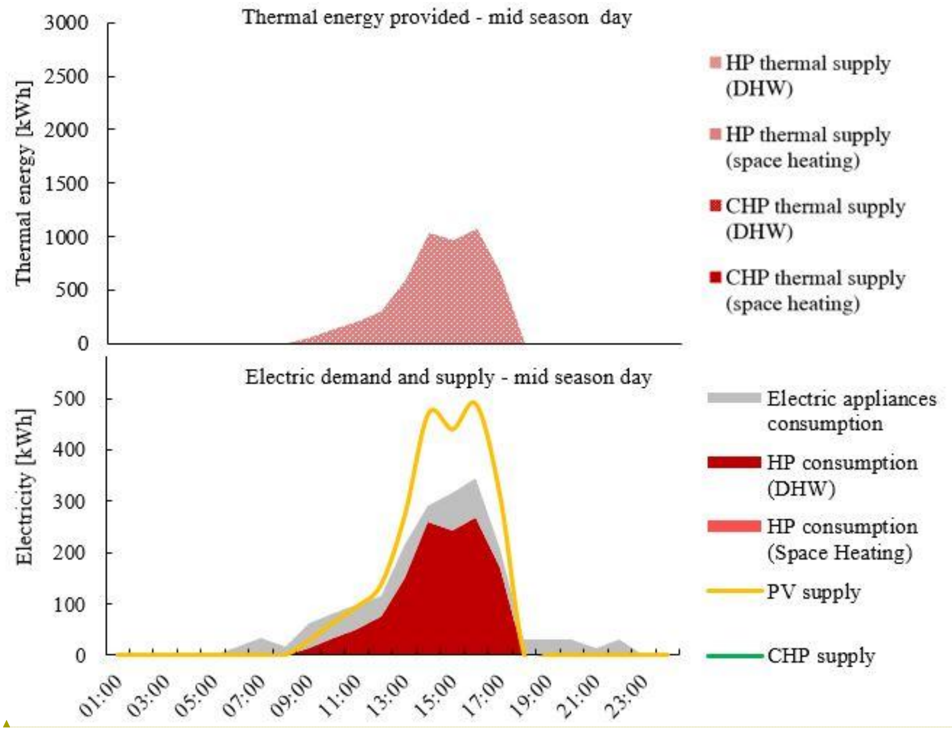

Figure 5. Thermal and electric results for the reference mid-season day.

Lastly, in the reference summer day, there is a high availability of PV electricity, which is in phase with space cooling load, electric load in office buildings and with the proposed charging profile of DHW storages. Moreover, the use of groundwater loop with GWHPs for space cooling connected in series with those for DHW preparation allows a considerable heat recovery and an estimated saving on the electricity consumption for DHW equal to 43% (compared to an option with GWHPs connected to independent groundwater wells). This way, 32% of the daily electricity demand (GWHPs and electric loads in office buildings) is purchased from the grid while the amount of electricity sold to the grid is equal to 37% of the PV daily generation. The results are represented in Figure 6.

In the summer condition, the only way to further decrease the energy interchange with the grid could be to add energy storage units to store in-excess PV electricity generated around midday for a delayed use at night.

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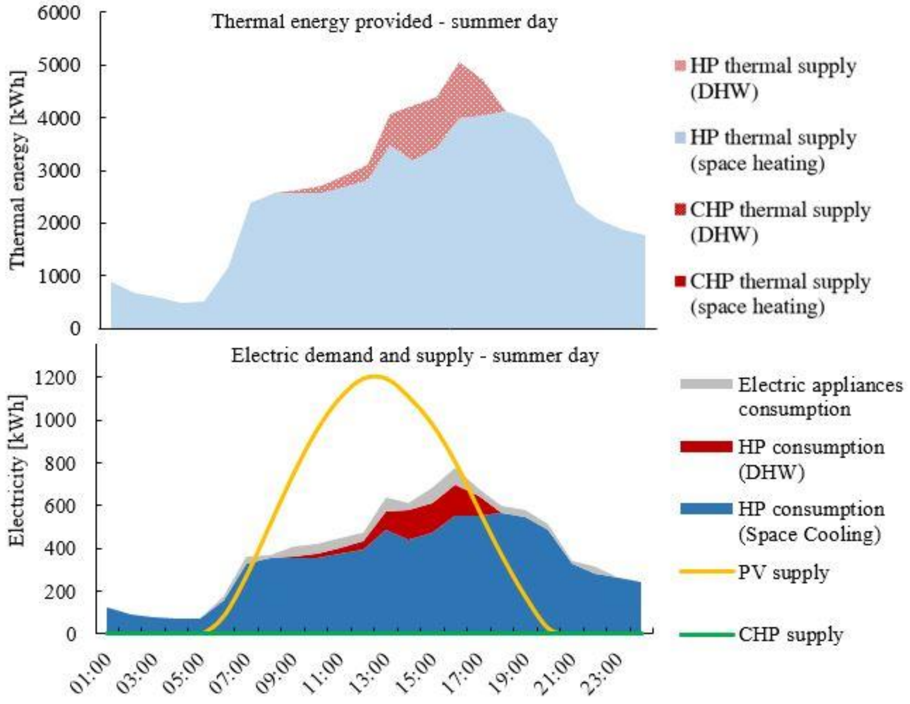

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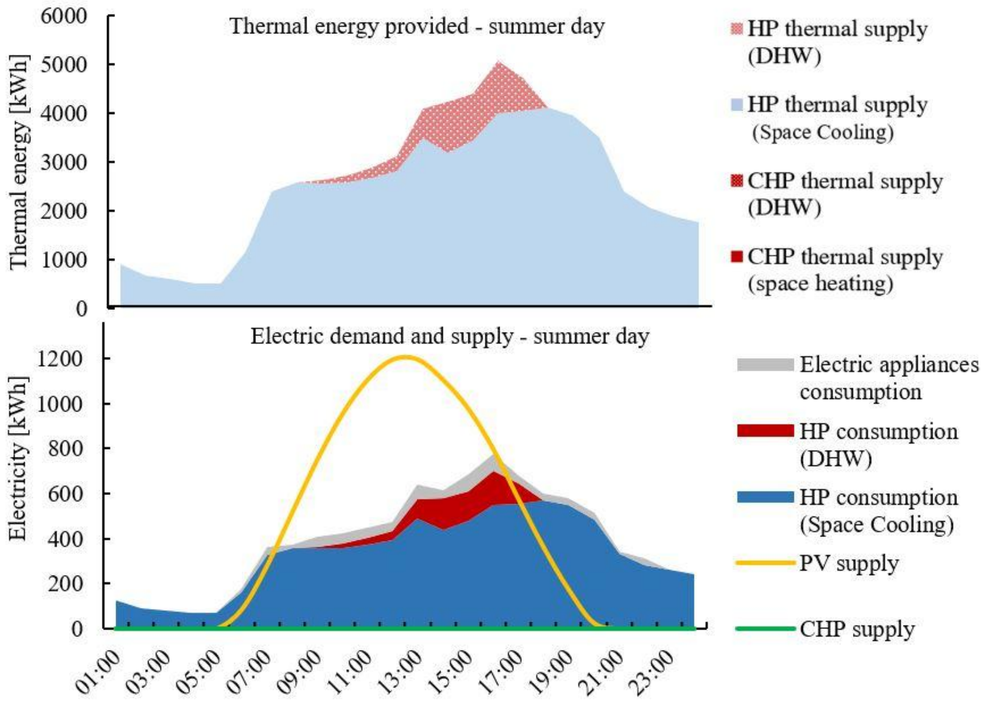

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Figure 6. Thermal and electric results for the reference summer day.

