Energy

Biomass District Heating System in Italy: a comprehensive model-based method for the assessment of energy, economic and environmental performance

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Abstract:	In the framework of the energy strategy toward 2050, district heating systems (DHS) offers a great flexibility in terms of heat generation technologies and renewable resources integration, resulting, in case of proper management and supply conditions, in fossil primary energy and greenhouse gases savings compared to conventional technologies. In Italy, only the 2.5% of the thermal final uses are satisfied by DHS and, although widely available over the territory, those fuelled by wooden biomass represent less than the half of the total. Many studies in this framework have highlighted the need of methods and tools for a better understanding of the operative conditions, of the potentialities and of the optimal evolution of biomass DHS. To that end, a proper simulation model has been developed and calibrated on a real case study operating in cogeneration, in an urban area of Northern Italy. After investigating the current performance of the real case, some criticalities have been described and new operating scenarios have been defined and simulated. The achieved results represent a support for the stakeholders involved in BDHS and for future energy policies, providing hints on possible challenging evolutive scenarios and on measures to enhance the energy performance and the economic appeal.

Highlights

- The role of district heating systems (DHS) is investigated for EU and Italy
- A focus on Italian biomass DHS is presented and a representative case is selected
- A model of a real case is developed by TRNSYS, calibrated with monitored data
- The current and alternative scenarios are modelled and simulated
- Results can support stakeholders involved in the evolution of BDHS and DH policies

Esteemed Editor,

considering the topics, the audience and the authority of the Energy Journal, we are pleased of presenting you our manuscript entitled “Biomass District Heating System in Italy: a comprehensive dynamic modelling approach for the assessment of Energy, Economic and environmental performance”

The research origins in the framework of the European and national energy targets for the next decades focusing on role of thermal needs in buildings. It is certainly known that district heating systems (DHS) have a great potential to that end, since they offer a great flexibility in terms of heat generation technologies and renewable resources integration. In case of proper management and supply conditions, this potential allows fossil primary energy and greenhouse gases savings, compared to the most diffuse technologies operating at building scale.

Nevertheless, in many EU countries e.g. in Italy, DHS cover only a small part of the thermal final uses and they are mainly fuelled by fossil fuels and operate at high temperatures, making absolutely untapped the thermal RES potential suitable for innovative district thermal systems. In this context, a transition has to be planned consisting in the evolution and expansion of the existing DHS and in the creation of new networks developed with a smarter concept and approach.

To that end, many scholars have underlined the need of methods and tools for a better understanding of the operative conditions and of the potentialities for an optimal evolution.

The research here presented focuses on wood biomass DHS in Italy (a source widely spread since 1/3 of the Italian territory is covered by forests) and presents the development of a simulation model calibrated on a real case study operating in cogeneration, in an urban area of Northern Italy. More in detail, a dynamic model has been developed, tested and calibrated thank to the collection of real data achieved by a long-lasting monitoring campaign. Many assumptions have been carried out to ensure an appropriate computational weight and to envisage the replicability of the model for other case studies, even if the technological features and the components have been closely tailored on the case study selected.

The model has been implemented by the well-known and widely validated Trnsys, considering also the TESS library. The robustness of the method has been proved also following the ASHRAE Guideline 14 for the calibration and validation of the parts related to network and users heat load model.

In addition to the simulation of the current operation, the research evaluates new operating scenarios, providing hints on possible challenging measures to enhance the energy, environmental and economic performance of similar systems as a support for the stakeholders involved in BDHS and for future energy policies.

We hope that our manuscript can be evaluated as innovative, considered and shared with scholars and other stakeholders involved DHS and related entities and industries.

Sincerely,

The authors

CRediT author statement

G. Ferla: Methodology, Software, Formal analysis, Data curation, Investigation, Writing – Original draft, Writing – review and editing, Visualization
P. Caputo: Conceptualization, Supervision, Project administration, Writing – Original draft, Writing – review and editing

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:

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The authors thank Editor and Reviewers for their precious work and for appreciating the research.
The answers are reported in blue in the following.
Sincerely,
The authors

Editor #: The review of your paper is now complete, the Reviewers' reports are below. As you can see, the Reviewers present important points of criticism and a series of recommendations. We kindly ask you to consider all comments and revise the paper accordingly in order to respond fully and in detail to the Reviewers' recommendations. If this process is completed thoroughly, the paper will be acceptable for a second review.

The authors have checked all recommendations and have responded accordingly as reported below.

Reviewer #1: The article has been corrected and supplemented. I have received a reply to all my suggestions. I'm satisfied and in my opinion the article is of appropriate quality and can be published.

The authors thank the reviewer for the revision work and for appreciating our study.

Reviewer #2: The authors have inattentively replied the previous proposed comments. Besides, there are some ambiguous parts. The authors should reply the following comments:

1. Main assumptions should be given in Section 2.2.1. However, the authors gave the working parameters and how they use program in this section. Moreover, the main assumptions can be given as a paragraph; referring the manuscript lenght looks like unmeaning.

The authors thank for the comment. Section 2.2.1 has been revised as suggested to better highlight the main assumptions adopted has been carried out. In particular, the main assumptions have been summarised at the end of section 2.2.1.

2. Fig.5 and 7 should be redrawn. These figures are given as careless.

In order to better explain the model layout and the assumptions carried out, Fig. 5 and 7 report respectively the general layout of the model (divided in the three sub-routines, also represented in Fig. 1, 2 and 3) and a zoom-in on the substation sub-routine.
In order to provide readers a better understanding of these figures, as suggested, Fig. 5 have been redrawn by also including a distinction between constant and variable parameters (as also requested in the following comment).
Concerning Fig. 7, a more detailed description has been integrated in the text in order to clarify the labels used in the picture and to better explain the model operations.

3. The constant and variable parameters should be given in detail

Thanks to your suggestion, the constant and variable parameters have been highlighted in Fig. 5.

4. "The possibility to customize and adapt the model (different sources and operative conditions)." This study presents this situation or TRNSYS? The novelty of this study is unclear, give as net and concrete please.

The possibility to create and customize a model is given by TRNSYS. As explained in the manual, the software can be indeed considered as an interface for modelling energy systems with FORTRAN language. The sentence of the manuscript
"The possibility to customize and adapt the model (different sources and operative conditions)."
is referred to the fact that the model developed in the present study can be easily adapted to further BDHS case studies.
In this context, this paper aims to assess the energy and environmental performances of a representative Italian BDHS and to verify improved options.
In comparison with other available literature studies, this paper provides:

- detailed energy and environmental balances of the selected plant, carried out by using mainly primary data, which were collected involving the plant managers and operators;
- a various set of improved scenarios, allowing to assess how different items can affect the energy and environmental performances of the analysed plant;
- the possibility to customize the model in order to simulate different DHS and relative improved scenarios.

5. What is the main contribution of this study?

The authors upgraded the introduction according to this last comment and to the previous one.

Biomass District Heating System in Italy: a comprehensive model-based method for the assessment of energy, economic and environmental performance

ABSTRACT

In the framework of the energy strategy toward 2050, district heating systems (DHS) offers a great flexibility in terms of heat generation technologies and renewable resources integration, resulting, in case of proper management and supply conditions, in fossil primary energy and greenhouse gases savings compared to conventional technologies. In Italy, only the 2.5% of the thermal final uses are satisfied by DHS and, although widely available over the territory, those fuelled by wooden biomass represent less than the half of the total. Many studies in this framework have highlighted the need of methods and tools for a better understanding of the operative conditions, of the potentialities and of the optimal evolution of biomass DHS. To that end, a proper simulation model has been developed and calibrated on a real case study operating in cogeneration, in an urban area of Northern Italy. After investigating the current performance of the real case, some criticalities have been described and new operating scenarios have been defined and simulated. The achieved results represent a support for the stakeholders involved in BDHS and for future energy policies, providing hints on possible challenging evolutive scenarios and on measures to enhance the energy performance and the economic appeal.

KEYWORDS

Biomass; District Heating Systems; Energy Simulation Model; Energy and Environmental Performance; ORC; Real cases.

NOMENCLATURE

RE: Renewable Energy
PE: Primary Energy
GHG: Greenhouse Gases
SH: Space Heating
RES: Renewable Energy Source
HP: Heat Pump
DHS: District Heating System
DH: District Heating
HDH: Heating Degree Hour
DHW: Domestic Hot Water
TD: Thermal Driven
PEF: Primary Energy Factor
DC: Dry Coolers
NG: Natural Gas
CF_{net}: Net Cash-Flow
PBT: Payback Time
BAT: Best Available Technology
DHC: District Heating and Cooling
BDHS: Biomass District Heating System
EF: Emission Factor
CHP: Combined Heat and Power
DHN: District Heating Network
ED: Electric Driven

ORC: Organic Rankine Cycle
HX: Heat Exchanger
CL: Control Logic
SCR: Selective Catalic Reduction
HDD: Heating Degree Day
SST: Substation
TES: Thermal Energy Storage

1 INTRODUCTION

Despite the growth of the renewable energy (RE) share in the global primary energy (PE) supply in the last decade, according to the recent developments in the European and global strategies [1] all countries are called to decarbonize the energy sector in the future.

This process involves though several challenges due to the interdependencies between the energy sector and the economic, social and environmental dimensions of human development [2].

Achieving the EU climate objectives (i.e. a reduction of the overall greenhouse gas (GHG) emissions by 80-95% by 2050 compared to 1990 levels [3]) requires indeed a complete transformation of the energy system [4].

One of the main challenges for the building sector, which is one of the main contributors to GHG emissions and PE consumption, is the decarbonization of the heating and cooling sector that is dominated by space heating (SH) and accounts for approximately 50% of EU-28 final energy demand and around the 80% of the end-use energy in European buildings [5]. Among the available renewable energy sources (RES), till now only biomass has been widely used for heating purposes (12%), while solar thermal, geothermal and heat pumps (HP) are still marginal in many countries [6]. Thermal needs are mainly provided by domestic devices operating at building level or at buildings unit level. An alternative solution is represented by district heating systems (DHS) that implies an infrastructure for distributing heat produced in a centralized facility through a network of underground insulated pipes for covering residential and commercial heating demands such as SH and domestic hot water (DHW).

DHS appears in Europe at the beginning of the 20th century and currently covers the 10% of the heating market with approximately 6,000 different systems and a global distribution network's trench length of almost 200,000 km [7]. Due to its flexibility, DHS can be fuelled by fossil fuels, renewable energies and waste heat. DHS have undergone an evolution and technological maturation [8] that placed them in an important position in the modern European carbon emissions mitigation challenges [9]. Several review studies carried out concerning the European context provided a precious effort in the definition and classification of DHS evolution [10]. One recognized classification identifies five different DHS generations. The first and second generations were mainly fuelled by coal steam boilers or fossil CHP; hot water on the users' side was 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, i.e. 60-70°C) and the reduction in the heat demand of buildings, the third generation is characterized by reduced distribution temperatures (80-90°C) of water. The evolution toward the fourth and fifth generations has been characterized by a further lowering of the distribution temperatures, higher energy efficiencies, integration with RES and higher automation [11].

Research on solutions for improving 2nd and 3rd generation DHS, as the one here presented, are as fundamental as the ones on 4th and 5th generation DHC considering that they currently co-exist and their development runs in parallel, for the following reasons:

- 3rd generation DHS are the most diffused in Europe and Italy [10];
- Many emission sub-systems in existing buildings work with high temperatures;
- HT industrial waste heat, HT geothermal heat and biomass are largely available and more suitable for 3rd generation DHS [12].

At the end of 2019, in Italy, with about 250 plants, DHS covered around 2.5% of the total heat demand, with a total thermal capacity, i.e. the total of basic and backup power installed, of 9,065 MW, which 906 MW are provided by CHP (combined heat and power) [13]. Presently the most part of these plants is fuelled by fossil fuels [14], underlining the urgent need of a transition towards RES-based DHS.

Even if the development of a comprehensive model for dynamically simulating the operations of a BDHS is quite rare in literature, most of the studies focus indeed on a particular component (such as the biomass boiler, the ORC or the distribution network), few recent contributions can be found, e.g. [15], [16] and [17]. The authors of [15] proposed a detailed dynamic optimization model of gas turbine Biomass-CHP hybrid systems, applied to DHS. The model studied, validated with measured data, was used to analyse and to define the optimal size of the components in such hybrid systems. Similarly, the authors of [16] presented a model-based methodology for the assessment of the energy, economic and environmental performance of a biomass CHP connected to a DHS. The model proposed, quite simplified for the part simulating the users heat demand (measured data are taken as input), is instead highly detailed for what concern the generation unit, especially for the biomass combustion model, and the DHN. Main aim of the study is to test the simulation model to assess the average conversion efficiencies of the CHP unit, thus providing reliable estimations for energy cost predictions. Another interesting study is provided in [17], where a simulation tool is developed and used to optimize the size (electric power) of a cogeneration plant based on a biomass-fired Organic Rankine Cycle and connected to an existing district heating network, maximizing profitability.

1.1 Focus on the Italian biomass district heating system framework

The authors have been involved in a long-lasting survey on Biomass DHS (BDHS) associated to Fiper [18] which results are reported in [19] and in other publications in progress. Thanks to the availability of operative data for the most part of the Italian plants it was possible to provide and update a quite exhaustive picture of the national context under the energy, environmental and economic point of view.

The last update of this study, referring to 2019 data, treats 82 BDHS operating in Italy, a sample that can be considered highly representative of the whole national portrait, since, with a total of 423 MW from biomass, it covers the 93% in terms of thermal power with the respect of the total installed thermal power of the Italian BDHS, including also the several mini systems (biomass thermal power ≤ 1 MW) scattered over the territory. A summary of the main features of the sample analysed is provided in Table 1.

Table 1. Summary of the main features of the Italian BDHS updated at the end of 2019 (source of data: Fiper and associated plants)

Parameter	Unit	Value
Numbers of plants of the sample	-	82
Number of plants with co-generation units	-	39
Total installed biomass power	MW	423
Total installed thermal power (biomass and back up boilers)	MW	786
Average size of thermal power (only biomass boilers)	MW	5.1
Gross thermal efficiency	%	74%
Gross electric efficiency	%	18%
Global heat losses (all the sample)	%	33%
Global heat losses (non-CHP plants)	%	29%
Linear heat density	kWh/m/y	1018
Fossil PE savings	%	69%

CO_2 savings	%	65%
CO_2 EF (1)	g_{CO2}/kWh	60
NOx EF (2)	mg_{NOx}/kWh	355.3
PM EF (3)	mg_{PM}/kWh	14.8

EF[1]: emission factor (pollutants emissions divided by PE consumed, in a year)

(1) Based on the values of the current regulation for each fuel, where biomass is considered renewable at 80% [20]

(2) Based on a sample of 32 BDHS

(3) Based on a sample of 28 BDHS

The Italian BDHS are in general small sizes and located in mountain areas, according to the approach that enhance the sustainable use of the resources locally available, but the sustainability of BDHS in urban context is endorsed by several existing examples and related studies [21].

The several local benefits achievable by the spread of BDHS are widely described in [19] where, after investigating the effects of the BDHS taking into account energy, environment and economy aspects, it is underlined the need of methods and tools for a better understanding of the operative conditions, of the potentialities and of the optimal evolution of BDHS.

Considering the current lack of a unified development strategy for the national BDHS context together with the lack of proper tools for system design, the research aims to provide a solid and reliable contribution to stakeholders, decision makers and researchers.

The development of a comprehensive dynamic simulation model able to reproduce the operative conditions of a case study BDHS, selected in a way to be representative of the average plant in the Italian framework, represents an innovative contribution to that end.

The results could support the individuation of actions to be addressed in the future support schemes necessary for the evolution of existing DHS and the optimization of the use of the available biomass by this technology, increasing the interest of stakeholders involved in this supply chain and policymakers.

2 MATERIALS AND METHOD

As anticipated in section 1.1, the research concerns the development of a simulation model tailored on a properly selected real case study. All the components of the model have been calibrated on the basis of monitoring data collected at the case study. The heat load model of users and the heat distribution assumptions have been validated with historical data through the *Ashrae guideline 14* [22] approach, resulting into acceptable error margins according to the selected time scale for the simulations. After investigating the current performance of an existing CHP-BDHS case study, some criticalities have been described and new operating scenarios have been defined and simulated.

2.1 Case study

The selection of the sample real case has been based on the deep knowledge of the Italian BDHS matured over the years. In fact, according to Figure 1, the real case has been selected, among those with a complete set of data, in a way to be representative of the average BDHS in the

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[1] Emission factors represent the quantity of pollutant emitted for a unit of PE (e.g. g_{CO2}/kWh) adopted in an energy conversion process.

Italian context and, at the same time, representative of a consistent cluster of CHP-BDHS, for which criticalities and room for improvement have been identified. Moreover, the case study selected is located in an urban area of *Pianura Padana*, a large flat region in northern Italy with well-known environmental criticalities, enabling the possibility to explore such delicate but promising application.

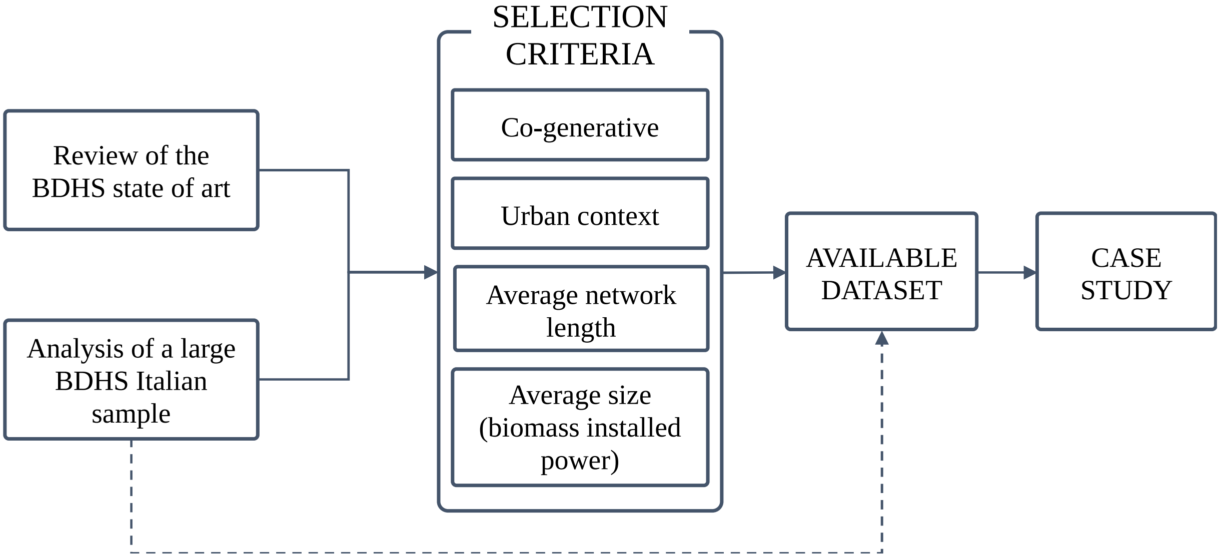

Fig. 1. Procedure for the selection of the real case

The selected BDHS, located near Milan, in a quite densely populated urban area of Lombardy Region, in Northern Italy, was founded in 2009. It is powered by wood chips, coming from the same region. Through a district heating network (DHN) approximately 4 km long, it provides SH to almost 2,000 users while producing electricity, which is fed directly into the national grid.

Due to economic sustainability reasons linked to the support schemes in force for the promotion of renewable electricity generation[2], as many other CHP-BDHS realized in similar contexts, the case study operates with an electric driven (ED) logic: the management is aimed at maximizing the electricity production to be sold to the national grid instead of following the users heat demand. The heat produced by the CHP is however supplied through the DHN to five substations for SH only, i.e. during winter season, i.e. from 15th of October to the 15th of April[3], while no DHW heating is provided. This management logic allows the biomass boiler to operate almost constantly in full load conditions all over the year, however the amount of heat dissipated in summer and mid seasons is quite high.

Core of the generation system is a 9.6 MW woodchips boiler connected to an Organic Rankine Cycle (ORC)[4] module providing nominal powers of about 1 MW electric and 4.2 MW thermal. The cold side of the ORC's condenser is directly plugged into the primary water circuit and operates between 90°C and 60°C in nominal conditions. The generation unit is completed by a 3 MW auxiliary flat plate oil/water heat exchanger (HX) that recovers heat from the thermal oil leaving the ORC module during heat demand peaks. An auxiliary biomass boiler (5 MW) and

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[2] Electricity is sold to the national electric grid at 0.28 €/kWh, as explained in section 2.3.

[3] Heating season is defined by law in Italy according to the climatic zones based on the range of heating degree days (HDD) [23].

[4] ORC is a quite recent CHP technology that exploit, in a Rankine cycle, the high latent heat in the liquid-vapor phase change of particular organic fluids with high molecular mass.

a gas boiler (12 MW) are included into the generation system, but they are never used and hence they will not be included in the model.

The flowrate of water inside DHN pipes is controlled by a differential pressure logic, regulating the operations of the pumping system in the central unit in order to maintain the designed pressure level in the network. Each substation is equipped with two plate HXs connecting the primary DHN loop to the secondary circuits distributing hot water to dwellings. In order to match the heat demand of users, a valve upstream of the HX regulates the inlet flow rate in the DH side.

Table 2. Summary of the main parameters of the case study BDHS

Parameter	Unit	Value
Installed biomass power	MW_{th}	14.6
Installed aux. power	MW_{th}	12
Installed ORC power	MW_{th}	4.2
	MW_{el}	0.99
Fluegas abatment technology		Cyclonic filter, bag filter, DeNOx (SCR[5])
DHN length	km	4
Number of substations	-	5
Heated volume	m^3	160,000

2.2 Energy modelling approach

The present section provides a brief description of the steps required for the development of the model.

According to [24], to address the increasing complexity of DHS design, great effort should be made in developing simplified but complete models with the aim of properly supporting the design of new DHS. A proper model should be able to simulate operative conditions of a system in different configurations in dynamic regime, in a way to assess, in early design phase, the best economic and energy efficient solutions according to the boundary conditions of each case.

The model was implemented through Trnsys [25], a transient simulation environment based on FORTRAN language. The software includes a standard library with approximately 150 models (called *types*) ranging from pumps to multi-zone buildings, wind turbines to electrolysers, weather data processors to economics routines, and from basic HVAC equipment to cutting edge emerging technologies. A further library was available for the present study, developed by TESS [26] integrating the standard one.

A scheme of the model, including the central unit, the DHN and the substation is reported respectively in Figure 2, 3 and 4.

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[5] Selective catalytic reduction.

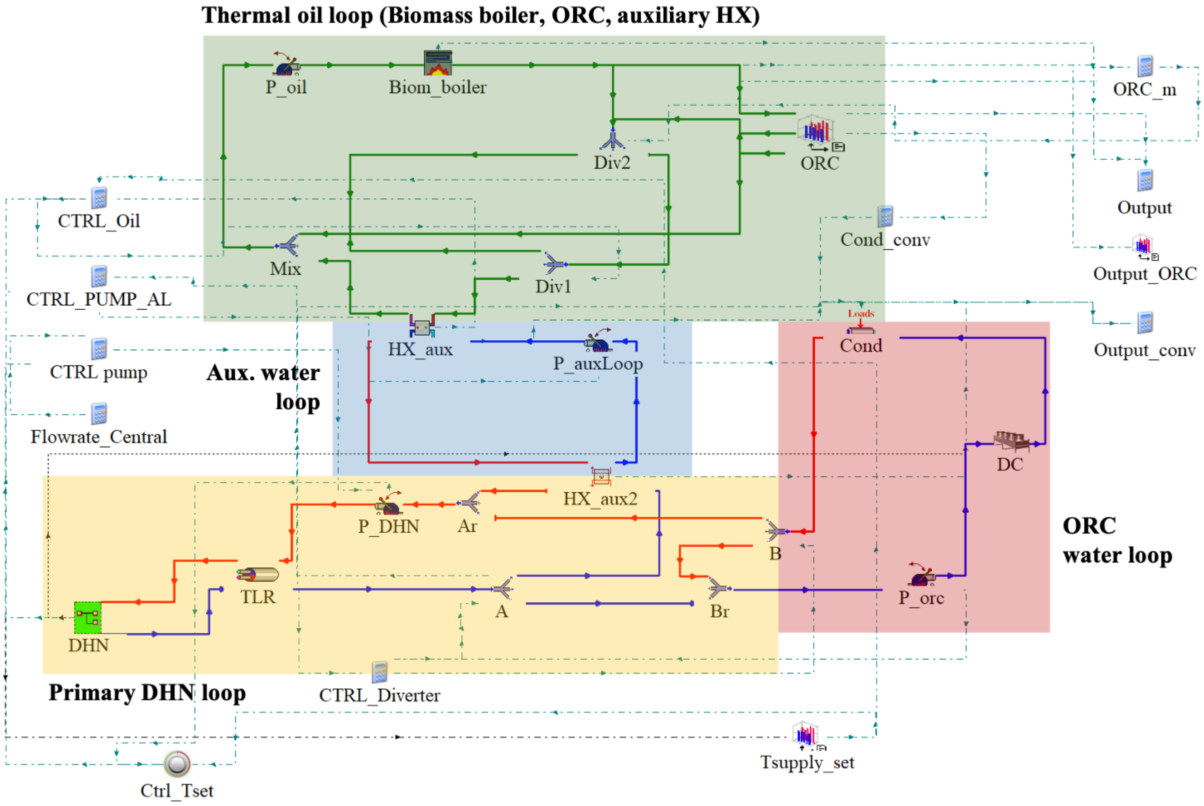

Fig. 2. Trnsys' layout of the central unit sub-routine (screenshot)

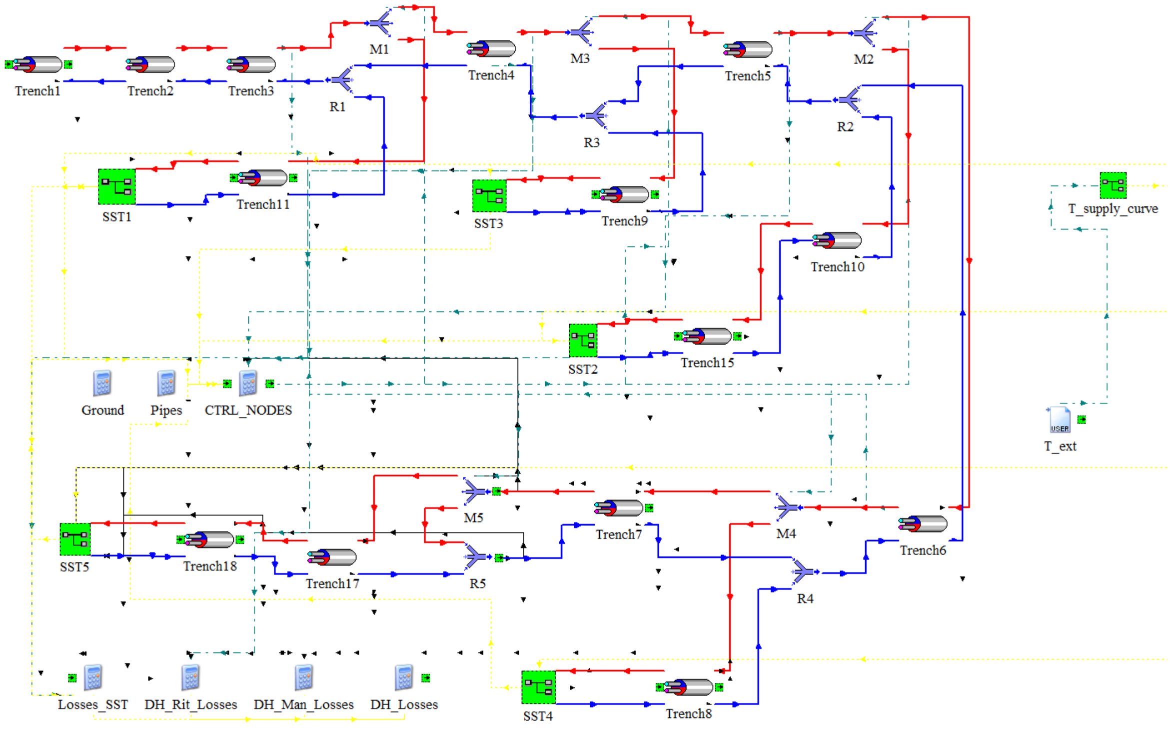

Fig. 3. Trnsys' layout of the DHN sub-routine (screenshot)

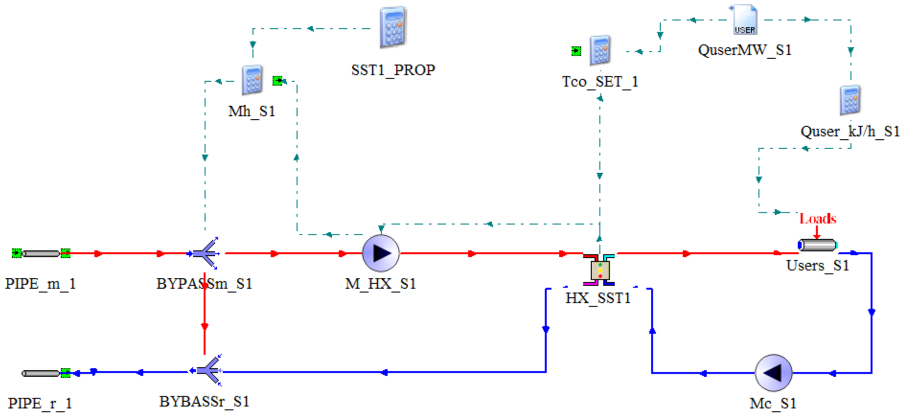

Fig. 4. Trnsys' layout of the substation sub-routine (screenshot)

The central unit subroutine (Fig. 2) is composed by 4 groups of *Types*, representing the thermal oil loop, the auxiliary water loop, the ORC water loop, and the primary water loop. Besides the main technological components (Biomass boiler, ORC unit, pumps and HX), it can be noticed the presence of calculators, useful elements through which the input and output of each component can be adjusted and where the equation for controlling the plant operation can be written (in Fortran language). In Fig. 3, the distribution network is represented. It is composed by the underground pipes (*trench1*, *trench2*, etc.), the diverting and mixing valves and the substations subroutines. In Fig. 4 the *substation 1* subroutine is presented as example, equal to the others. The latter is composed by a HX connecting the distribution network to the users' loop. As represented, the users' loop is not dynamically simulated, and the heat demand is provided as input through the component "Users_S1".