Furthermore, to better assess the benefits of the proposed configuration, also the fraction of the total primary energy (PE) demand covered by RES was calculated for the 3 reference days. PE considers the total primary energy demand for buildings operation (space heating, space cooling, DHW preparation and electric appliances of office buildings), the renewable energy coming from biomass (it is considered as 80% renewable and 20% non-renewable according to Italian regulation), from PV (100% renewable) and from groundwater (100% renewable) ~~[39].~~[42]. For the electricity taken from the grid, the PE conversion factors were assumed respectively equal to 2.42 (electricity to total primary energy), 1.95 (electricity to non-renewable primary energy) and 0.47 (electricity to renewable primary energy) [~~39~~42]. Obtained values are reported in Table 3 and refer to two ways: A) including in the balance also the renewable energy sold and then purchased from the grid; and B) without including the energy sold to the grid.

Field Code Changed

	Winter	Mid-season	Summer
A) The fraction of the total PE demand covered by renewables (including energy sold to the grid)	83%	>100%	>100%
B) The fraction of the total PE demand covered by renewables (excluding energy sold to the grid)	82%	92%	91%

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Table 3. The fraction of primary energy demand covered with RES.

Thus, the proposed configuration ensures considerable coverage by renewables of the total PE demand also in winter conditions, where the low contribution of PV energy and the relevant space heating demand would require a high amount of electricity from the grid in absence of the CHP unit.

6. CONCLUSIONS AND FURTHER DEVELOPMENTS

In the present work, the assessment of an innovative generation district thermal plant coupled with weather dependant and non-weather dependant RES is presented, analysing the case of a new nearly zero-energy district near Milan (Northern Italy). The main results can be summarized as follows:

- The integration of a small size wood biomass CHP and GWHPs coupled with roof-integrated PV systems in a district heating system may be successful. The choice of proper temperature levels and optimal operative parameters ensures a synergist operation with a low request for grid electricity. Especially in the winter season when the availability of solar energy is scarce, as in the proposed application context, the combination with a biomass CHP is a promising solution.
- The proposed configuration is feasible under the energy point of view, allowing to achieve the scope of designing a nearly zero-energy district with a high penetration of renewable energy sources, according to the current regulatory framework.
- The developed method could be replicated, supporting feasibility evaluations of similar systems also in other contexts of application toward new generation district thermal systems, characterized by both heating and cooling demand and by a high-performance building's design.

Further detailed yearly simulations will be performed in the prosecution of the research, in order to assess system performance for the whole year. This will allow a more detailed focus on other aspects of DH, such as the linear heat density and heat losses along with the network.

Other insights will regard the optimization of thermal storage systems and the eventual integration of electric storage systems for in-excess PV electricity aimed to further decrease the energy interchange with the grid.

The next stage of the research will investigate also how economic issues (e.g. the local price of biomass, its sources and supply basin and the cost of pre-treatments and transportation) can affect the management and control of the overall supply system, including the maintenance costs of the system, taking into account the current framework of supporting mechanisms, and the energy market and policies for heat and power production by renewable energies. These issues can be better explored by a multi-objective analysis or by a sensitivity analysis on biomass price, incentives, and systems performances, once the design conditions will be definitively settled. In this framework, other management options can be simulated according to “energy community” concept that is currently being implemented in Italy. In this case, the role of prosumers may imply different strategies of PV electricity generation and, consequently, different optimized operating conditions.

Symbols

Q_{users_W}	buildings thermal needs in winter;
Q_{users_S}	buildings thermal needs in summer;
Q_{DHW}	DHW thermal needs at the users’ side;
$Q'_{max,CHP}$	maximum thermal power provided by CHP and GWHPs powered just by electricity from CHP;
Q'_{FL_CHP}	thermal power provided by CHP in operation at full load;
Q_{FL_CHP}	heat provided by CHP in operation at full load;
Q_{PL_CHP}	heat provided by CHP in operation at partial load;
E'_{FL_CHP}	electric power provided by CHP in operation at full load;
E_{FL_CHP}	electricity provided by CHP in operation at full load;
E_{PL_CHP}	electricity provided by CHP in operation at partial load;
E_{BIPV}	electricity provided to the GWHPs by BIPV;
E_{N_Grid}	electricity provided to the GWHPs from the national grid;

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A renewable energy scenario for a new low carbon settlement in Northern Italy: biomass district heating coupled with heat pump and solar photovoltaic system

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ABSTRACT

In the framework of the building sector de-carbonization, the case of a new nearly zero-energy district, located in the Milan urban area (Italy), is presented. In particular, the scope of the work is to demonstrate that the proposed energy concept, based on the combination of low-energy building design and high-efficiency technical systems, allows the reduction of the final energy uses. After the evaluation of the energy needs, a low-temperature and small-size wood biomass district thermal plant was designed to be integrated with groundwater heat pumps (GWHP) and solar photovoltaic (PV) systems, taking up the challenge to design an almost full-renewable urban district by means of a Multi-Energy System. The core is a biomass boiler coupled with a small combined heat and power (CHP) unit with a twin-screw steam expander (TSSE). The heat produced by the CHP satisfies a consistent fraction of space heating and domestic hot water (DHW) needs during the winter season. GWHPs coupled with PV satisfy remaining thermal needs in winter and the entire thermal needs in mid-season and in the summer period. The obtained outcomes prove the benefits of the combination of a wood biomass CHP with GWHPs and PV with a significant share of renewable energies.

KEYWORDS

Wooden Biomass; District Heating; Low-Carbon District; Multi-Energy Systems; Photovoltaic Systems; Heat Pumps.

ACRONYMS AND ABBREVIATIONS

BDHP – Biomass District Heating Plants
BIPV – Building-Integrated Photovoltaic
CHP – Combined Heat and Power
COP – Coefficient Of Performance
DH – District Heating
DHS – District Heating System
DHW – Domestic Hot Water
EER – Energy Efficiency Ratio
GSHP – Ground Source Heat Pump
GWHP – Groundwater Heat Pump
HP – Heat Pump

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LCOE - Levelized Cost of Electricity
LHD – Linear Heat Density
MES – Multi-Energy System
ORC – Organic Ranking Cycle
PE – Primary Energy
PM – Particulate Matter
PV – Photovoltaic
RES – Renewable Energy Sources
TSSE – Twin-Screw Steam Expander
ULT – Ultra-Low Temperature

1. INTRODUCTION

Nearly 40% of global energy-related CO_2 emissions are attributable to buildings and about two-third of this fraction is directly related to operational emissions [1]. The revised Energy Performance of Buildings Directive (EPBD 2018/844/EU) [2], amending the previous EPBD (2010/31/EU) [3], is aimed to increase the rate of building renovation and strengthen the energy requirements for new buildings, towards a more energy-efficient and smarter building sector. These aims are even more urgent in northern Italy where atmospheric emissions of pollutants and a number obsolete and low-efficiency domestic combustion systems are still in operation.

Nevertheless, the total electrification of the building sector, even if combined to the energy efficiency improvement, implies a huge increase of building-related electricity consumptions and peak power demand, which may overload the power grid [4], requiring strategies for load matching [5], load shifting [6] and peak demand reduction [7]. In this context, thermal and electric networks for smart districts or cities have a key role, allowing the interconnection of distributed energy resources (renewables, combined heat and power generators, etc.), storage systems, and loads (electrical and thermal), balancing the supply and demand locally. Such Multi-Energy Systems (MES) are able to couple weather dependant renewable energy sources with non-weather dependant ones (like biomass), reducing thus the use of storage technologies and increasing, at the same time, the reliability of the whole system [8]. Several examples of MES applied to buildings already proved the convenience of such strategy both in terms of energy consumption and in the reduction of the impact on the national grid [9]. In fact, in MES the production peak by RES will be entirely absorbed by electric systems and used to directly cover energy needs for heating/cooling/DHW of buildings or stored in the thermal/electric storage systems. In such regard, solutions at the district and urban level should consider bi-directional energy streams among buildings and electrical grids and thermal networks at different temperature levels [10]. However, the MES application is still limited, so the present work aims to increase the scientific knowledge on such topics as well as the awareness of the feasibility of advanced energy systems.