2.2.1 Main components and modelling assumptions

Many assumptions have been carried out to ensure an appropriate computational weight and to envisage the replicability of the model for other case studies, even if the technological features and the components have been closely tailored on the case study selected.

The selection of the components of the energy model has been carried out to reliably represent the real operative conditions of the system and they are briefly described in the following. The BDHS runs, in the base case scenario, at full load along the whole year, in order to constantly generate about 1 MW of electric power through the ORC module. During the heat load peaks from DHN, an auxiliary water loop within the central unit switches on when the supply temperature falls under the set point temperature (in the range 70-90 °C, according to a specific function based on external temperatures). Actually, for the most part of the winter, the supply temperature is in the range 80-85°C, while the return temperature is in the range 55-65°C.

The set of input and parameters related to the whole model, i.e. the technical features of the components installed in the BDHS and the operative conditions, have been provided by the plant manager. In the following figure (Fig. 5), the general scheme of the model developed is provided and the main constant and variable parameters are highlighted.

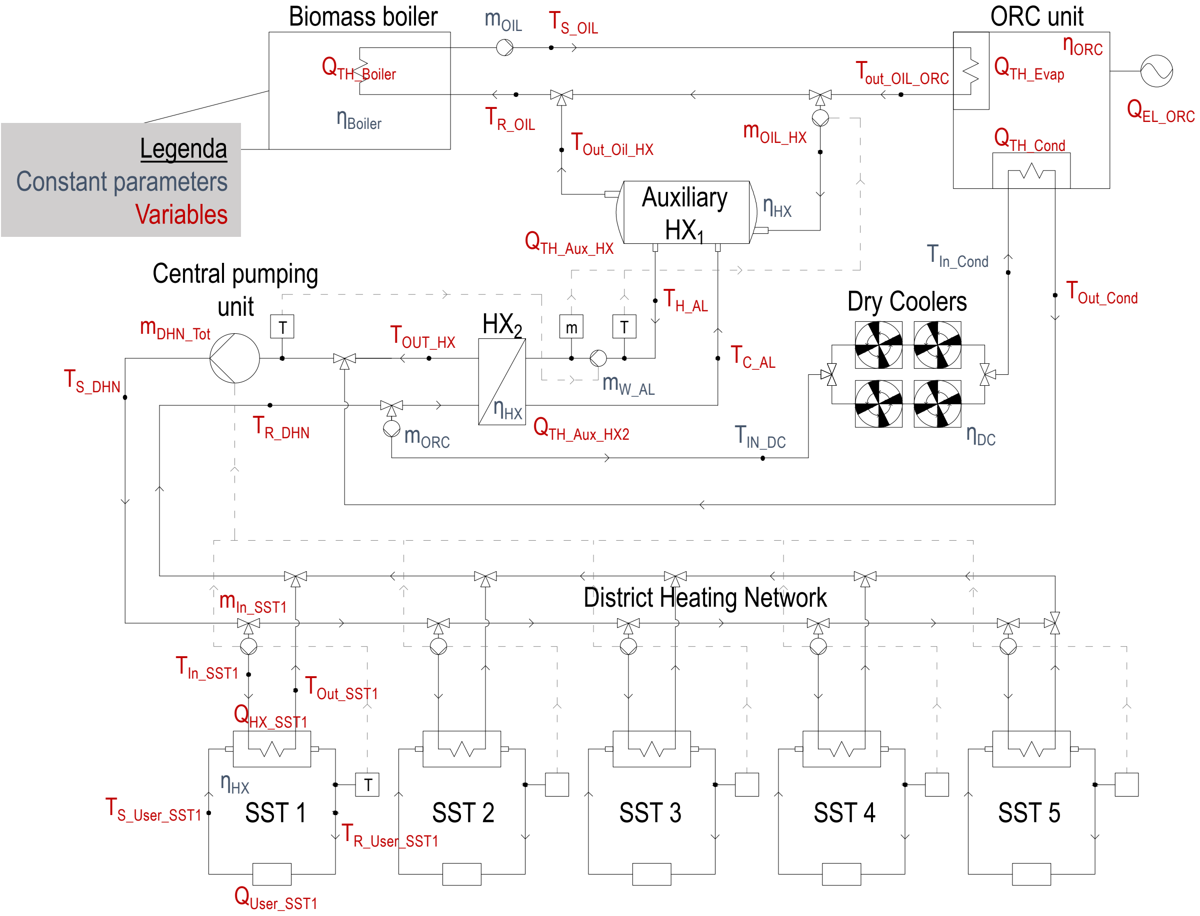

Fig. 5. General layout of the model (constant and variable parameters)

In the following table (Tab. 3), a brief explanation of the label used and the corresponding nominal values assigned to each point are provided. Since the values provided in the table are the design ones, they represent an indication of the operative conditions, nevertheless such values are computed at each time step in function of the boundary conditions and hence they can vary dynamically.

Table 3 Description of the labels used, and nominal values of the points highlighted in Fig. 5

Label	Description	Nominal values	UM
Q_{TH_Boiler}	Thermal power of the biomass boiler	8	MW
η_{Boiler}	Efficiency of the biomass boiler	0,75	-
m_{Oil}	Thermal oil flowrate	140	m^3/h
m_{Oil_HX}	Thermal oil flowrate in the aux. HX	0-132	m^3/h
T_{S_OIL}	Supply temperature of the thermal oil from biomass boiler	314	°C
T_{R_OIL}	Return temperature of the thermal oil in the biomass boiler	216	°C
η_{ORC}	Efficiency of the ORC components	see Chp. 2.2.1	
η_{HX}	Efficiency of the HXs	0,95	-
η_{DC}	Efficiency of the DCs	0,9	-
$T_{Out\_Oil\_ORC}$	Outlet temperature of the thermal oil from the ORC	254	°C
$T_{Out\_Oil\_HX}$	Outlet temperature of the thermal oil from the HX1	216	°C

$Q_{TH\_Aux\_HX}$	Thermal power exchanged in the aux. HX	0-2.4	MW
T_{H_AL}	Hot side temperature of the auxiliary water loop	102	° C
T_{C_AL}	Cold side temperature of the auxiliary water loop	72	°C
m_{W_AL}	Water flowrate in the auxiliary water loop	72.4	m^3/h
M_{ORC}	Water flowrate in the ORC water loop	121	m^3/h
Q_{TH_cond}	Thermal power provided by the ORC’s condenser	4.2	MW
Q_{EL_ORC}	Electric power produced by the ORC’s turbine	1	MW
Q_{TH_Evap}	Thermal power absorbed by the ORC’s evaporator	5.3	MW
T_{In_Cond}	Inlet temperature of water in the ORC’s condenser	60	°C
T_{Out_Cond}	Outlet temperature of water from the ORC’s condenser	90	°C
T_{In_DC}	Inlet temperature of water in the DCs	60	°C
$Q_{TH\_Aux\_HX2}$	Thermal power provided by the HX2	0-2.4	MW
T_{Out_HX}	Outlet temperature of water from HX2	90	°C
T_{S_DHN}	Supply temperature of water in the DHN	90	°C
T_{R_DHN}	Return temperature of water from the DHN	60	°C
m_{DHN_tot}	Water flowrate in the DHN	90-400	m^3/h
m_{In_SST1}	Water flowrate in substation 1	16-50	m^3/h
T_{S_SST1}	Inlet temperature of water in substation 1	90	°C
T_{R_SST1}	Outlet temperature of water from substation 1	60	°C
Q_{HX_SST1}	Thermal power exchanged in HX of substation 1	0-2	MW
$T_{S\_ User\_SST1}$	Supply temp. of water to users connected to substation 1	90	°C
$T_{R\_User\_SST1}$	Return temp. of water from users connected to substation 1	60	°C
Q_{User_SST1}	Thermal power delivered to users connected to substation 1	0-2	MW

In addition, a set of hypotheses and assumptions have been defined as summarised in the following list:

- The heating demand of users is not dynamically simulated. A simplified method for estimating hourly heat demand from weekly monitored data has been defined, preventing a heavy computational weight. The method is described in the following;
- The distribution losses in the secondary loops and in buildings are neglected. This assumption has been taken into consideration in the definition of the heating demand model, by considering the monitored data measured in the substation HX rather than in buildings;
- The efficiency of the woodchips boiler and HXs is assumed to be constant along the simulation year;
- The control logic has been simplified. While the real operation of the pumping unit is controlled by a differential pressure logic, in the model it has been simplified by implementing a control logic where the flowrate imposed at the pumping unit is the sum of the flowrates needed in each substations to cover the users’ the thermal demand.

Further details are reported below, component by component.

Biomass boiler

The biomass boiler has been modelled starting from *Type 700* of the Trnsys TESS library (*Simple boiler with efficiency inputs* [27]). This subroutine calculates the thermal power required to keep a certain mass flow of the carrier, the thermal oil in this case, above a set point outlet temperature. Taking into consideration a constant boiler efficiency throughout the year, the subroutine calculates then the PE used.

ORC Module

Thanks to the availability of performance data at partial load, the ORC module has been simulated as a *black box*, through data interpolation. To this end, the *Type 581 (Multi-dimensional data interpolation* [27]) from the TESS library has been adopted. The available nominal data at partial load, obtained by the producer company, were elaborated to draw a nominal performance map for the ORC module, able to provide thermal and electric efficiencies and the outlet temperatures of oil and water in function of the thermal input at the evaporator (Fig. 6).

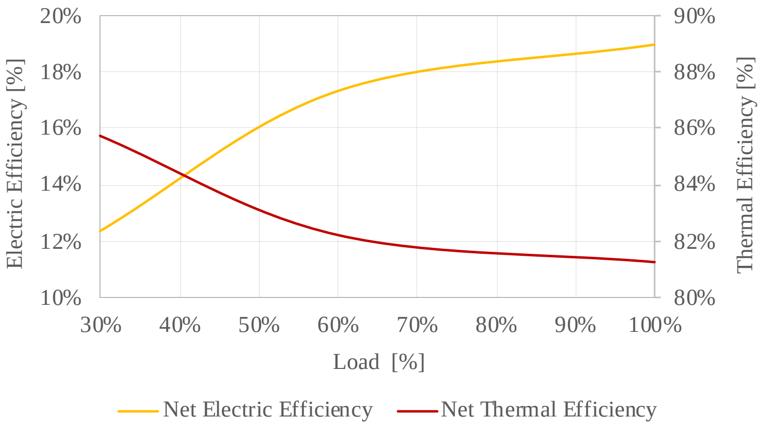

Fig. 6. Nominal net electric and thermal efficiency at partial load of the ORC

Control logic (CL)

The simulation starts at each time-step by calculating, in each substation, the value of water flow rate needed to exchange with the user side's network the amount of heat to match the heating demand of the buildings. In this model, the heat demand of the users is considered to be equal as the heat exchanged into the substation HX, without simulating the distribution efficiency in the user's side (distribution losses on users' loop are already included into the heat load data).

The circulating flow rate in the whole network is assumed then to be the sum of the computed substations' flow rates, and it is pumped in the network by the main pump in the central thermal station. Once the flow rate of water requested by the DHN has been heated up to the set temperature by the combination of the ORC's condenser and the auxiliary HX (when needed), it is supplied to the network. At each substation node, a diverter is installed and controlled to convey the proper fraction of the flow rate into the substation in order to satisfy the heat demand of each

For the simulation of the flat-plate HX in the substations, and the assessment of the amount of water flowing into each substation, the *Type 512* (*sensible heat exchanger with hot-side modulation* [27]) has been adopted. The algorithm of this component computes at each time step a control signal (CSsst,i) between 0 and 1 for regulating the operation of an hydraulic pump placed upstream the HX (source side) in order to satisfy a heat demand on the load side (users' secondary loop). The flowrate that is needed in each substation's HX ($m_{SST,HXi}$) is calculated with Eq. 1 and allow to determine at each time step, according to the supply temperature in previous time step, the amount of heat delivered to each substation.

Considering the technological limit of the hydraulic pumps installed in the central unit of the case study (minimum flowrate equal to 90 m^3/h), in each substation a minimum flowrate is set

(m_{H_min}). The final value of flowrate for each substation ($m_{sst,i}$) is calculated at each time step with Eq. 2 and Eq. 3 in relation the users heat demand and the minimum flowrate of pumps. If the minimum flowrate is higher than the requested one, the difference between the two is by-passed (Fig. 7).

$$\dot{m}_{SST,HXi} = CS_{sst,i} \cdot m_{H\_max} \text{ [kg/h]} \qquad \text{[Eq. 1]}$$

$$\dot{m}_{SST,i} = \begin{cases} \dot{m}_{SST,HXi}, & \dot{m}_{SST,HXi} > \dot{m}_{H\_min} \\ \dot{m}_{H\_min}, & \dot{m}_{SST,HXi} < \dot{m}_{H\_min} \end{cases} \text{ [kg/h]} \qquad \text{[Eq. 2]}$$

$$\dot{m}_{bypass} = \dot{m}_{SST,i} - m_{H\_min} \text{ [kg/h]} \qquad \text{[Eq. 3]}$$

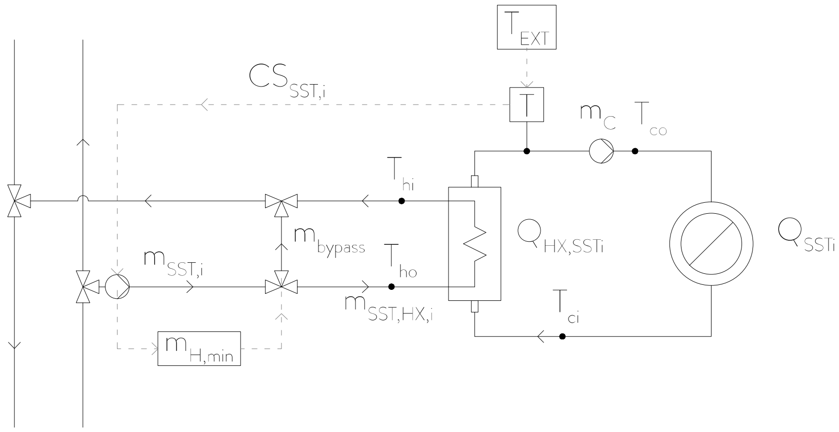

Fig. 7. Scheme of the substation model

Thermal energy storage (TES)

One of the proposed solutions for the improvement of the BDHS energy performance is the adoption of a TES device, currently absent in the real case study. The adoption of a TES in the central unit, at the ORC condenser outlet, enables the absorption of the DHN daily heat load variations, in a way to minimize the amount of heat dissipated. Considering the main features of the case study, the most suitable technology appears to be a steel tank TES filled with water with constant volume, without internal auxiliary heating device, without hydraulic separation of the network and with the storage tank plugged into the primary network in parallel to the respect of the ORC unit and the auxiliary HX. A configuration in series is also tested, but in real condition it would require a complete re-organization of the central unit (higher investment cost)

The sizing process has been carried out through a critical review of the simulation-based daily variations' method described in [28] and [29]. Two main subtasks were accomplished: the definition of the TES volume and its integration within the model. This component is modelled by *Type 158* (*Thermal Storage - Constant Volume Liquid* [30]), representing a cylindrical tank with a vertical configuration, fluid-filled with constant volume.

Distribution network

The heat distribution network consists in a twin pipe trench (supply and return) divided into a main branch and the secondary ones reaching the substations. Heat losses along the network depend on the difference of temperature between the ground and the heat carrier, the surface of the pipes (length and diameters) and the property of the ground and of the pipes.

The distribution network is modelled by *Type 951* from the Trnsys TESS library (*buried twin-pipe* [27]). The heat transfer model is based on the borehole thermal resistance and the fluid-to-fluid thermal resistance. This subroutine basically models a double cylindrical pipe (supply and return) that is filled with liquid and which is buried at a uniform depth below ground. The liquid in the pipe is modelled as an axial series of isothermal liquid nodes.

Heat demand model

Considering the challenge of simulating the whole system's behaviour and the availability of data at weekly level as heat demand in the different substations, an approach based on historical data and external temperatures has been adopted. This approach (Fig. 8) allows to parametrize the heat absorbed by a group of buildings in the substations starting from historical data from the monitoring campaign (daily, weekly or monthly) according to the external temperature of a reference year *x*.

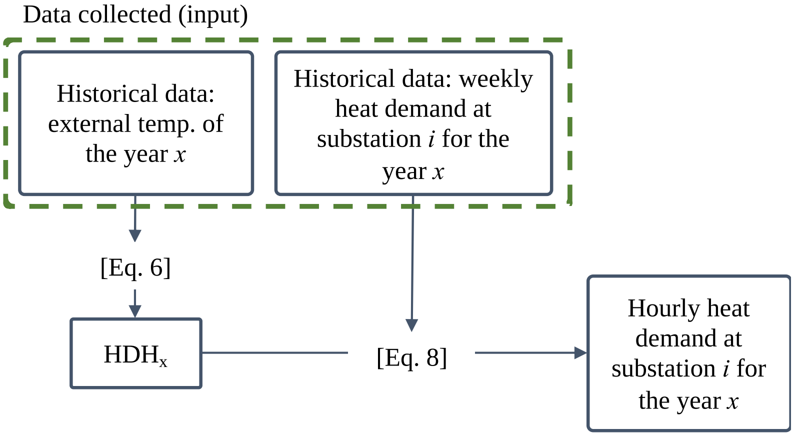

Fig. 8. Scheme of the method adopted for modelling the heat demand of users

In this case the approach results to be quite accurate considering that all the buildings connected to the case study network, a part space orientation, are identical, with same materials, volumes, envelope and age of construction. Indeed, the hourly heat demand for SH of each building can be expressed as [24]:

$$Heating\ demand\ [kWh] = U\ \left[\frac{kW}{m^2 \cdot K}\right] \cdot A\ [m^2] \cdot HDH\ [K \cdot h] \qquad \text{[Eq. 4]}$$

Where:

- U: thermal transmittance of building's envelope;
- A: building's envelope surface;
- HDH: Heating Degree-Hours related to the geographical location of the building.

Considering that differences of the thermal flows (U·A) values between the buildings of the case study district are negligible, the HDH concept alone has been used to disaggregate the weekly historical data collected at hourly level. This process allows to determine a heat load model for one year with hourly scale, referred to the year in which the data were collected.
The case study BDHS supplies hot water for heating to the residential units during day and night, no DHW or space cooling is provided. The measured data of heat absorbed at the substations' HXs are available with a weekly rate for each of the 5 substations for a several heating seasons.

Since heating is provided also during night (by regulations, in Italy RES' fuelled heating plants have no time restrictions in providing heat to residential users [23]) two different set point temperatures have been adopted to calculate the HDH values.

$$\begin{aligned} \mathrm{T_{set\_day}} &= 20\ ^{\circ}\mathrm{C} \text{ from 7:00 to 23:00} \\ \mathrm{T_{set\_night}} &= 15^{\circ}\mathrm{C} \text{ from 23:00 to 7:00} \end{aligned} \qquad \text{[Eq. 5]}$$

$$\mathrm{HDH} = \begin{cases} \mathrm{T_{set\_day}} - \mathrm{T_{ext}}, & 5{:}\,00 < \mathrm{t} < 23{:}\,00 \\ \mathrm{T_{set\_night}} - \mathrm{T_{ext}}, & 23{:}\,00 < \mathrm{t} < 5{:}\,00 \end{cases} \qquad \text{[Eq. 6]}$$

$$\mathrm{HDH}_{week} = \sum_{i}^{week} \mathrm{HDH}_i \qquad \text{[Eq. 7]}$$

$$\mathrm{Q}_i = \mathrm{Q}_{\mathrm{week},i} \cdot \frac{\mathrm{HDH}}{\mathrm{HDH_{week}}} \qquad \text{[Eq. 8]}$$

Where:

$\mathrm{T_{set}}$	°C	Reference set point temperature inside the heated buildings
$\mathrm{T_{set}}$	°C	Monitored hourly external temperature
HDH	K h	Heating Degree Hours
$\mathrm{HDH_{week}}$	K week	Weekly sum of HDH
$\mathrm{Q}_{\mathrm{week},i}$	MWh	Monitored weekly value of heat absorbed at the substation i
Q_i	MWh	Simulated hourly value of heat absorbed at the substation i

Despite being quite simplified, this method ensures a sufficient accuracy when historical data are available. A greater accuracy could be obtained by simulating the thermal behaviour of each building of the district analysed; this topic can be faced as further development of the research, after an accurate evaluation of the "costs and benefits" of such alternative approach, by a comparison of the precision achieved in the estimation of the heat demand and of the effects on the whole model to the increased computational weight.

2.3 Approach to the environmental and economic model

The environmental and economic model has been developed in an Excel spreadsheet as a plug-in of the Trnsys energy model. Part of the output is printed in a .csv[6] file that constitute the dynamic input to the environmental and economic model. The environmental analysis is carried out by combining the data of biomass boiler flue gas flow rate, output of the dynamic simulation, and the concentrations of pollutants. The aim is to highlight the main pollutants emissions related to biomass combustion and compare them with the ones of conventional technologies.

The economic model starts from the simulation output and the data collected at the case study (e.g. electricity consumption) and takes into account the price of heat sold, the cost of biomass, the incentives for electricity etc., in a way to obtain a yearly economic balance.

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[6] A comma-separated values (CSV) file is a delimited text file that uses a comma to separate values. Each line of the file is a data record. Each record consists of one or more fields, separated by commas.

These two parts of the model are integrated in the whole structure of the simulations as summarised by the following scheme (Fig. 9). In tab. 4 the summary of the main assumptions adopted for the evaluations is reported.

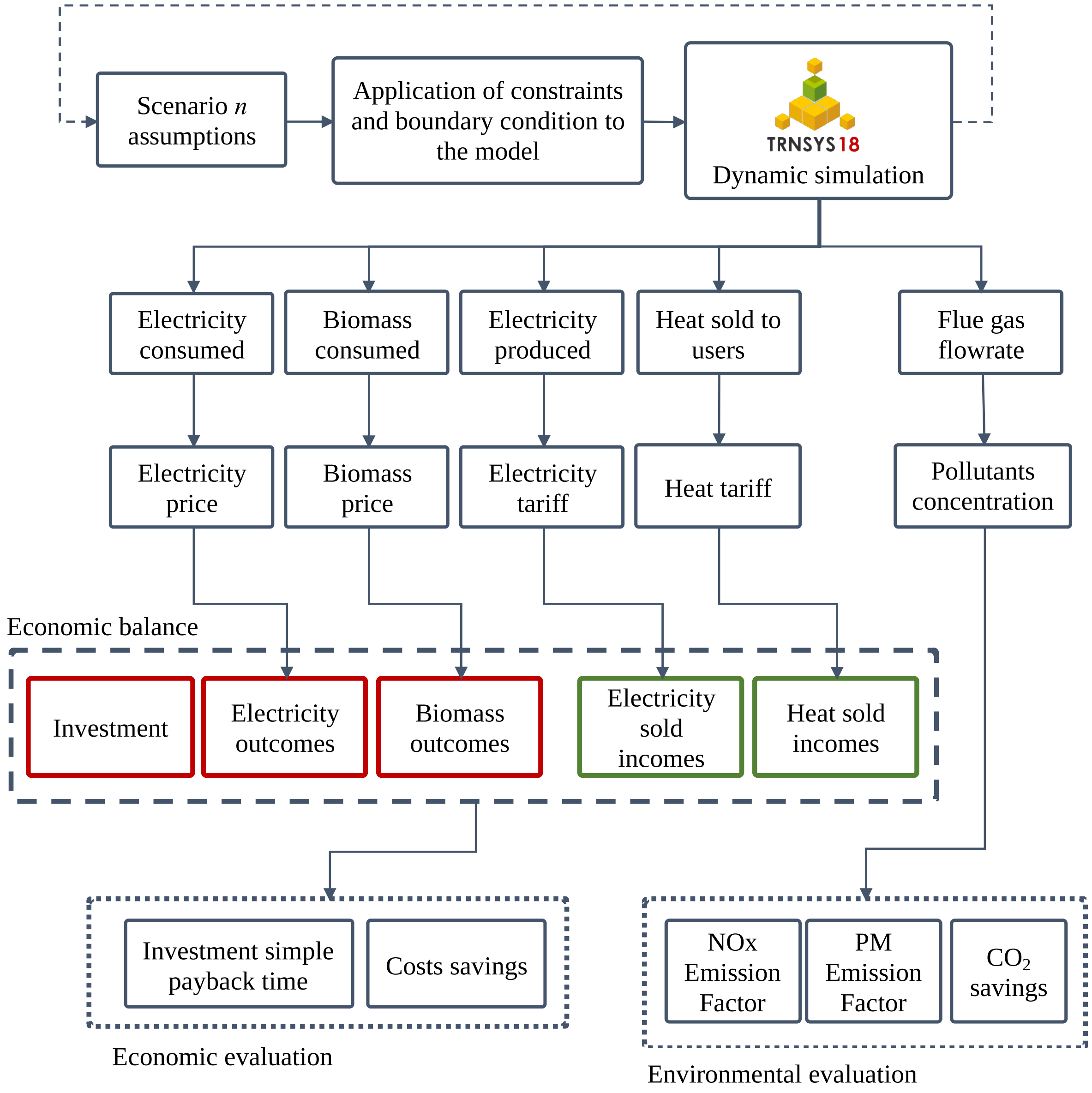


Fig. 9. Approach for economic and environmental evaluation

Table 4. Summary of the main assumptions for the economic and environmental evaluation

Parameter	Unit	Value	Ref.
Woodchip's price	€/ton	42	Available from Camera di Commercio Milano-Brianza [31]
Heat sold tariff	€/MWh	96.27	Statistics from Fiper
Subsidised tariff (feed-in) on electricity sold	€/MWh	280	Feed-in tariff (*Tariffa Omnicomprensiva* [32])
Non-subsidised tariff on electricity sold	€/MWh	F1: 35.65 F2: 39.87 F3: 27.24	Data collected from case study (1)

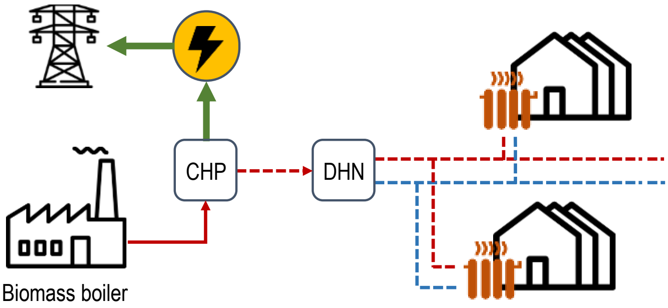
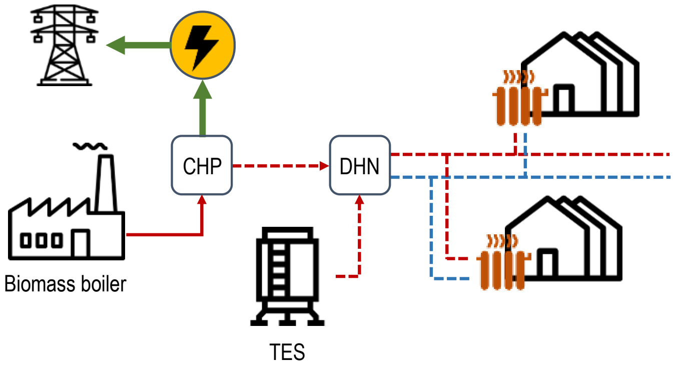
Cost of investment (TES, 320 m^3)	€	220,000	Market price
Low Heating Value (LHV) of woodchip	kWh/kg	2.84	Statistics from Fiper

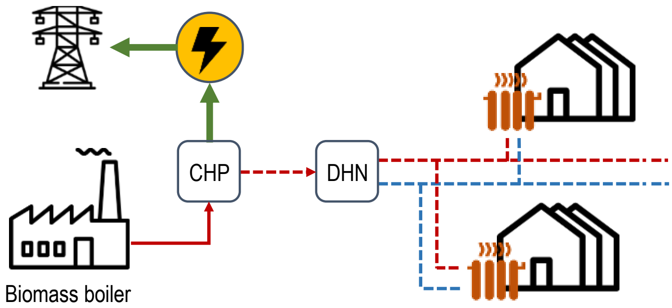
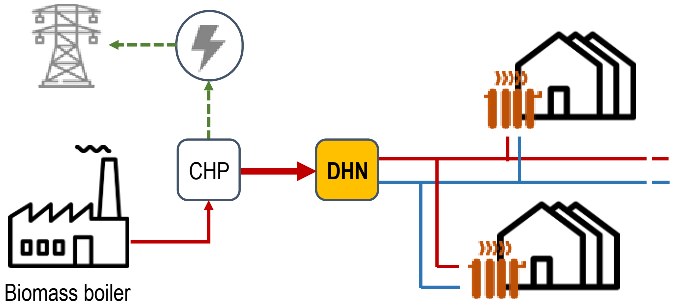
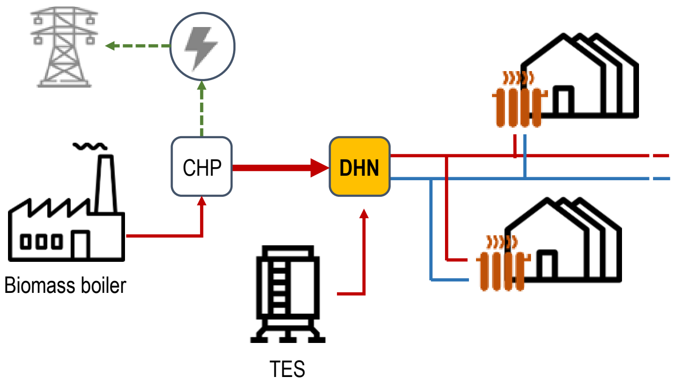
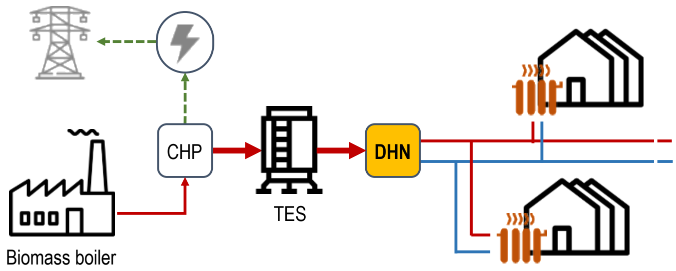
[1] F1, F2, F3 contract typology based on time bands depending on the hour of the day

2.3.1 Definition of scenarios

The developed model is not only adopted to investigate the current performance (i.e. the baseline, called SC_0), but is can be adopted also as optimization tool in order to overcome eventual criticalities, to catch the effects of possible challenging evolutions and measures to enhance the energy performance and the economic appeal of these systems. To that end, based also to the expertise acquired on the DH and on the Italian BDHS sector, for the investigated real case the most promising energy efficient solutions have been individuated and several improving scenarios have been defined accordingly. Main solutions fostered are the integration of TES and a shift in the CL. The scenarios developed, simulated with the same weather file used for the baseline scenario, have been then compared under the energy and environmental point of view. A further analysis on the economic effectiveness of the solutions proposed is provided in terms of simple payback time of the investment involved. The scenarios have been defined following an iterative logic, by adding/varying one property at a time, as described in table 5.