2. EVOLUTION OF DISTRICT HEATING SYSTEMS

District Heating Systems (DHS) have undergone an evolution and technological maturation [11] that placed them in an important position in the modern European carbon emissions mitigation challenges [12]. Referring to the European context, approximately 6,000 different systems can be found with a global distribution network's trench length of almost 200,000 km [13]. Several review studies carried out concerning the European context provided a precious effort in the definition and classification of DHS evolution. A recognised classification identifies five different district heating (DH) generations. Following this scheme, the first and second generations were mainly fuelled by coal steam boilers and some examples of CHP and hot water on the users' side were directly heated up with steam or with pressurized high-temperature water (over 100°C). Following the technological evolution of emission systems in buildings (i.e. radiators, gradually working at lower temperature 70°C), and the reduction in the heat demand of buildings, the 3rd generation is characterized by reduced distribution temperatures (80-90°C) of water and is equipped with control and management technologies. First examples of large-scale CHP and integration between fossil and renewable fuels were shown up [14]. The evolution toward the recent 4th and 5th generations has been characterized by a further lowering of the distribution temperatures, higher energy efficiencies and integration with RES. The classification in different generations is combined with another one based on the temperature levels, identifying high temperature, low temperature and ultra-low temperature systems. Indeed the adoption of low-temperature DH networks offers potential savings compared to high-temperature DH due to heat loss reduction and lower pumping energy demand [15]. The 5th generation of DHS presents the possibility to satisfy both heating and cooling demand for different buildings connected to the same grid [16]. The new generation DHS implies the integration of different energy sources, often RES or waste heat. This can be achieved for instance through the decentralization of heat pumps (HP), operating at low temperatures, which are able to meet the heating, cooling and DHW demand of each building, stabilize the power grid and facilitate the integration of different RES [17]. In addition, this configuration may enhance the exploitation of local RES, as PV systems installed on roofs or, in particular cases, wind farms, producing heat in combination with local CHP systems [18]. Further, the heat pump COP has increased thanks to lower operating temperatures [19]. The integration of different RES as biomass, PV and geothermal with heat pumps and solar thermal storage in MES has become attractive for district heating networks [20]. Hast et al. [21] studied the adoption of thermal energy storage in a CHP based DH plant, showing that large heat storage coupled with heat pumps helps to produce more renewable electricity and increase revenues, reducing impacts of electricity price fluctuation. Moreover, the integration of energy storage systems (ESS) with CHP based DH is very effective with more fluctuating thermal loads and higher RES penetration [22].

2.1. Weather dependant and non-weather dependant sources integration at district level across Europe: significant case studies

The feasibility and the benefits deriving from coupling weather dependant (e.g. solar) and non-weather dependant (e.g. biomass) renewable sources [23] are demonstrated through a large number of systems currently in operation. In Slough (United Kingdom), these concepts were applied in the development of mini DHS, where different renewable heat technologies are integrated with PV tiles and thermal storage [24]. The 10 single-family houses are supplied by 165 metres of pipes where water for heating purpose is kept at 55°C through the combined use of a biomass boiler, solar thermal collectors and heat pumps. DHW is provided at 43°C by instantaneous heat exchangers. Unless heat losses amounted to 28%, the system is able to cover 100% of the demand for heating and DHW from RES, representing a successful example of sustainable technology integration.

In Ludwigsburg (Germany) [25], a gas-fired CHP was integrated with a ground source heat pump (GSHP) and decentralized thermal storage. Particular attention was given to the sizing and management of heat generators and to the optimization of storages' charge strategy.

The housing area of Zum Feldlager in Kassel (Germany) [26] represents another interesting example of a low carbon district where geothermal heat is integrated with solar energy. With the adopted configuration, about 80% of heating and DHW energy needs are supplied by a low-temperature district heating grid powered by RES. A centralized GSHP feeds the network with water at 40°C, while decentralized heat exchangers, solar collectors and thermal storages allow covering the DHW demand. Moreover, considering the Italian context, even if just few

4th generation systems are in operation, it worth to mention the case of 3 pilot projects that have been recently started coupling ultra-low temperature (ULT) networks, geothermal heat sources and HPs in substations. These systems are located in three small cities of the Province of Brescia, in Northern Italy. The first is in operation since 2018 and integrates geothermal heat and waste heat from the local industry. This DHS operates by a ULT network at 13°C. The second is in operation since 2014 and is equipped by a small ULT network providing heat to a school campus. The network is powered by a geothermal system exploiting groundwater and distribute heat to two substations equipped with HPs. The last is in operation since 2013 and consists in an ULT open-loop working at 12/8 °C in winter and 15/17 °C in summer supplied by a 90 kW GSHP coupled with a PV system of 20 kWp [27].

Within the RELaTED project [28], four case studies of multi-renewable sources district heating and cooling systems are implemented, with the aim to introduce innovative solutions for the design of decentralized ULT networks.

2.2. District heating systems in the Italian context: barriers and constraints

Despite the significant cases mentioned above, the diffusion of efficient DHS promoted at European level and the described evolution of the current existing plants toward multi-generative systems and low-temperature heating supply is still hampered by existing barriers related to the regulatory, administrative and economic difficulties. In particular, in Italy DH has been so far hindered by inappropriate energy policies and financial supporting scheme. According to 2019 annual report of AIRU [29], the national association of DH in Italy, 341 high-temperature DHS are in operation providing mostly space heating and Domestic Hot Water (DHW) services to 358 Mm^3 in terms of buildings volume for users in 198 cities along a total network length of 4,446 km.

As mentioned, these DHS are mainly fuelled by fossil fuels and characterised by high-temperature levels. Despite an important diffusion of such technologies and a fast growth of the sector between 2000 and 2013, most of the recent developments regard few extensions of existing networks, highlighting the stagnation of the sector and the difficulty to promote investments on new and advanced systems (i.e. 4th and 5th generation DH). This trend is in contrast to the directive 2012/27/CE [30], member states have been demanded to draft a potential evaluation and an associated policy strategy for the development of the DH sector [29,31]. Also concerning the one hundred Biomass District Heating Plants (BDHP), that currently satisfy only the 2-3% of the total Italian building heating demand with a total installed power of 614 MW_t [32], only few examples can be categorized as 4th generation (Figure 1). Instead, the mentioned technical literature demonstrates that the integration of wood biomass in advanced 4th and 5th generation DHS can be a viable and pivotal solution toward de-carbonization, especially in 100% renewable new districts and even in urban contexts, which could benefit from higher linear heat density (LHD) of the grids and from the local availability of biomass by-products such as pruning from urban green areas. On the contrary, an unfavourable market of pellet and wood chip may limit the penetration of biomass-based technologies [33]. For this reason, the implementation of a well-designed biomass supply-chain is fundamental to ensure sustainable management from the economic and environmental point of view.