Table 5. Summary of the scenarios defined and simulated

	Layout	**CL**	**TES**	**Support scheme**
SC_0		ED	No	Current (feed-in tariff)
SC_1		ED	Yes (in parallel)	Current (feed-in tariff)

SC_2		ED	No	Absent
SC_3		TD	No	Absent
SC_4		TD	Yes (in parallel)	Absent
SC_5		TD	Yes (in series)	Absent

Scenarios without incentives represent the extreme condition of potential future regimes where the current support scheme would be drastically changed; this will probably implies a shift toward a thermal driven (TD) logic. To this end, SC_3, SC_4 and SC_5 have been defined considering a TD approach, in which the heat production follows the heat demand from users. In these cases, the electricity production is considered as a by-product of the heat produced and is considered to be entirely sold to the grid at the price regulated by the current market. In SC_3 and SC_4, a storage device is added to the model in two different configurations in order to evaluate its effectiveness with a TD approach and the difference between the two configurations.

Through the economic model, a simple payback time for the investment related to storage is calculated in order to evaluate whether the integration of this component could be sustainable or not, under the above-described boundary conditions.

2.4 Key energy, environmental and economic indicators

The energy performance of the case study BDHS has been mainly evaluated through the analysis of the simulation output. However, a set of indicators, listed below, have been defined and calculated for each time step and averaged on the year and the heating season in order to evaluate and compare the different scenarios simulated, where *ex-ante* refers to the energy system substituted by the BDHS and *ex-post* refers to the actual BDHS.

- Thermal Efficiency (Eff_{th}):

$$Eff_{th} = {Q_{th_{sold}}}/{PE_{biom}} \; [\%_{PE}] \qquad \text{[Eq. 9]}$$

- Electric Efficiency (Eff_{el}):

$$Eff_{el} = {Q_{el_{sold}}}/{PE_{biom}} \; [\%_{PE}] \qquad \text{[Eq. 10]}$$

- Primary Energy Factor (PEF) [33]:

$$PEF = {Delivered\ energy}/{Primary\ energy} = \frac{(Q_{th_{sold}} + Q_{el_{sold}})}{PE_{biom}} \; [\%_{PE}] \qquad \text{[Eq. 11]}$$

- DHN losses:

$$DHN\_losses = {Q_{th_{losses,DHN}}}/{Q_{th_{prod}}} \; [\%_{Q,th\_prod}] \qquad \text{[Eq. 12]}$$

- Heat dissipated in dry coolers (DC):

$$DC\_diss = {Q_{th_{diss,DC}}}/{Q_{th_{prod}}} \; [\%_{Q,th\_prod}] \qquad \text{[Eq. 13]}$$

- Fossil Primary Energy savings (fPES):

$$fPE_{savings} = \frac{(fPE_{ex-ante} - fPE_{ex-post})}{fPE_{ex-ante}} \; [\%] \qquad \text{[Eq. 14]}$$

$$fPE_{ex-ante} = Q_{th_{sold}} \cdot \frac{1}{\eta_{th,NG}} \cdot f_{p,nren,NG} + Q_{el_{sold}} \cdot \frac{1}{\eta_{el,NES}} \cdot f_{p,nren,NES} \; [\text{MWh}] \qquad \text{[Eq. 15]}$$

$$fPE_{ex-post} = PE_{biom} \cdot f_{p,nren,biom} \; [\text{MWh}] \qquad \text{[Eq. 16]}$$

Where:

- $\eta_{th,NG}$: Thermal efficiency of NG boilers
- $\eta_{el,NES}$: Electric efficiency of the national electric system
- $f_{p,nren,i}$: Conversion factor in non-renewable PE for the source *i*

The evaluation of the environmental impact is addressed by the comparison between the simulated configurations and the *ex-ante* scenario, in terms of two relevant macro-pollutants emissions. The *ex-ante* scenario is defined according to the geographical location of the case study and consists in natural gas (NG) boilers for SH and the national electric grid for the electricity production. For the EF, an alternative calculation is proposed. This KPI is normally provided in relation with the source of PE. With the aim of comparing EF of the scenarios simulated with conventional technologies, according to the complexity of a BDHS in relation to individual heating devices, the emissions of PM and NOx have been evaluated on the heat sold.
The KPIs considered are the following:

- CO_2 emissions savings ($CO_{2\_savings}$):

$$CO_{2_{savings}} = \frac{(CO_{2\_ex-ante} - CO_{2\_ex-post})}{CO_{2\_ex-ante}} \text{ [\%]} \qquad \text{[Eq. 17]}$$

$$CO_{2\_ex-ante} = Q_{th_{sold}} \cdot \frac{1}{\eta_{th,NG}} \cdot EF_{CO_2\_NG} + Q_{el_{sold}} \cdot \frac{1}{\eta_{el,NES}} \cdot EF_{CO_2\_NES} \text{ [tons]} \qquad \text{[Eq. 18]}$$

$$CO_{2\_ex-post} = PE_{biom} \cdot EF_{CO_2\_biom} \text{ [tons]} \qquad \text{[Eq. 19]}$$

- Emission Factor (EF), based on PE:

$$EF = {\dot{v}_{fluegas} \cdot c_i} \Big/ {Q_{th_{sold}}} \text{ [mg}_i\text{/kWh]} \qquad \text{[Eq. 20]}$$

Where:
- $\dot{v}_{fluegas}$: yearly volumetric flowrate of flue gas [Nm^3]
- c_i: average concentration of the macro-pollutant *i* [mg_i/Nm^3][7]

In the economic evaluations, in order to estimate the impacts only related to the energy fluxes, the investment costs, O&M and interests have been neglected, therefore the yearly cash-flows (Eq. 21) calculated do not represent the actual balance of the plant. Nevertheless, considering that the other costs are more or less constant for all the scenarios, the comparison of the net cash-flows allow to estimate cost savings and payback time, respectively defined in Eq. 22 and Eq. 23. The comparison among different scenarios is divided into two groups, one considering the subsidised tariff on the electricity sold and the other with the non-subsidised one.

- Net cash-flow (CF_{net}):

$$CF_{net} = (profit_{heat} + profit_{electricity}) - (cost_{electricity} + cost_{biomass}) \text{ [€]} \qquad \text{[Eq. 21]}$$

- Cost savings (c_{sav}):

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[7] Data of macro-pollutants' concentration was provided by the case study manager and are referred to the optimal abatement technology, obtaining concentrations far below the law limits

$$c_{sav} = \frac{CF_{SC_i} - CF_{SC_b}}{CF_{SC_b}} \text{ [\%]} \qquad \text{[Eq. 22]}$$

- Simple Payback-Time (PBT):

$$PBT_i = {Investment}/{CF_{net,i}} \text{ [years]} \qquad \text{[Eq. 23]}$$

Where:

- SC_i: Scenario i
- SC_b: Baseline scenario

3 Results and discussion

The results obtained on the basis of the current operative conditions (SC_0) can be resumed as it follows:

- The BDHS, with around 18,021 tons of wooden biomass, is able to distributes 11,699 MWh for SH to the users during the heating season and to provide to the national grid 8,394 MWh of renewable electricity;
- The main benefit is expressed by the fossil PE savings, quantified in the 73% on yearly basis with the respect of the mentioned *ex-ante* scenario;
- Fossil PE savings is mainly related to the heat sold; outside the heating season it depends only by renewable electricity production and, despite the large amount of by-produced heat is dissipated on yearly basis, compared to the national electric grid, it is averagely the 65%.
- The distribution losses through the network account, on yearly basis, to the 12.6% of the heat produced;
- The BDHS enables a 52.3% of annual CO_2 savings with the respect of the *ex-ante* scenario;
- The adoption of best available technologies (BAT) for flue gas treatment enable to limit the emissions of PM and NOx within levels that are suitable also for compromised urban areas.

In addition, the high amount of heat dissipated along a year affects the thermal efficiency and most of the indicators calculated. Therefore, the combination of ED approach and size based on peak is not optimal under the energy and environmental point of view. In fact, the average thermal efficiency on the heating season only is around 47%, far from the one of alternative and conventional heating devices (e.g. individual NG boiler), while the yearly average is around 22%.

3.1 TES integration

The integration of TES represents a valid solution for energy improvement of DHS, well suitable for biomass system (high thermal inertia) and even more suitable when a CHP unit is foreseen. The integration of storage is tested both under ED and TD approach and, in both cases, benefits under the energy point of view are evident.

The TES design has been carried out to absorb the daily variations in the heat load. The storage capacity is designed to be enough to absorb only the positive variations of the load with the respect of the available thermal power at the ORC and not all the variations with the respect of the average daily load (procedure advised for non-CHP plants). Considering the peculiar characteristics of the case study, a volume of 320 m^3 has been assessed as the most suitable for absorbing the daily load peaks.

3.2 Key energy considerations

The main effect on the energy performance related to the integration of a properly sized TES and the shift toward a TD approach is an improved management of the energy fluxes and, as a consequence:

- An overall reduction of the heat dissipated (storage load shifting);
- A slight reduction of the heat losses along the DHN (optimized supply temperature).

In order to appreciate such improvement, in the following table, the main energy KPIs are provided with seasonal and yearly scale for all the configuration simulated.

Table 6. Summary of the environmental KPI for all the configurations simulated

	SC_0 (baseline)	SC_1 (baseline)	SC_3 (baseline TD)	SC_4 (TD+TES-parallel)	SC_5 (TD+TES-series)
fPE savings	72.9%	73%	80.6%	78.5%	83.5%
Eff_{th_y}	22.5%	22.7%			
Eff_{th_hs}	44.7%	45.3%	47.9%	51.4%	56.1%
Eff_{el}	16.8%	16.8%	15.1%	14.9%	16.3%
PEF_{y}	39.3%	39.6%			
PEF_{hs}	61.3%	62.1%	63%	66.3%	72.4%
DHN_{losses_y}	12.6%	11%			
DHN_{losses_hs}	11.7%	10.4%	12.6%	13.2%	13.5%
DC_{diss_y}	56.7%	57.4%			
DC_{diss_hs}	27.3%	26.9%	19.3%	0.3%	4.5%

As a result of the energy evaluation on the scenarios simulated, considering an existing BDHS with a CHP module, a TD approach coupled to the integration of a TES properly sized is resulted to be the optimal configuration among the one tested. For the case study analysed, the shift toward TD logic and the TES in parallel (SC_5) has provided a consistent improvement in terms of thermal efficiency and PEF, respectively increased by the 137% and the 76% with the respect of the baseline scenario.

By analysing the fPE savings at monthly level it is possible to notice that the magnitude of this variable is strictly related to the heat sold: the more the heat produced at the ORC condenser is valorised, the more the plant is able to save fossil PE with the respect of the *ex-ante* scenario. Outside the heating season the value of fPE savings is only given by renewable electricity production and, despite the large amount of by-produced heat through co-generation is dissipated, compared to the national electric grid the case study is able to save averagely the 65% of fPE consumption.

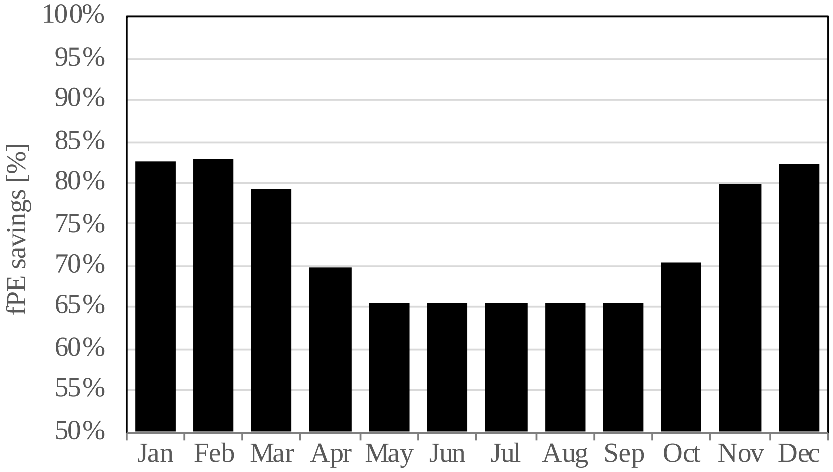

Fig. 10. Monthly distribution of fPE savings for SC_0

In terms of heat losses and dissipation, considering the comparison between SC_0 and the optimal one (SC_5), it is possible to notice that the yearly and seasonal heat dissipation in DC is improved respectively by the 74% and the 54%.

With TD configuration (SC_3), in which the plant operates for only half year i.e. during the heating season, the BDHS case study, in view of an annual consumption of around 8,400 tons of woodchips, is able to produce 3,500 MWh of electricity and to provide to DH users 11,700 MWh for SH.

In the comparison of TES with TD logic to baseline TD, while providing to users the same amount of heat as all the other scenarios (11,700 MWh), the configuration involving TES consumes 7,590 tons of woodchips while dissipating only 33 MWh, the 98% less than SC_3, producing also 3,300 MWh_{el}.

Due to the improved energy fluxes' management given by load shifting, the scenario with TES in TD logic shows an overall higher PEF during the whole heating season.

In order to better understand how the case study works in the different configurations simulated, in the following picture the main energy fluxes are represented for a winter and a mid-season reference day.

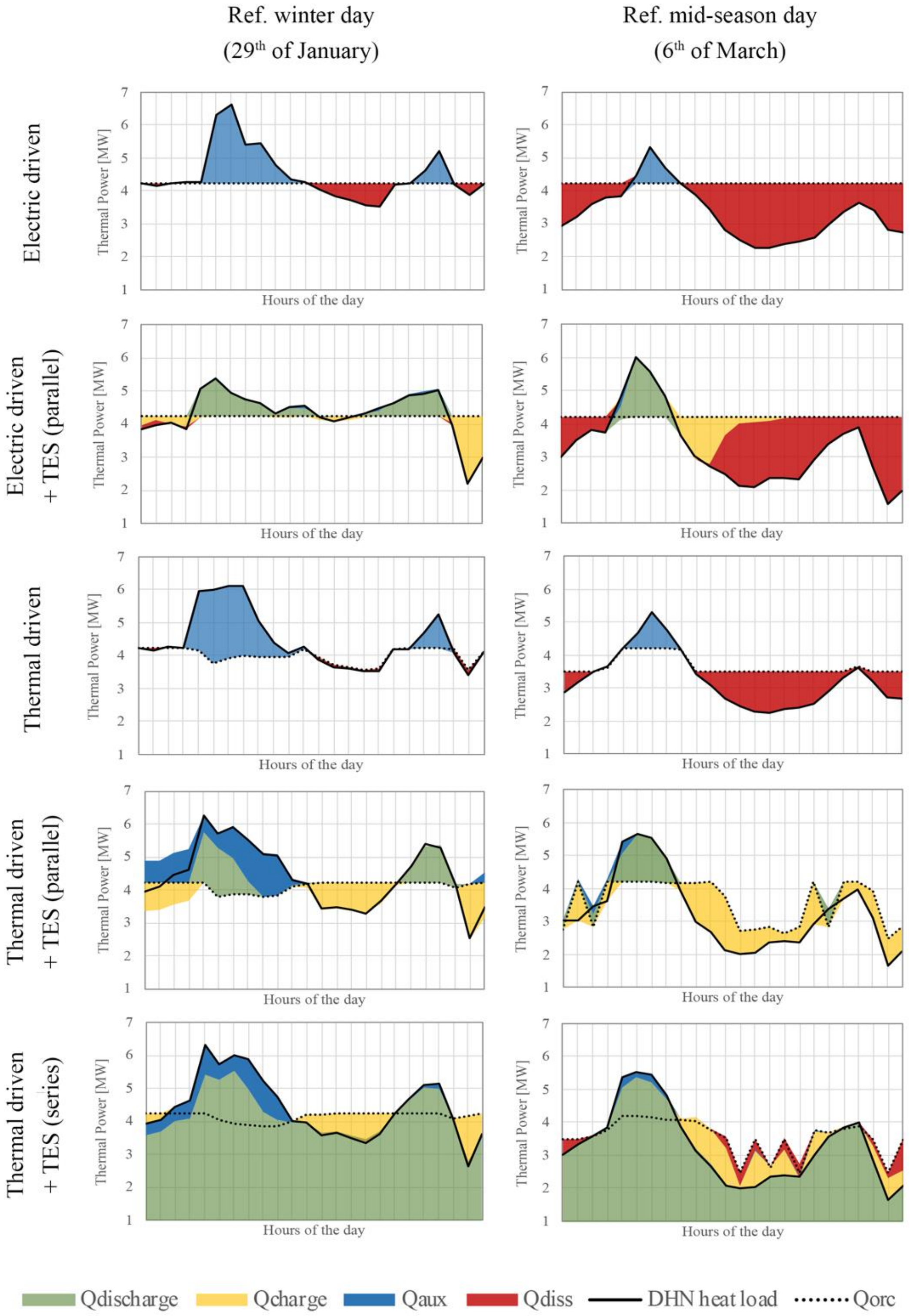

Fig. 11. Main energy fluxes in the high and mid-season reference day. Where Qdischarge is the heat discharged by TES, Qcharge is the heat charged in TES, Qaux is the heat provided by the auxiliary HX, Qdiss is the heat dissipated in DC, DHN heat load is the load at the central unit (users demand + DHN losses) and Qorc is the heat provided by ORC.

3.3 Key environmental indicators

Similar to fPE savings, the baseline in SC_0 shows promising performance in terms of CO_2 savings, with a yearly average of 52.3% in comparison with the *ex-ante* scenario, reaching values of 76,4% for the optimal scenario (SC_5).

On the side of NOx and PM emissions, the comparison between the simulated scenarios and the *ex-ante* scenario highlights a more critical situation, but also in this case best results are achieved for SC_5 (Tab. 7). For the optimal scenario (SC_5), the EF for thermal production calculated for NOx and PM amounted to 305 mg_{NOx}/kWh_{th_sold} and 11.4 mg_{PM}/kWh_{th_sold}, respectively. While the corresponding indicators for a NG boiler amount respectively to 161.2 mg_{NOx}/kWh_{th_sold} and 0.85 mg_{PM}/kWh_{th_sold} according to [19]. This gap between the technology analysed and the reference ones, is mainly due to the nature of the resource used. Indeed, if one hand the use of biomass allows to exploit a widespread and mostly untapped renewable resource allowing high CO_2 and fPE savings, on the other hand considering that biomass is a solid resource, the comparison in terms of NOx and PM emissions with NG technologies, a gaseous resource, is inevitably in favour of NG.

Nevertheless, the results have been also compared to biomass domestic devices (respectively 633.3 mg_{NOx}/kWh_{th_sold} and 686.6 mg_{PM}/kWh_{th_sold} according to [19]: considering the use of biomass for thermal purposes, large plants such as the case study evaluated, allow a more environmentally sustainable use of biomass in comparison of domestic devices. It is important to stress that these comparisons do not take into account the environmental benefits deriving from the electricity generation due to CHP in the *ex-post* scenarios.

Table 7. Summary of the environmental KPI for all the configurations simulated

		SC_0 (baseline)	SC_1 (baseline)	SC_3 (baseline TD)	SC_4 (TD+TES-parallel)	SC_5 (TD+TES-series)
CO_2 savings	%	52.28%	52.34%	71.08%	67.67%	76.40%
EF_{Th_PM}	mg_{PM} / kWh_{th_sold}	28.6	28.5	13.4	12.1	11.4
EF_{Th_NOx}	mg_{NOx} / kWh_{th_sold}	761.9	759.5	356.2	323.1	305.0

3.4 Key economic indicators

For each scenario, the economic impacts are estimated in terms of cost savings and simple payback time. The scenarios have been divided into two groups depending on the adoption or not of the current subsidised tariff for renewable electricity production.

The baseline scenario has been analysed as it is (with ED logic) but considering the tariff for selling the electricity produced equal to the ones applied to the electricity bought. In this case, outside heating season, the cash flow is negative, even during April and October, when the heat is sold for half a month. Considering that a shift toward a TD approach is evidently needed in this case, a TD control has been simulated. The resulting scenario represents the baseline of the group of scenarios evaluated without the current subsidization scheme in order to assess the economic impact of TES integration with TD approach. The main source of incomes is represented by the heat sold; net incomes are quite reduced in this case, but on yearly level the economic balance result to be still important, around 730 k€. If the yearly cash flow of this scenario is compared to the one of SC_2 (Fig. 12), the net incomes result to be the 140% higher, confirming that without the current subsidization program, an ED approach is no more sustainable.

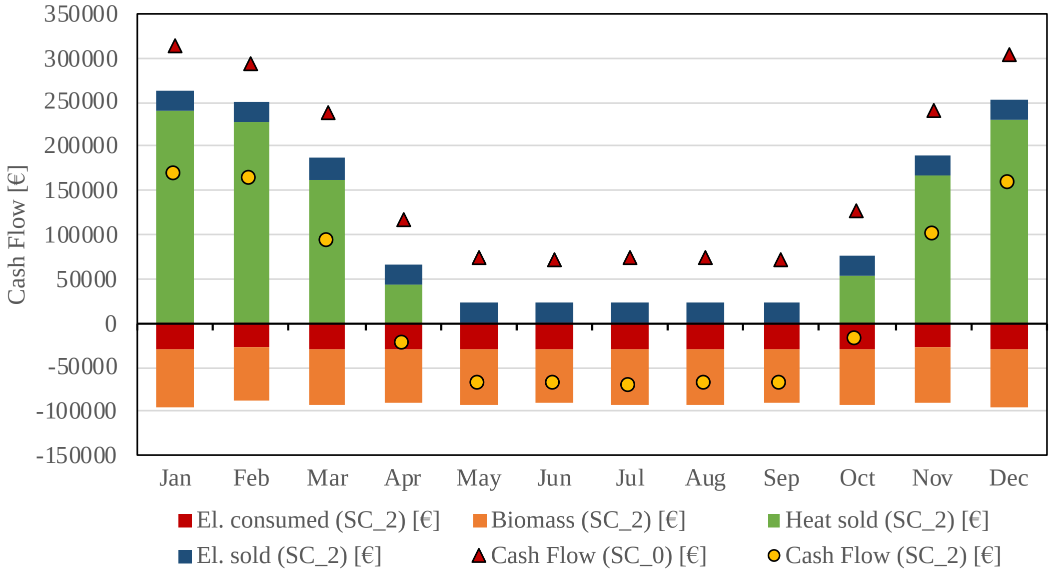

Fig. 12. CF_{net} comparison of SC_0 and SC_2

The comparison between SC_5 and SC_0 shows similar values of biomass valorisation in view of an almost halved biomass consumption. For each ton of biomass burnt the plant is able to generate yearly incomes of about 107 € (112 €/ton for SC_0). More in general the plant in this configuration proved to maintain a certain profitability, 1.69 € of incomes generated for each € spent for plant operations.

The integration of TES, and in particular the configuration in series, results in an improved cash flow. Compared to SC_3, the yearly outcomes increase by the 4% with SC_4 (TES in parallel) and by the 6.3% with SC_5 (TES in series). Accordingly, the simple PBT of the thermal storage calculated for both configurations is around 7.5 years for SC_4 and 4.8 years for SC_5. These features make SC_5 the optimal one.

4 Conclusions and further developments

Currently DHS have a marginal role in satisfying SH in buildings in Italy. In particular, despite the large availability of wood from forests, BDHS satisfy less than 1% of the national SH demand.

However, DHS fuelled by renewable sources or waste heat are constantly increasing and drivers for busting this trend should be activated [34], also toward the achievement of defined targets on thermal renewable sources. To that end, the adoption of innovative methodologies or tools, such as the one proposed in the present paper, could support the design and diffusion of new BDHS. Indeed, as estimated in [19] for the Italian territory, a potential of about 0.8-1.5 GW of power could be installed.

According to [19], the main detected pros of BDHS are related to the possibility of exploiting an almost renewable source, programmable and suitable for thermal purposes, with positive effects in terms of environmental protection, climate change reduction and saving of fossil PE. In addition, despite the difficulties related to the high investment costs (mainly related to the realisation of the networks), benefits on the local economy are evident, also due to the creation of local enterprises. Conversely, the main detected cons of BDHS are related to the economic and normative instability (variation of price of fuels and changes or drastic reduction of the supporting mechanisms), to the new regulatory policies aimed at the standardization of the management and monitoring conditions of DHS also in case of small size systems, and to other non-technical barriers, including eventual preconceptions to biomass combustion for air pollutants reasons. The reduction of heat lost and dissipated between heat generation and final users seems to be the most important driver to improve the efficiency of these systems. And this can be achieved also by an optimization of the coupling between thermal needs of users and thermal production. To this end, it is also important to underline the need of a review of the actual subsidization mechanism for the heat sold through BDHS, currently in favour of users only.

In order to deep these issues, a simulation model has been developed, tested and validated with the capability to explore the technical features and the energy, environmental and economic performance.

From the different results achieved and discussed, lessons have been learnt:

1. Considering the peculiar characteristics of CHP modules (instability, low partial load performance, etc.) and biomass combustion technologies (high thermal inertia, long time delay etc.), the adoption of thermal storage devices is a promising solution thanks to the ability of “decoupling” heat demand and heat production, allowing an improved and more efficient energy management. This feature is extremely important if considering the highly fluctuating nature of heat load profiles the central unit of DHS. For the case study analysed the integration of TES in TD logic allowed to increase the thermal efficiency of the plant by the 20%;
2. The sizing of CHP units should be designed to satisfy the base thermal load from users instead of peaks, in order to guarantee full load conditions for the highest possible number of hours along the year;
3. CHP cogeneration can help in maximizing benefits related to the energy exploitation of biomass. In order to reduce the risk of perverse effects that compromise thermal efficiencies, supporting mechanisms for heat generation should be developed both at local and national level;
4. Despite from the environmental point of view the application of BDHS in urban context remain a delicate issue, if local biomass basins are available, small-medium size systems represent an interesting opportunity toward RES DHC, enhancing also the implementation of circular economy paradigms;
5. Even if the research does not include a systematic economic analysis based on forecasts and alternative scenarios for evaluating the actual evolution of the markets, the economic impact of the feed-in tariff expiration is evaluated; results demonstrate the appropriateness of TES and TD logic.

Further developments of the research could concern the integration of other local renewable sources, taking into account the evolution of the energy market, of the building stock performance, of the climatic conditions, and therefore referring to DHC able to provide both heating and cooling and to adopt cascade heat management, even with low-temperature systems, according also to recent research such as [10]. Moreover, different scenarios of thermal needs (DHW and commercial dwellings) and network extensions could be integrated and evaluated through the model.

In conclusion, this research is a basis for the analytic and systematic identification the future challenges of BDHS in the framework of the path towards sustainable energy systems able to combine energy efficiency and exploitation of local sources, stimulating the diffusion of BDHS in a reasonable and sustainable way.

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References

1. Intergovernmental Panel on Climate Change (IPCC) (2014) Climate change 2014: mitigation of climate change. Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
2. Papadis, E., & Tsatsaronis, G. (2020). Challenges in the decarbonization of the energy sector. Energy, 118025.
3. UNFCCC, Paris Agreement, 12 December 2015. https://unfccc.int/sites/default/files/english_paris_agreement.pdf [last access: 10/5/21]
4. Mathiesen, B. V., Bertelsen, N., Schneider, N. C. A., García, L. S., Paardekooper, S., Thellufsen, J. Z., & Djørup, S. R. (2019). Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. Aalborg Universitet
5. T. Fleiter et al., “Profile of heating and cooling demand in 2015” (2017) Heat Roadmap Europe Deliverable 3.1.
6. IEA (2020), CO2 Emissions from Fuel Combustion: Overview, IEA, Paris
7. Bloomberg NEF. Sector Coupling in Europe: Powering Decarbonization. Potential and policy implications of electrifying the economy. https://www.eaton.com/gb/en-gb/company/news-insights/energy-transition/sector-coupling.html
8. Lund H, Alberg P, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating : Research and results 2018;164. https://doi.org/10.1016/j.energy.2018.08.206.
9. Lund H, Möller B, Mathiesen B V., Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. https://doi.org/10.1016/j.energy.2009.11.023.
10. Caputo, P., Ferla, G., Belliardi, M., & Cereghetti, N. (2020). District Thermal Systems: State of the Art and Promising Evolutive Scenarios. A focus on Italy and Switzerland. Sustainable Cities and Society, 102579.
11. Buffa, S., Cozzini, M., D’Antoni, M., Baratieri, M., & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. Renewable and Sustainable Energy Reviews, 104, 504-522.
12. Lund, H., Østergaard, P. A., Nielsen, T. B., Werner, S., Thorsen, J. E., Gudmundsson, O., Arabkoohsar A., Mathiesen, B. V. (2021). Perspectives on fourth and fifth generation district heating. Energy, 227, 120520
13. AIRU (Italian association of urban heating), 2020 Annual report, Alkes Editrice, 2021 (in Italian).