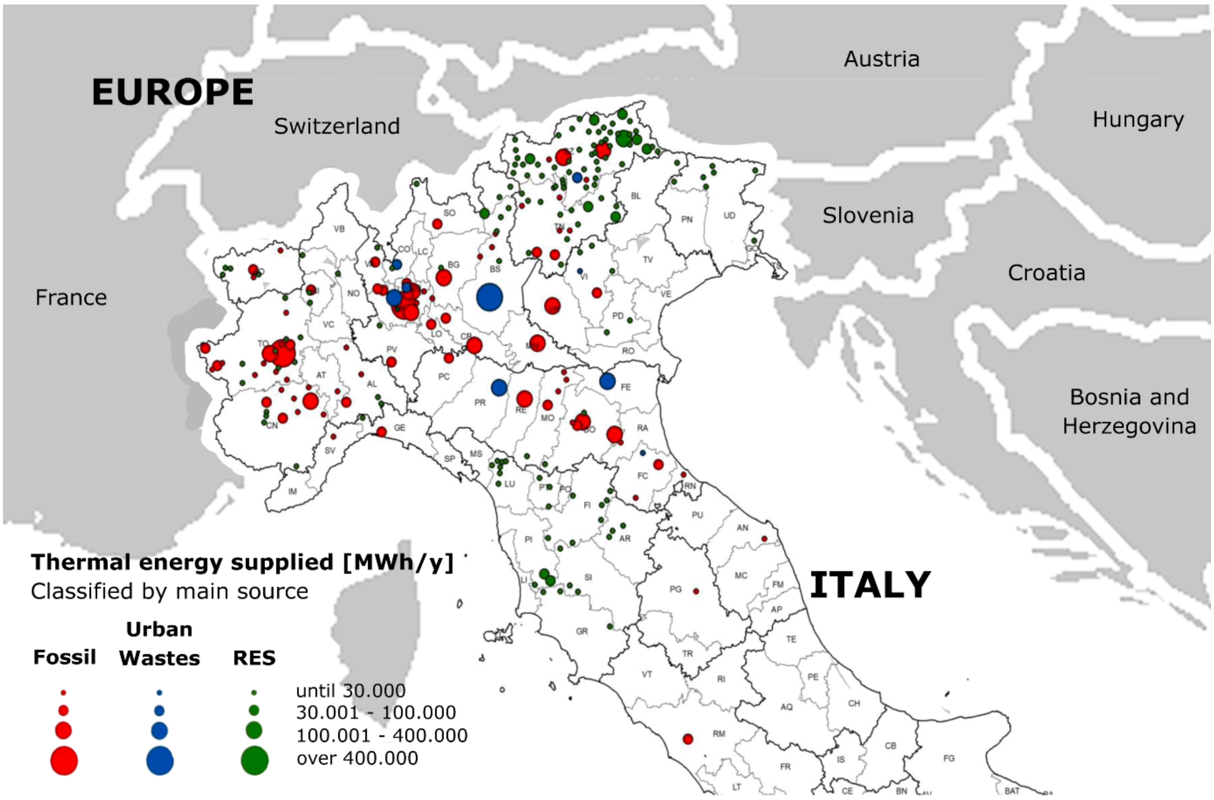

Figure 1. Map of the Italian municipalities served by DHS, classified by the main energy source adopted (more than 50% of the primary energy adopted is provided by that source), adapted from [31].

Another barrier to the penetration of biomass DHS is related to air quality issues since the particulate matter (PM) emissions have become even more important in flat areas of northern Italy. This theme is much debated and represents a non-technical barrier versus biomass combustion. Oppositions to biomass combustion are justified if obsolete and low efficient domestic technologies are adopted, while they are inapposite in the case of BDHP that are always equipped with proper components and sections aimed at emissions control and abatement.

The study here presented lies exactly in this framework, presenting the design of a new district near Milan, in northern Italy, where weather dependant and non-weather dependant RES are integrated into an innovative multi-source network for providing heating, cooling and DHW.

3. CASE STUDY

According to the new definition of Smart City, based on a network of efficient buildings able to provide and consume energy on-site, a new neighbourhood called “Milano 4 You” is currently under development in the Milan urban area. In detail, the district is designed according to sustainability concepts, which can be considered an interesting example due to the adopted technologies in the planning phase.

Site	Milan
Latitude	45°
Heating Degree-Days	2645
Cooling Degree-Days	343
Max. temp. – July [°C]	31.9

Min. temp. – December [°C]	-6.9
Max. monthly global irradiation on the horizontal plane – July [kWh/m^2 month]	187
Min. monthly global irradiation on the horizontal plane – December [kWh/m^2 month]	27

Table 1. Representative parameters of the reference climatic context elaborated through Meteonorm Software [34].

The performance of the settlement was already preliminarily assessed in a previous research work, according to different possible scenarios [35]. Among them, according to the peculiarities of the project (mix of residential and tertiary high-performance buildings), to the context (available renewables) and to the project's objectives (willingness to avoid fossil fuels and to implement energy networks) the following solution was selected and assessed in detail.

It considers a generation plant able to integrate different RES, consisting of a small-size wooden biomass CHP system coupled with electric heat pumps and building-integrated photovoltaic (BIPV) systems. Moreover, the reference data about buildings' energy demand has been updated according to the design novelties still in progress.

Dynamic simulations have been performed in EnergyPlus [36] to estimate the energy needs of the buildings, considering two reference buildings that well represent the residential and non-residential destinations of the "Milano 4 You" district. The main features of the reference buildings are reported in Table 2.

According to the summarized boundary conditions, the energy demand of the two buildings has been calculated. The results were then extended to the total heated/cooled net floor area equal to 89,090 m^2 (64,490 m^2 residential and 24,600 m^2 non-residential).

	residential building	***non-residential building***
Surface/Volume [-]	*0.40*	*0.22*
Windows to wall ratio [%]	20%	30%
U opaque [W/m^{2}K]	0.2	0.18 (average)
U glazed [W/m^{2}K]	1.1	1.2
g [-]	0.8	0.52
Heating setpoint [°C]	20	20
Cooling setpoint [°C]	26	26
Infiltration [Vol/hr]	0.52	0.56 during occupation (8am to 8pm);
Internal gain [W/m^2]	2,3 W/m^2 (occupancy profile provided by SIA2024-2015)	6 W/m^2 (8am to 8pm);
Lighting	-	4 W/m^2 (Dimmerable)
Daylighting set point	-	300 lux on the work plan
Shutter	-	Venetian blinds
DHW demand	ASHRAE standards	-

Table 2. Main features of the reference buildings.

The total annual energy need for heating, cooling and DHW are equal to 1,350 MWh, 3,300 MWh and 1,600 MWh, respectively. According to preliminary results of the design phase, a thermal power peak of about 1.8 MW is experienced during the heating season (Space heating and DHW). Therefore, the selection of a proper CHP size was hindered by the low availability of such low size solutions on the market.

The annual electric consumption of appliances in non-residential buildings amounts to 540 MWh. It must be noted that electricity demand for home appliances was not considered in the analysis since, according to the current Italian regulation in force during the preliminary design of the settlement, it must be supplied by individual PODs (Points of Delivery) and cannot be provided by a district generation system.

4. METHOD FOR THE HYBRID DISTRICT HEATING SYSTEM DESIGN

According to the energy concept based on a network for thermal purposes, the configuration designed is mainly constituted by two water loops. As already introduced, the main generation system consists of a biomass boiler combined with a small CHP unit, able to satisfy most of the space heating and DHW needs during its operation period in the heating season. Energy is provided to a water loop, maintained at 55°C, which is connected to the buildings by means of substations (the district heating system units that connect the network and internal building heating systems) with heat exchangers connected to buildings' distribution systems and DHW storages. Since the CHP is thermal driven, but not sized on the winter peak, the remaining part of thermal energy demand, not covered by the CHP during the winter, and the whole thermal need for DHW in mid-seasons, is provided by decentralized water-to-water heat pumps connected with a low-temperature district groundwater loop. The length of both networks is approximately 1 km. Considering only the heat provided by the CHP during the winter season (space heating and DHW), the heat density of the network amount to 2.1 MWh/m, in line with the reality of district heating systems in operation in Italy [32]. In addition, a heat density of 1.5 MWh/m is reported as minimum threshold for DHS feasibility, attesting the appropriateness and the efficiency of the network design [37].

In the summer period, the entire cooling demand is covered by GWHPs which may indeed take advantage of the heat discharged by GWHPs for DHW connected in series to the same groundwater loop. Electricity needs of heat pumps and the electric appliances in office buildings are covered by the CHP electric output (during its operation period), by photovoltaic systems integrated on the roofs and by the grid, as the last option. The scheme of the energy supply concept is shown in Figure 2.

The BIPV systems are sized to cover a substantial part (80-100%) of the electricity demand of the heat pumps in the mid-seasons and in the cooling period and – more in general – to maximize the exploitation of solar energy. Such sizing criteria is based on 3 main assumptions:

1. the presence of the net metering mechanism, which allows to obtain a remuneration for the electricity fed into the grid;
2. the fact that in the analysed context the levelized cost of electricity (LCOE) from PV is approximately half of the grid price, ensuring a high convenience of PV generation;
3. the presence in the district of additional electric loads not related to heating/cooling/DHW (e.g. electric vehicles charging stations) and of energy storage systems, which maximize instantaneous energy self-consumption.