14. Aste, N., Buzzetti, M., Caputo, P., and Del Pero, C. (2018). Regional policies toward energy efficiency and renewable energy sources integration: Results of a wide monitoring campaign. Sustainable Cities and Society, 36, pp. 215-224
15. Sami, S., & Marin, E. (2017). Simulation of solar photovoltaic, biomass gas turbine and district heating hybrid system. International Journal of Sustainable Energy and Environmental Research, 6(1), 9-26.
16. Sartor, K., Quoilin, S., & Dewallef, P. (2014). Simulation and optimization of a CHP biomass plant and district heating network. Applied Energy, 130, 474-483.
17. Uris, M., Linares, J. I., & Arenas, E. (2015). Size optimization of a biomass-fired cogeneration plant CHP/CCHP (Combined heat and power/Combined heat, cooling and power) based on Organic Rankine Cycle for a district network in Spain. Energy, 88, 935-945.
18. Italian federation involving the most part of the Italian BDHS. https://www.fiper.it [last access: 10/5/21]
19. Caputo, P., Ferla, G., & Ferrari, S. (2019). Evaluation of environmental and energy effects of biomass district heating by a wide survey based on operational conditions in Italy. Energy, 174, 1210-1218.
20. Italian Ministry of Economic Development (MiSE) with Ministries of Environment and Protection of Territory and Sea, of Infrastructures and Transports, of Health and of Defence. Inter-ministerial Decree 26/06/2015 - Application of the energy performances calculation methodologies and definition of previsions and minimum requirements of buildings. Official Journal of the Italian Republic, 2015 (in Italian).
21. Ferla, G., Caputo, P., Colaninno, N., & Morello, E. (2020). Urban greenery management and energy planning: A GIS-based potential evaluation of pruning by-products for energy application for the city of Milan. Renewable Energy, 160, 185-195.
22. ASHRAE, ASHRAE Guideline 14-2002: Measurement of Energy Demand and Savings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2002.
23. President of the Republic Decree (DPR) 26 August 1993, n. 412, Regulations for thermal plants design, installation, operation and maintenance aimed to the energy consumption control, actuating art. 4, comma 4, of the Law 9 January 1991, n. 10. (In Italian)
24. Talebi, B., Mirzaei, P. A., Bastani, A., & Haghighat, F. (2016). A review of district heating systems: modeling and optimization. Frontiers in Built Environment, 2, 22.
25. http://www.trnsys.com [last access: 10/5/21]
26. http://www.tess-inc.com/trnsys/trnsys.html [last access: 10/5/21]
27. http://www.trnsys.com/tess-libraries/TESSLibs17_General_Descriptions.pdf [last access: 10/5/21]
28. Gadd, H., & Werner, S. (2013). Daily heat load variations in Swedish district heating systems. Applied Energy, 106, 47-55.
29. Pakere, I., Purina, D., Blumberga, D., & Bolonina, A. (2016). Evaluation of thermal energy storage capacity by heat load analyses. Energy Procedia, 95, 377-384.
30. http://www.trnsys.com/assets/docs/03-ComponentLibraryOverview.pdf [last access: 10/5/21]
31. https://www.milomb.camcom.it/rilevazione-prezzi [last access: 10/5/21] (In Italian)
32. Italian Ministry of Economic Development (MiSE) with Ministries of Environment and Protection of Territory and Sea. Law Decree 24/12/2008 - Incentives for the production of electricity from renewable energy sources. Official Journal of the Italian Republic, 2008 (in Italian).

33. Latõšov, E., Volkova, A., Siirde, A., Kurnitski, J., & Thalfeldt, M. (2017). Primary energy factor for district heating networks in European Union member states. Energy Procedia, 116, 69-77.
34. Brückner, S., Schäfers, H., Peters, I., & Lävemann, E. (2014). Using industrial and commercial waste heat for residential heat supply: A case study from Hamburg, Germany. Sustainable Cities and Society, 13, 139-142.

Biomass District Heating System in Italy: a comprehensive model-based method for the assessment of energy, economic and environmental performance

ABSTRACT

In the framework of the energy strategy toward 2050, district heating systems (DHS) offers a great flexibility in terms of heat generation technologies and renewable resources integration, resulting, in case of proper management and supply conditions, in fossil primary energy and greenhouse gases savings compared to conventional technologies. In Italy, only the 2.5% of the thermal final uses are satisfied by DHS and, although widely available over the territory, those fuelled by wooden biomass represent less than the half of the total. Many studies in this framework have highlighted the need of methods and tools for a better understanding of the operative conditions, of the potentialities and of the optimal evolution of biomass DHS. To that end, a proper simulation model has been developed and calibrated on a real case study operating in cogeneration, in an urban area of Northern Italy. After investigating the current performance of the real case, some criticalities have been described and new operating scenarios have been defined and simulated. The achieved results represent a support for the stakeholders involved in BDHS and for future energy policies, providing hints on possible challenging evolutive scenarios and on measures to enhance the energy performance and the economic appeal.

KEYWORDS

Biomass; District Heating Systems; Energy Simulation Model; Energy and Environmental Performance; ORC; Real cases.

NOMENCLATURE

RE: Renewable Energy
PE: Primary Energy
GHG: Greenhouse Gases
SH: Space Heating
RES: Renewable Energy Source
HP: Heat Pump
DHS: District Heating System
DH: District Heating
HDH: Heating Degree Hour
DHW: Domestic Hot Water
TD: Thermal Driven
PEF: Primary Energy Factor
DC: Dry Coolers
NG: Natural Gas
CF_{net}: Net Cash-Flow
PBT: Payback Time
BAT: Best Available Technology
DHC: District Heating and Cooling
BDHS: Biomass District Heating System
EF: Emission Factor
CHP: Combined Heat and Power
DHN: District Heating Network
ED: Electric Driven

ORC: Organic Rankine Cycle
HX: Heat Exchanger
CL: Control Logic
SCR: Selective Catalic Reduction
HDD: Heating Degree Day
SST: Substation
TES: Thermal Energy Storage

1 INTRODUCTION

Despite the growth of the renewable energy (RE) share in the global primary energy (PE) supply in the last decade, according to the recent developments in the European and global strategies [1] all countries are called to decarbonize the energy sector in the future.

This process involves though several challenges due to the interdependencies between the energy sector and the economic, social and environmental dimensions of human development [2].

Achieving the EU climate objectives (i.e. a reduction of the overall greenhouse gas (GHG) emissions by 80-95% by 2050 compared to 1990 levels [3]) requires indeed a complete transformation of the energy system [4].

One of the main challenges for the building sector, which is one of the main contributors to GHG emissions and PE consumption, is the decarbonization of the heating and cooling sector that is dominated by space heating (SH) and accounts for approximately 50% of EU-28 final energy demand and around the 80% of the end-use energy in European buildings [5]. Among the available renewable energy sources (RES), till now only biomass has been widely used for heating purposes (12%), while solar thermal, geothermal and heat pumps (HP) are still marginal in many countries [6]. Thermal needs are mainly provided by domestic devices operating at building level or at buildings unit level. An alternative solution is represented by district heating systems (DHS) that implies an infrastructure for distributing heat produced in a centralized facility through a network of underground insulated pipes for covering residential and commercial heating demands such as SH and domestic hot water (DHW).

DHS appears in Europe at the beginning of the 20th century and currently covers the 10% of the heating market with approximately 6,000 different systems and a global distribution network’s trench length of almost 200,000 km [7]. Due to its flexibility, DHS can be fuelled by fossil fuels, renewable energies and waste heat. DHS have undergone an evolution and technological maturation [8] that placed them in an important position in the modern European carbon emissions mitigation challenges [9]. Several review studies carried out concerning the European context provided a precious effort in the definition and classification of DHS evolution [10]. One recognized classification identifies five different DHS generations. The first and second generations were mainly fuelled by coal steam boilers or fossil CHP; hot water on the users’ side was 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, i.e. 60-70°C) and the reduction in the heat demand of buildings, the third generation is characterized by reduced distribution temperatures (80-90°C) of water. The evolution toward the fourth and fifth generations has been characterized by a further lowering of the distribution temperatures, higher energy efficiencies, integration with RES and higher automation [11].

Research on solutions for improving 2nd and 3rd generation DHS, as the one here presented, are as fundamental as the ones on 4th and 5th generation DHC considering that they currently co-exist and their development runs in parallel, for the following reasons:

- 3rd generation DHS are the most diffused in Europe and Italy [10];
- Many emission sub-systems in existing buildings work with high temperatures;
- HT industrial waste heat, HT geothermal heat and biomass are largely available and more suitable for 3rd generation DHS [12].

At the end of 2019, in Italy, with about 250 plants, DHS covered around 2.5% of the total heat demand, with a total thermal capacity, i.e. the total of basic and backup power installed, of 9,065 MW, which 906 MW are provided by CHP (combined heat and power) [13]. Presently the most part of these plants is fuelled by fossil fuels [14], underlining the urgent need of a transition towards RES-based DHS.

Even if the development of a comprehensive model for dynamically simulating the operations of a BDHS is quite rare in literature, most of the studies focus indeed on a particular component (such as the biomass boiler, the ORC or the distribution network), few recent contributions can be found, e.g. [15], [16] and [17]. The authors of [15] proposed a detailed dynamic optimization model of gas turbine Biomass-CHP hybrid systems, applied to DHS. The model studied, validated with measured data, was used to analyse and to define the optimal size of the components in such hybrid systems. Similarly, the authors of [16] presented a model-based methodology for the assessment of the energy, economic and environmental performance of a biomass CHP connected to a DHS. The model proposed, quite simplified for the part simulating the users heat demand (measured data are taken as input), is instead highly detailed for what concern the generation unit, especially for the biomass combustion model, and the DHN. Main aim of the study is to test the simulation model to assess the average conversion efficiencies of the CHP unit, thus providing reliable estimations for energy cost predictions. Another interesting study is provided in [17], where a simulation tool is developed and used to optimize the size (electric power) of a cogeneration plant based on a biomass-fired Organic Rankine Cycle and connected to an existing district heating network, maximizing profitability.

1.1 Focus on the Italian biomass district heating system framework

The authors have been involved in a long-lasting survey on Biomass DHS (BDHS) associated to Fiper [18] which results are reported in [19] and in other publications in progress. Thanks to the availability of operative data for the most part of the Italian plants it was possible to provide and update a quite exhaustive picture of the national context under the energy, environmental and economic point of view.

The last update of this study, referring to 2019 data, treats 82 BDHS operating in Italy, a sample that can be considered highly representative of the whole national portrait, since, with a total of 423 MW from biomass, it covers the 93% in terms of thermal power with the respect of the total installed thermal power of the Italian BDHS, including also the several mini systems (biomass thermal power ≤ 1 MW) scattered over the territory. A summary of the main features of the sample analysed is provided in Table 1.

Table 1. Summary of the main features of the Italian BDHS updated at the end of 2019 (source of data: Fiper and associated plants)

Parameter	Unit	Value
Numbers of plants of the sample	-	82
Number of plants with co-generation units	-	39
Total installed biomass power	MW	423
Total installed thermal power (biomass and back up boilers)	MW	786
Average size of thermal power (only biomass boilers)	MW	5.1
Gross thermal efficiency	%	74%
Gross electric efficiency	%	18%
Global heat losses (all the sample)	%	33%
Global heat losses (non-CHP plants)	%	29%
Linear heat density	kWh/m/y	1018
Fossil PE savings	%	69%

CO_2 savings	%	65%
CO_2 EF $^{(1)}$	g_{CO2}/kWh	60
NOx EF $^{(2)}$	mg_{NOx}/kWh	355.3
PM EF $^{(3)}$	mg_{PM}/kWh	14.8

EF[1]: emission factor (pollutants emissions divided by PE consumed, in a year)
(1) Based on the values of the current regulation for each fuel, where biomass is considered renewable at 80% [20]
(2) Based on a sample of 32 BDHS
(3) Based on a sample of 28 BDHS

The Italian BDHS are in general small sizes and located in mountain areas, according to the approach that enhance the sustainable use of the resources locally available, but the sustainability of BDHS in urban context is endorsed by several existing examples and related studies [21].

The several local benefits achievable by the spread of BDHS are widely described in [19] where, after investigating the effects of the BDHS taking into account energy, environment and economy aspects, it is underlined the need of methods and tools for a better understanding of the operative conditions, of the potentialities and of the optimal evolution of BDHS. ~~To this end, the present study is aimed at evaluating the performance of an existing BDHS and the effect of improving scenarios through the development of a dynamic simulation model.~~

Considering the current lack of a unified development strategy for the national BDHS context together with the lack of proper tools for system design, the research aims to provide a solid and reliable contribution to stakeholders, decision makers and researchers.

The development of a comprehensive dynamic simulation model able to reproduce the operative conditions of a case study BDHS, selected in a way to be representative of the average plant in the Italian framework, represents an innovative contribution to that end.

The results could support the individuation of actions to be addressed in the future support schemes necessary for the evolution of existing DHS and the optimization of the use of the available biomass by this technology, increasing the interest of stakeholders involved in this supply chain and policymakers.

2 MATERIALS AND METHOD

As anticipated in section 1.1, the research concerns the development of a simulation model tailored on a properly selected real case study. All the components of the model have been calibrated on the basis of monitoring data collected at the case study. The heat load model of users and the heat distribution assumptions have been validated with historical data through the *Ashrae guideline 14* [22] approach, resulting into acceptable error margins according to the selected time scale for the simulations. After investigating the current performance of an existing CHP-BDHS case study, some criticalities have been described and new operating scenarios have been defined and simulated.

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[1] Emission factors represent the quantity of pollutant emitted for a unit of PE (e.g. g_{CO2}/kWh) adopted in an energy conversion process.

2.1 Case study

The selection of the sample real case has been based on the deep knowledge of the Italian BDHS matured over the years. In fact, according to Figure 1, the real case has been selected, among those with a complete set of data, in a way to be representative of the average BDHS in the Italian context and, at the same time, representative of a consistent cluster of CHP-BDHS, for which criticalities and room for improvement have been identified. Moreover, the case study selected is located in an urban area of *Pianura Padana*, a large flat region in northern Italy with well-known environmental criticalities, enabling the possibility to explore such delicate but promising application.

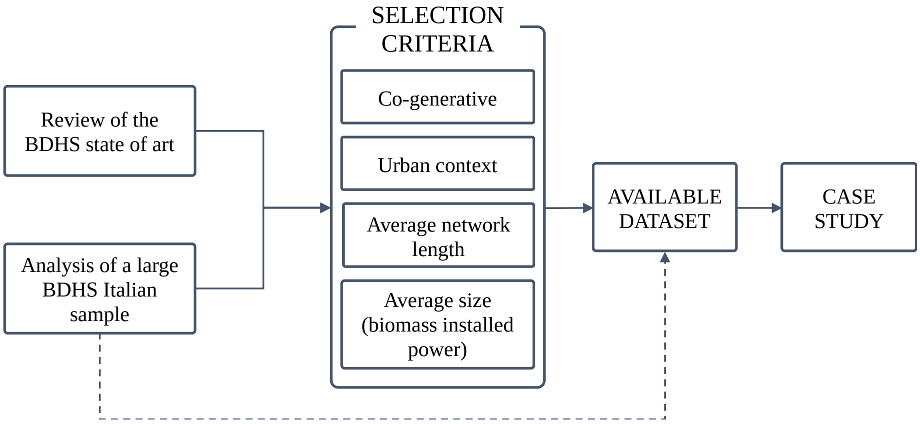

Fig. 1. Procedure for the selection of the real case

The selected BDHS, located near Milan, in a quite densely populated urban area of Lombardy Region, in Northern Italy, was founded in 2009. It is powered by wood chips, coming from the same region. Through a district heating network (DHN) approximately 4 km long, it provides SH to almost 2,000 users while producing electricity, which is fed directly into the national grid.