More in detail, it was considered that all the available surface of the buildings' roofs is covered with PV systems with a total peak power of 1660 kW_p. The size of the biomass system, which has a nominal thermal power of 800 kW and an electric power of 100 kW, was instead selected to cover a considerable fraction of the space heating and DHW demand in the winter period, where solar energy is scarcely available, according to a synergistic operation with GWHPs that is subsequently explained in detail. The selected heat pumps have a maximum power of 200 kW_t each for residential buildings and 500 kW_t for office buildings.

The DHW is prepared by mean of distributed heat exchangers installed in storage systems located in substations on the users' side secondary network, allowing to implement optimized charging profiles, maximizing the output of the CHP in the winter: storage tanks are heated when the space heating demand is low (thus using CHP energy); similarly, in summer and mid-seasons, storage tanks are heated when there is high PV generation.

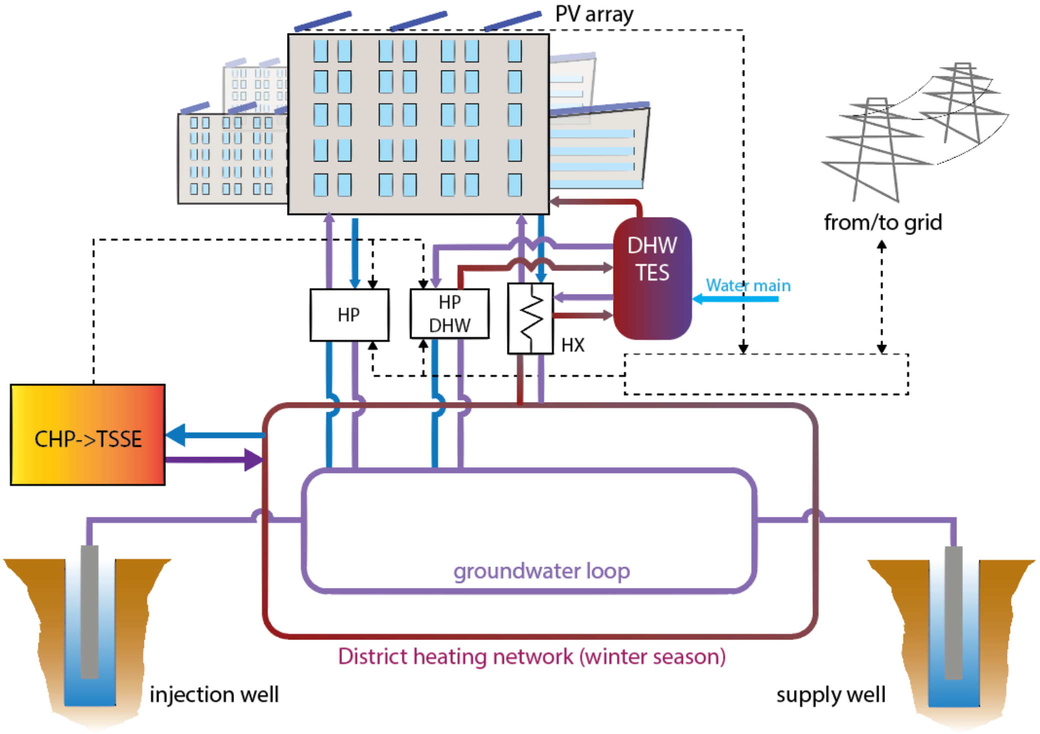

Figure 2. Scheme of the energy supply concept/strategy of the district.

4.1. Biomass CHP unit

The adoption of a CHP unit with a Twin-Screw Steam Expander (TSSE) was selected as the most feasible technology for energy conversion of wood biomass, according to techno-economic considerations. Stirling engines and pyrolysis-gasification coupled with gas cycles (gas turbine) were excluded because the experiences documented so far on a commercial scale are still too limited. Further, also conventional steam cycles are not proper at size lower than 1 electric MW and Organic Rankine Cycles (ORC), based on the same principle of steam turbines but using an organic working fluid, are in general expensive and characterised by complex and binding maintenance [38]. Therefore, another available CHP technology was explored for the present application, the mentioned TSSE since it is more compact, robust and simple. Moreover, as reported by [39], TSSE technology has proven to be a particularly cost-effective and reliable CHP solution when coupled with biomass boilers serving district heating networks. According to the information provided by companies involved in this sector, TSSE systems, able to harness saturated process steam and generate electricity, have been experimented in Europe and in Italy in different cases with sizes between 100 and 200 kW of net electric power.

The main components of the selected CHP system can be grouped in the following sections (as also shown in Figure 3): biomass storage section, combustion and steam generation section, TSSE section and treatment and expulsion of the flue gas.

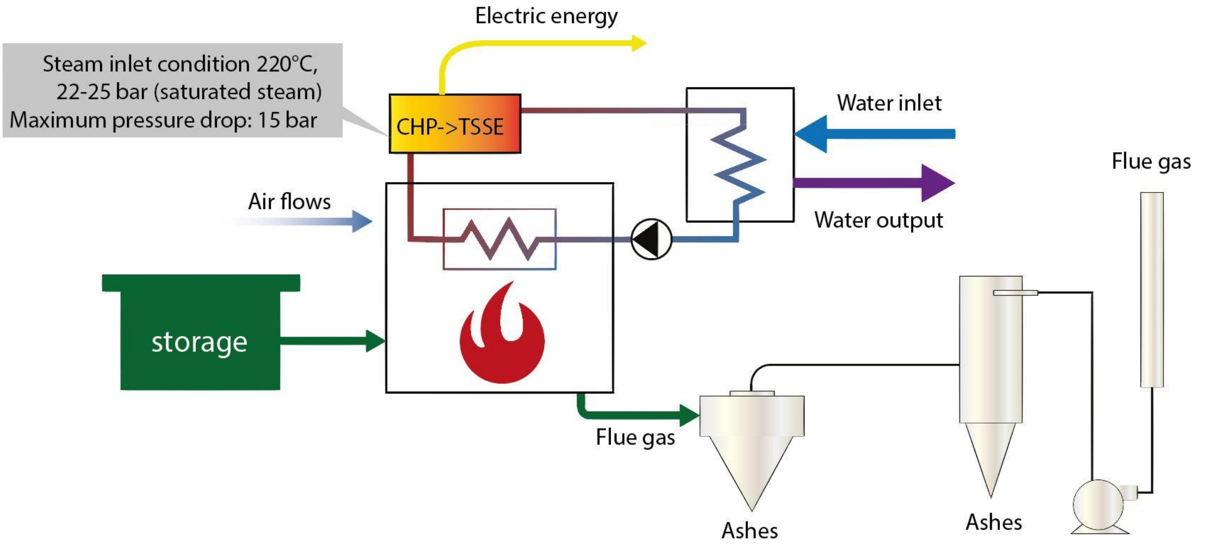

Figure 3. Scheme of the thermal power station with main components.

TSSE systems are characterized by an optimal thermal performance, while it allows producing electricity with gross yields in the order of 10%. These systems are able to generate electricity by fully adapting to the boundary conditions [40]. In particular, TSSE systems can provide tailored outputs from 75 to 630 kW of electric power and maintain stable performance even at partial load, according to the technical information provided by the manufacturers.

As already introduced, for the present case study, the size of the TSSE has been selected among market alternatives, according to the global needs of space heating and DHW of the district, based on an energy supply strategy that includes heat pumps and BIPV systems, with the aim to design a full-renewable district. Aware of the complexity of a proper selection of the size and operation mode of a CHP system, as described e.g. in [41], in the present case the minimum size available on the market of TSSE has been selected. It refers, in nominal conditions, to input biomass power of 1 MW, a gross electric power output of 100 kW and a net thermal power output of 800 kW, respectively. The electricity consumption for auxiliaries leads to an available electric net power of 85 kW. According to the electric to thermal ratio of the selected TSSE (about 1 to 8), the operative mode is thermal driven, i.e. it follows the heating needs in winter. As it will be described in the following sections, the selected size allows to increase energy efficiency, primary energy and greenhouse gases savings and economic effectiveness, according also to [41]. Back up boilers are not envisaged in this case, since the presence of GWHPs allow the robustness and redundancy of the overall system. From the electric point of view, there are two main loads in the district (electricity for HP operations and for electric appliances in the office buildings) and three sources (CHP, BIPV and the national grid). According to the main design criteria, such elements are matched to minimize the electricity interchanged with the national grid. Furthermore, given the small number of monitored 4th and 5th generation networks, it is not possible to provide a typical range of heat losses along with the network. However, in line with the ranges of values (5-15%) provided by [16], a constant average value of 10% has been conservatively assumed for heat losses along with the distribution network for the whole operating period of the CHP.

This value is also in accordance with [32], where a range of 10-15% of heat loss is reported for the most efficient 3rd generation DHS. Actual monitoring results that will be collected during the first year of district operation will be used to determine the heat losses in each condition.

4.2. Reference days

The performance of the abovementioned system has been evaluated in three reference days, which were selected as representative of the 3 different typical load conditions, as it follows:

- winter day, where significant space heating thermal loads are present (min/max external temperatures 0°C/5°C), together with DHW loads;
- summer day, where significant space cooling thermal loads are present (min/max external temperatures 18°C/34°C), together with DHW loads;
- mid-season day, where there are no space heating/cooling loads (min/max external temperatures 8°C/13.5°C) and just DHW loads are present.

These days are representative of the winter, mid and summer season, respectively. They have been selected because the first is the day with the average heating demand during the coldest months, the second has the average cooling demand in the hottest month and the last is a typical day during the mid-season, where DHW is the unique thermal load.

4.3. Control strategy in the winter season

The 3 different load conditions are handled with 3 different control strategies. During the winter season, the CHP module operates to cover thermal needs, i.e. space heating and DHW. Most of the heat demand is covered by the CHP module's thermal output while the remaining one is satisfied by the GWHPs, powered by the electricity output of the CHP module. Therefore, electricity produced by the CHP is assumed to be fully exploited for the operation of the GWHPs and auxiliaries.

Taking into account the nominal performance of the TSSE (85 kW net electric power and 800 kW net thermal power) and the nominal COP of the GWHPs in the specific operating conditions, the maximum heat power available results 1,225 kW, calculated by Equation 1 as it follows:

$$Q'_{max,CHP}[kW] = Q'_{FL\_CHP}[kW] + \left(E'_{FL\_CHP} \times COP\right)[kW] \tag{1}$$

Where:

$Q'_{max,CHP}[kW]$ is the maximum thermal power provided by CHP and GWHPs powered just by electricity from CHP;

$Q'_{FL\_CHP}[kW]$ is the thermal power provided by CHP in operation at full load;

$E'_{FL\_CHP}[kW]$ is the electric power provided by CHP in operation at full load;

COP is the coefficient of performance of the GWHPs in winter operation.

According to the dynamic simulation of the energy behaviour of the buildings included in the settlement, the thermal power peak in winter is 1,790 kW. During the typical winter day, the thermal needs (space heating + DHW) range from 549 kWh to 1,399 kWh. This last is higher than the maximum heat that can be provided as a sum of cogenerated heat and heat provided by GWHPs powered by cogenerated electricity. Therefore, in some hours, when the thermal needs are equal or higher than 1,225 kWh per hour, the CHP works at full load (Equation 2), while in others, when the thermal needs are lower than 1,225 kWh per hour, it works at partial load (Equation 3). Thanks to the configuration of the supply system, the thermal needs exceeding 1,225 kWh per hour are provided by the GWHPs powered by BIPV electricity, when available, or by electricity from the national grid (Equation 2).

$$Q_{users\_W}[kWh] = Q_{FL\_CHP}[kWh] + \left[\left(E_{FL\_CHP} + E_{BIPV} + E_{N\_Grid}\right) \times COP\right][kWh] \qquad (2)$$

$$Q_{users\_W}[kWh] = Q_{PL\_CHP}[kWh] + \left(E_{PL\_CHP} \times COP\right)[kWh] \qquad (3)$$

Where:
Q_{users_W} are the buildings thermal needs in winter;
Q_{FL_CHP} is the heat provided by CHP in operation at full load;
Q_{PL_CHP} is the heat provided by CHP in operation at partial load;
E_{FL_CHP} is the electricity provided by CHP in operation at full load;
E_{PL_CHP} is the electricity provided by CHP in operation at partial load;
E_{BIPV} is the electricity provided to the GWHPs by BIPV;
E_{N_Grid} is the electricity provided to the GWHPs from the national grid;
COP is the coefficient of performance of the GWHPs in winter operation.

The COP of the GWHPs has been evaluated considering the operating temperature levels (i.e. groundwater at 15°C and supply water at 35°C for space heating and 55°C for DHW) and the specific curve of performance of a commercial GWHP with the assumed sizes. A weighted COP has been calculated as described in Equation (4), resulting in a value of 5 in winter conditions.

$$COP = \frac{Q_{SH}}{(Q_{SH}+Q_{DHW})} \times COP_{SH} + \frac{Q_{DHW}}{(Q_{SH}+Q_{DHW})} \times COP_{DHW} \qquad (4)$$

Where:
Q_{SH} is the heat demand for space heating of all the buildings;
Q_{DHW} is the heat demand for DHW of all the buildings;
COP_{SH} is the GWHPs COP for space heating (output temperature: 35°C);
COP_{DHW} is the GWHPs COP for DHW preparation (output temperature: 55°C);

The CHP module's size and control logic have been designed in a way to maximize the exploitation of the cogenerated heat and thus minimize heat dissipation. On average, during the typical winter day, the CHP operation is at 82% of its full load. Further, also considering the consumption of electric appliances in commercial buildings, excess PV electricity and electricity from the national grid can be minimized.

4.4. Control strategy in mid-seasons and summer

During mid-seasons, when DHW is the only thermal need, the CHP unit is switched off and DHW is provided as follows (Equation 5).

$$Q_{DHW}[kWh] = \left[\left(E_{BIPV} + E_{N\_Grid}\right) \times COP\right][kWh] \qquad (5)$$

Where:
Q_{DHW} are the DHW thermal needs at the users' side;

E_{BIPV} is the electricity provided to the GWHPs by BIPV;
E_{N_Grid} is the electricity provided to the GWHPs from the national grid;
COP is the average coefficient of performance of the GWHPs in mid-season operation.

In this case, the COP of the GWHPs has been evaluated considering as operating temperature levels groundwater at 15°C and supply water at 55°C for DHW, resulting in a value of 3.9.
As already mentioned, the presence of DHW storage tanks allows the optimization of the charging strategy when there is high PV production, improving the load-matching between DHW needs and BIPV electricity generation. Also, in this case, the global balance takes into account the consumption of electric appliances in commercial buildings.
In summer, i.e. when cooling and DHW needs occur, the CHP unit is kept switched off and thermal needs are provided as follows (Equation 6 and 7).

$$Q_{users\_S}[kWh] = \left[\left(E_{BIPV} + E_{N\_Grid}\right) \times EER\right][kWh] \tag{6}$$
$$Q_{DHW\_S}[kWh] = \left[\left(E_{BIPV} + E_{N\_Grid}\right) \times COP\right][kWh] \tag{7}$$

Where:
Q_{users_S} are the buildings thermal needs for space cooling in summer;
Q_{DHW_S} are the DHW thermal needs at the users' side in summer;
E_{BIPV} is the electricity provided to the GWHPs by BIPV;
E_{N_Grid} is the electricity provided to the GWHPs from the national grid;
EER is the energy efficiency ratio of the GWHPs in summer operation.
COP is the coefficient of performance of the GWHPs in summer operation.

Analogously to winter operation, the EER of the GWHPs has been evaluated considering the operating temperature levels, i.e. groundwater at 15°C and supply water at 7°C for space cooling, resulting in a value of 7.1. For DWH production instead, the hourly COP was calculated based on the temperature difference between 55°C (DHW production) and the specific hourly discharging temperature of heat pumps dedicated to space cooling. In detail, the average COP for DHW preparation during the typical summer day resulted equal to 5.6, which is significantly higher than that of the mid-season day, equal to 3.9. This demonstrates that the connection in series of the GWHPs providing space cooling to those providing DHW allows a consistent heat recovery, increasing the overall efficiency of the system. In some conditions, where there is a good balance between cooling and DWH load, the groundwater loop can be also hydraulically isolated from wells with a significant additional energy saving.

5. RESULTS AND DISCUSSION

As introduced, in this phase of the research detailed energy simulations have been carried out in 3 reference days. The main obtained results are reported and commented hereafter.
In detail, in the reference winter day, the 62% of the total thermal energy demand (space heating and DWH) is covered by the CHP output, while the remaining 38% is supplied by the GWHPs; the 68% of the electricity needed from the latter to cover the thermal energy demand is represented by the CHP electric output. In total, just 17% of the daily electricity demand (GWHPs and electric needs in office buildings) is taken from the national grid, thus the remaining part is provided by the CHP supply and the PV supply. Lastly, the amount of electricity sold to the grid is equal to 16.5% of the PV daily generation.
In brief, the obtained results confirm the effectiveness of the control strategy described in the previous section, because the proposed configuration and operation logic ensures the total

hourly self-consumption of the thermal and electrical production of the CHP unit while minimizing the electricity interchange with the grid.

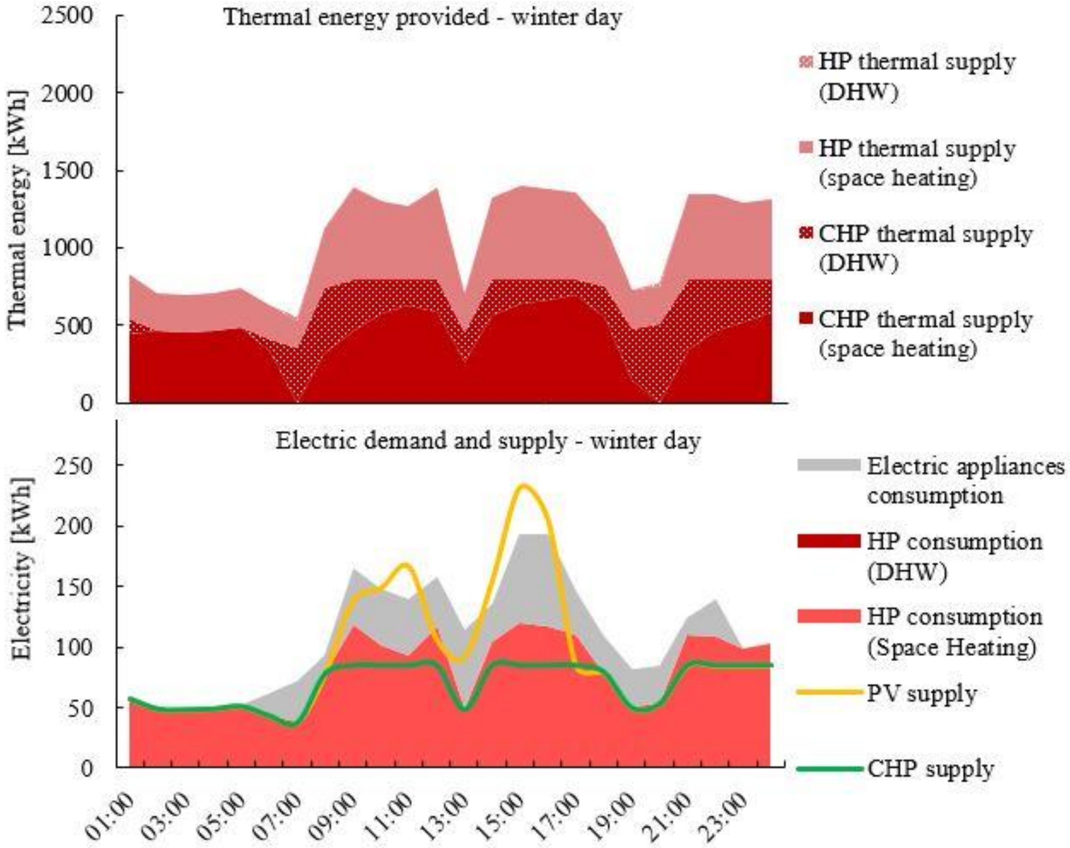

Figure 4. Thermal and electric results for the reference winter day.

In the reference mid-season day instead, the low thermal load (just DHW) and the adopted strategy to charge the DHW storages in the central hours of the day, allow the full coverage by using just the GWHPs, which are mainly powered by PV energy. Just 13.5% of the daily electricity demand (GWHP and electric needs in office buildings) is taken from the national grid, while the electricity sold to the grid is equal to 27% of the PV daily generation. The results are represented in Figure 5.

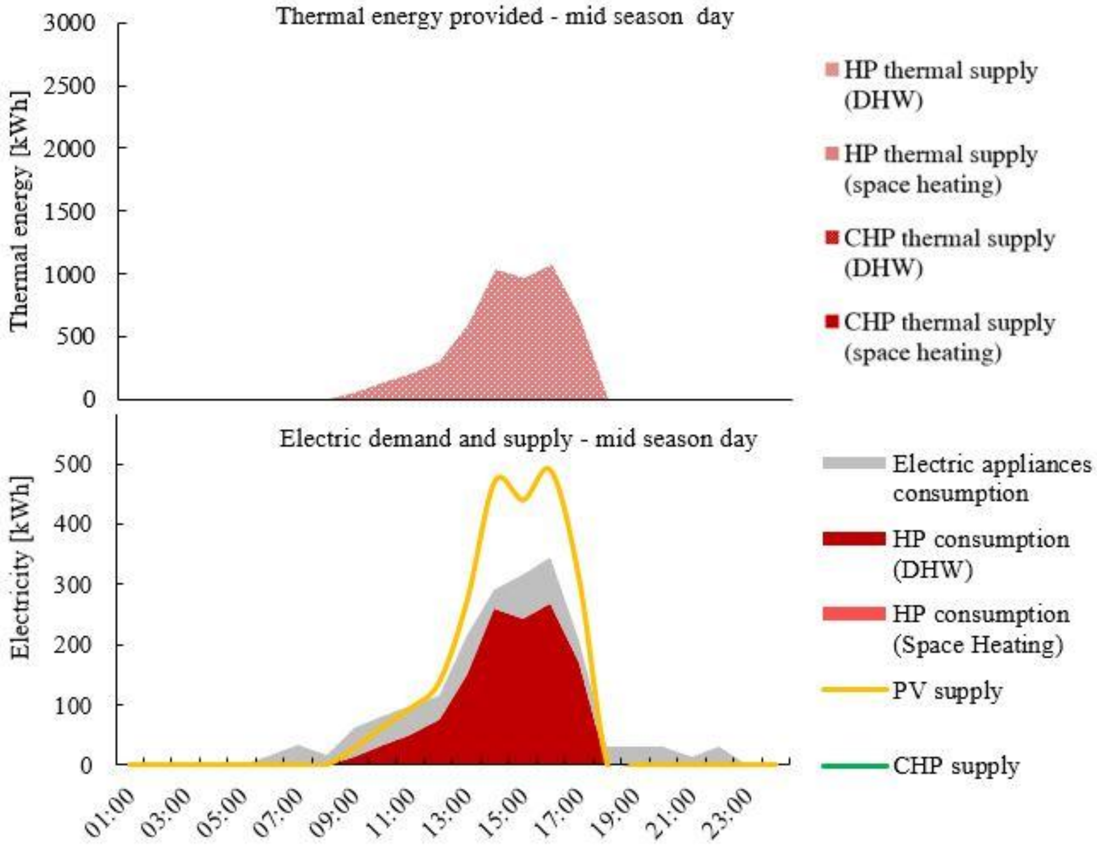

Figure 5. Thermal and electric results for the reference mid-season day.

Lastly, in the reference summer day, there is a high availability of PV electricity, which is in phase with space cooling load, electric load in office buildings and with the proposed charging profile of DHW storages. Moreover, the use of groundwater loop with GWHPs for space cooling connected in series with those for DHW preparation allows a considerable heat recovery and an estimated saving on the electricity consumption for DHW equal to 43% (compared to an option with GWHPs connected to independent groundwater wells). This way, 32% of the daily electricity demand (GWHPs and electric loads in office buildings) is purchased from the grid while the amount of electricity sold to the grid is equal to 37% of the PV daily generation. The results are represented in Figure 6.

In the summer condition, the only way to further decrease the energy interchange with the grid could be to add energy storage units to store in-excess PV electricity generated around midday for a delayed use at night.

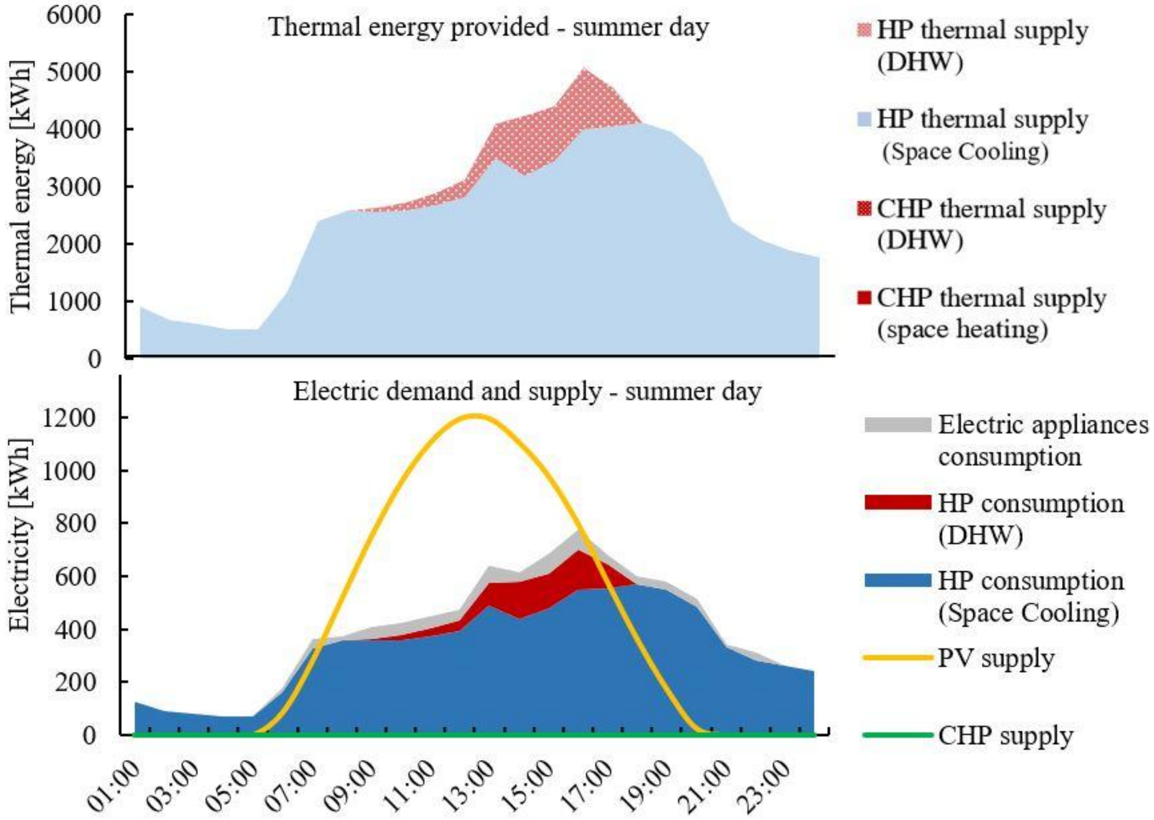

Figure 6. Thermal and electric results for the reference summer day.

Furthermore, to better assess the benefits of the proposed configuration, also the fraction of the total primary energy (PE) demand covered by RES was calculated for the 3 reference days. PE considers the total primary energy demand for buildings operation (space heating, space cooling, DHW preparation and electric appliances of office buildings), the renewable energy coming from biomass (it is considered as 80% renewable and 20% non-renewable according to Italian regulation), from PV (100% renewable) and from groundwater (100% renewable) [42]. For the electricity taken from the grid, the PE conversion factors were assumed respectively equal to 2.42 (electricity to total primary energy), 1.95 (electricity to non-renewable primary energy) and 0.47 (electricity to renewable primary energy) [42].

Obtained values are reported in Table 3 and refer to two ways: A) including in the balance also the renewable energy sold and then purchased from the grid; and B) without including the energy sold to the grid.

	Winter	**Mid-season**	**Summer**
A) The fraction of the total PE demand covered by renewables (including energy sold to the grid)	83%	>100%	>100%
B) The fraction of the total PE demand covered by renewables (excluding energy sold to the grid)	82%	92%	91%

Table 3. The fraction of primary energy demand covered with RES.

Thus, the proposed configuration ensures considerable coverage by renewables of the total PE demand also in winter conditions, where the low contribution of PV energy and the relevant space heating demand would require a high amount of electricity from the grid in absence of the CHP unit.

6. CONCLUSIONS AND FURTHER DEVELOPMENTS

In the present work, the assessment of an innovative generation district thermal plant coupled with weather dependant and non-weather dependant RES is presented, analysing the case of a new nearly zero-energy district near Milan (Northern Italy). The main results can be summarized as follows:

- The integration of a small size wood biomass CHP and GWHPs coupled with roof-integrated PV systems in a district heating system may be successful. The choice of proper temperature levels and optimal operative parameters ensures a synergist operation with a low request for grid electricity. Especially in the winter season when the availability of solar energy is scarce, as in the proposed application context, the combination with a biomass CHP is a promising solution.
- The proposed configuration is feasible under the energy point of view, allowing to achieve the scope of designing a nearly zero-energy district with a high penetration of renewable energy sources, according to the current regulatory framework.
- The developed method could be replicated, supporting feasibility evaluations of similar systems also in other contexts of application toward new generation district thermal systems, characterized by both heating and cooling demand and by a high-performance building's design.

Further detailed yearly simulations will be performed in the prosecution of the research, in order to assess system performance for the whole year. This will allow a more detailed focus on other aspects of DH, such as the linear heat density and heat losses along with the network. Other insights will regard the optimization of thermal storage systems and the eventual integration of electric storage systems for in-excess PV electricity aimed to further decrease the energy interchange with the grid.

The next stage of the research will investigate also how economic issues (e.g. the local price of biomass, its sources and supply basin and the cost of pre-treatments and transportation) can affect the management and control of the overall supply system, including the maintenance costs of the system, taking into account the current framework of supporting mechanisms, and the energy market and policies for heat and power production by renewable energies. These issues can be better explored by a multi-objective analysis or by a sensitivity analysis on biomass price, incentives, and systems performances, once the design conditions will be definitively settled. In this framework, other management options can be simulated according to “energy community” concept that is currently being implemented in Italy. In this case, the role of prosumers may imply different strategies of PV electricity generation and, consequently, different optimized operating conditions.

Symbols

Q_{users_W}	buildings thermal needs in winter;
Q_{users_S}	buildings thermal needs in summer;
Q_{DHW}	DHW thermal needs at the users’ side;
$Q'_{max,CHP}$	maximum thermal power provided by CHP and GWHPs powered just by electricity from CHP;
Q'_{FL_CHP}	thermal power provided by CHP in operation at full load;
Q_{FL_CHP}	heat provided by CHP in operation at full load;
Q_{PL_CHP}	heat provided by CHP in operation at partial load;

E'_{FL_CHP}	electric power provided by CHP in operation at full load;
E_{FL_CHP}	electricity provided by CHP in operation at full load;
E_{PL_CHP}	electricity provided by CHP in operation at partial load;
E_{BIPV}	electricity provided to the GWHPs by BIPV;
E_{N_Grid}	electricity provided to the GWHPs from the national grid;

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HIGHLIGHTS

1. Provide an overview of the evolution of district heating networks.
2. Propose a solution for energy decarbonization of new settlements.
3. Show how biomass CHP, PV systems and heat pumps may be successfully integrated.
4. Propose an effective control strategy to enhance local-RES self-consumption.