Due to economic sustainability reasons linked to the support schemes in force for the promotion of renewable electricity generation[2], as many other CHP-BDHS realized in similar contexts, the case study operates with an electric driven (ED) logic: the management is aimed at maximizing the electricity production to be sold to the national grid instead of following the users heat demand. The heat produced by the CHP is however supplied through the DHN to five substations for SH only, i.e. during winter season, i.e. from 15th of October to the 15th of April[3], while no DHW heating is provided. This management logic allows the biomass boiler to operate almost constantly in full load conditions all over the year, however the amount of heat dissipated in summer and mid seasons is quite high.

Core of the generation system is a 9.6 MW woodchips boiler connected to an Organic Rankine Cycle (ORC)[4] module providing nominal powers of about 1 MW electric and 4.2 MW thermal. The cold side of the ORC's condenser is directly plugged into the primary water circuit and

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[2] Electricity is sold to the national electric grid at 0.28 €/kWh, as explained in section 2.3.

[3] Heating season is defined by law in Italy according to the climatic zones based on the range of heating degree days (HDD) [23].

[4] ORC is a quite recent CHP technology that exploit, in a Rankine cycle, the high latent heat in the liquid-vapor phase change of particular organic fluids with high molecular mass.

operates between 90°C and 60°C in nominal conditions. The generation unit is completed by a 3 MW auxiliary flat plate oil/water heat exchanger (HX) that recovers heat from the thermal oil leaving the ORC module during heat demand peaks. An auxiliary biomass boiler (5 MW) and a gas boiler (12 MW) are included into the generation system, but they are never used and hence they will not be included in the model.

The flowrate of water inside DHN pipes is controlled by a differential pressure logic, regulating the operations of the pumping system in the central unit in order to maintain the designed pressure level in the network. Each substation is equipped with two plate HXs connecting the primary DHN loop to the secondary circuits distributing hot water to dwellings. In order to match the heat demand of users, a valve upstream of the HX regulates the inlet flow rate in the DH side.

Table 2. Summary of the main parameters of the case study BDHS

Parameter	Unit	Value
Installed biomass power	MW_{th}	14.6
Installed aux. power	MW_{th}	12
Installed ORC power	MW_{th}	4.2
	MW_{el}	0.99
Fluegas abatment technology		Cyclonic filter, bag filter, DeNOx (SCR[5])
DHN length	km	4
Number of substations	-	5
Heated volume	m^3	160,000

2.2 Energy modelling approach

The present section provides a brief description of the steps required for the development of the model.

According to [24], to address the increasing complexity of DHS design, great effort should be made in developing simplified but complete models with the aim of properly supporting the design of new DHS. A proper model should be able to simulate operative conditions of a system in different configurations in dynamic regime, in a way to assess, in early design phase, the best economic and energy efficient solutions according to the boundary conditions of each case.

The model was implemented through Trnsys [25], a transient simulation environment based on FORTRAN language. The software includes a standard library with approximately 150 models (called *types*) ranging from pumps to multi-zone buildings, wind turbines to electrolysers, weather data processors to economics routines, and from basic HVAC equipment to cutting edge emerging technologies. A further library was available for the present study, developed by TESS [26] integrating the standard one.

~~Many assumptions have been carried out to ensure an appropriate computational weight and to envisage the replicability of the model for other case studies, even if the technological features and the components have been closely tailored on the case study selected.~~

A scheme of the model, including the central unit, the DHN and the substation is reported respectively in Figure 2, 3 and 4.

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[5] Selective catalytic reduction.

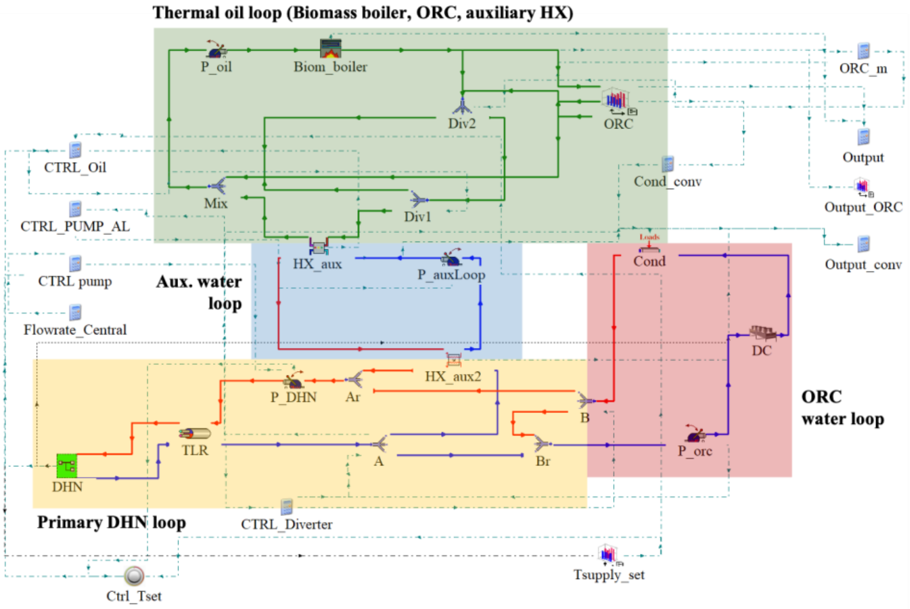

Fig. 2. Trnsys' layout of the central unit sub-routine (screenshot)

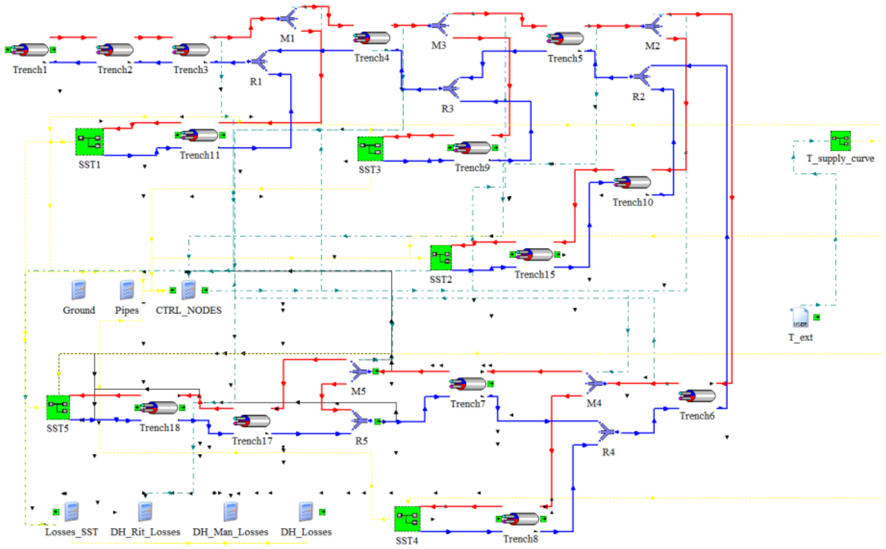

Fig. 3. Trnsys' layout of the DHN sub-routine (screenshot)

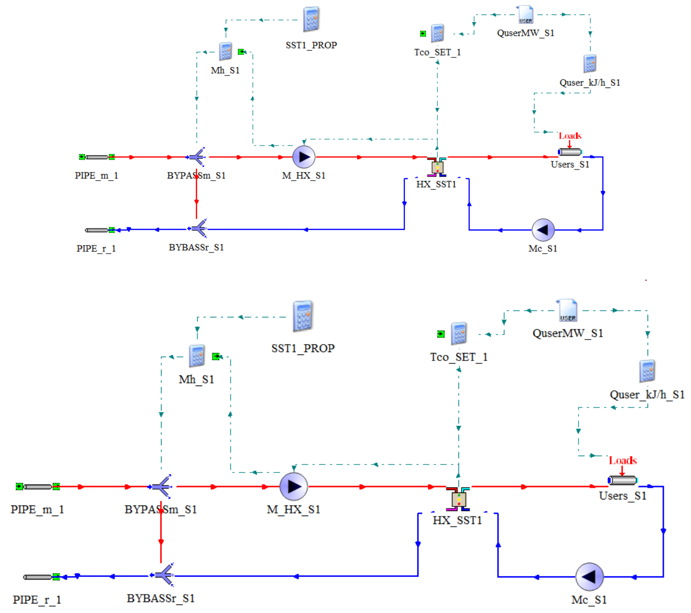

Fig. 4. Trnsys' layout of the substation sub-routine (screenshot)

The central unit subroutine (Fig. 2) is composed by 4 groups of *Types*, representing the thermal oil loop, the auxiliary water loop, the ORC water loop, and the primary water loop. Besides the main technological components (Biomass boiler, ORC unit, pumps and HX), it can be noticed the presence of calculators, useful elements ~~though~~through which the input and output of each component can be adjusted and where the equation for controlling the plant operation can be written (in Fortran language). In Fig. 3, the distribution network is represented. It is composed by the underground pipes (*trench1*, *trench2*, etc.), the diverting and mixing valves and the substations subroutines. In Fig. 4 the *substation 1* subroutine is presented as example, equal to the others. ~~This subroutine~~The latter is composed by a HX connecting the distribution network to the users' loop. As represented, the users' loop is not dynamically simulated, and the heat demand is provided as input through the component "Users_S1".

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2.2.1 Main components ~~of the energy model~~and modelling assumptions

~~The model is divided into three main sub-routine representing the central generation unit, the DHN and the users' side (Figure 5).~~

Many assumptions have been carried out to ensure an appropriate computational weight and to envisage the replicability of the model for other case studies, even if the technological features and the components have been closely tailored on the case study selected.

The selection of the components of the energy model has been carried out to reliably represent the real operative conditions of the system and they are briefly described in the following. The BDHS runs, in the base case scenario, at full load along the whole year, in order to constantly generate about 1 MW of electric power through the ORC module. During the heat load peaks from DHN, an auxiliary water loop within the central unit switches on when the supply temperature falls under the set point temperature (in the range 70-90 °C, according to a specific function based on external temperatures). Actually, for the most part of the winter, the supply temperature is in the range 80-85°C, while the return temperature is in the range 55-65°C.

The set of input and parameters related to the whole model, i.e. the technical features of the components installed in the BDHS and the operative conditions, have been provided by the plant manager. In the following figure (Fig. 5), the general scheme of the model developed is provided and the main constant and variable parameters are highlighted.

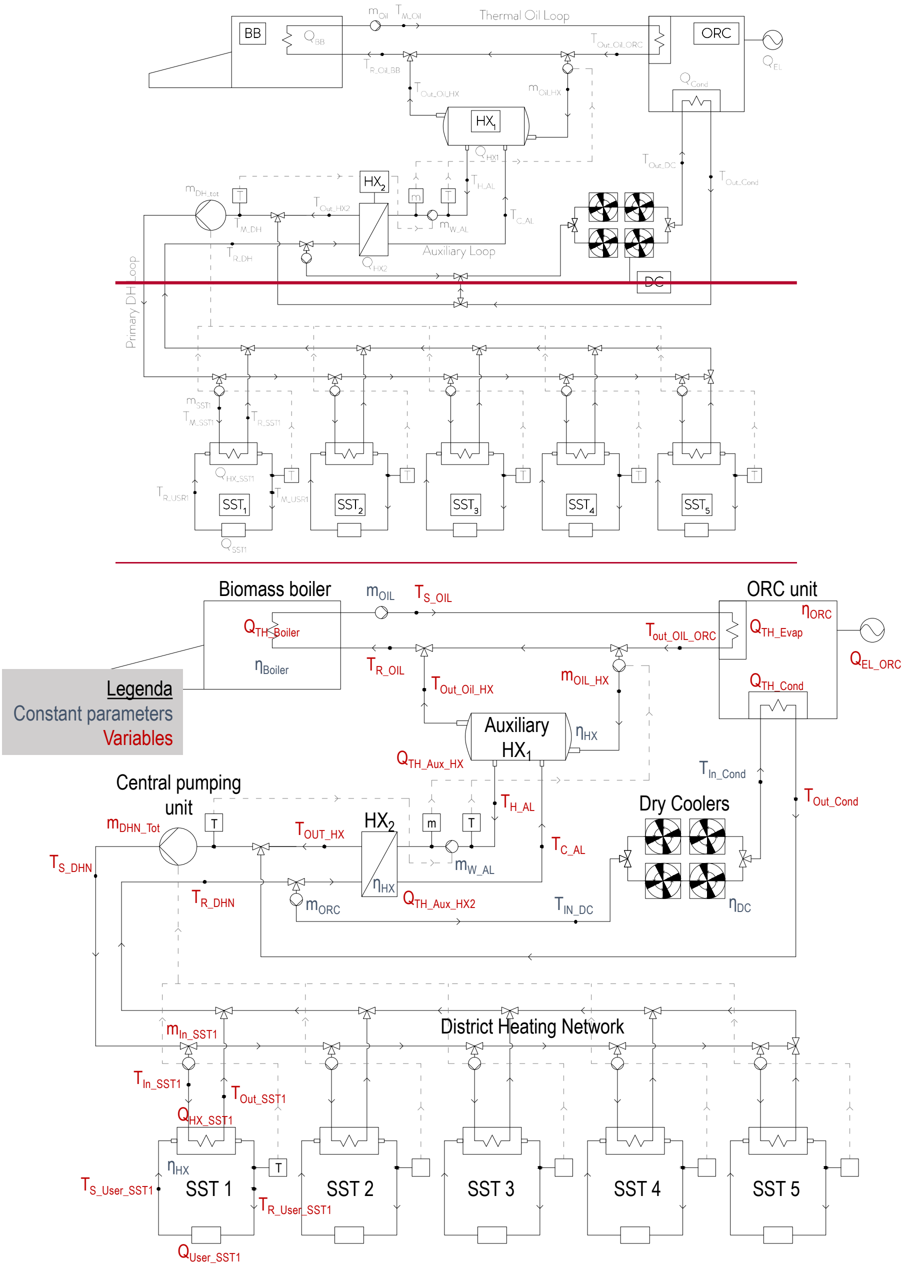

Fig. 5. General layout of the ~~case study~~ model (constant and variable parameters)

In the following table (Tab. 3), a brief explanation of the label used and the corresponding nominal values assigned to each point are provided. Since the values ~~indicated~~provided in the table are the design ones, they represent an indication of the operative conditions, nevertheless such values are computed at each time step in function of the boundary conditions and hence they can vary dynamically.

Table 3 Description of the labels used, and nominal values of the points highlighted in Fig. 5

Label	Description	Nominal values	UM
~~Q_{BB}~~Q_{TH_Boiler}	~~Heat produced in~~Thermal power of the biomass boiler	8	MW
η_{Boiler}	Efficiency of the biomass boiler	0,75	-
m_{Oil}	Thermal oil flowrate	140	m^3/h
m_{Oil_HX}	Thermal oil flowrate in the aux. HX	0-132	m^3/h
~~T_{M_Oil}~~T_{S_OIL}	~~Outlet~~Supply temperature of the thermal oil from biomass boiler	314	°C
$T_{R\_}$~~$_{Oil\_BB}$~~$_{OIL}$	Return temperature of the thermal oil in the biomass boiler	216	°C
η_{ORC}	Efficiency of the ORC components	see Chp. 2.2.1	
η_{HX}	Efficiency of the HXs	0,95	-
η_{DC}	Efficiency of the DCs	0,9	-
$T_{Out\_Oil\_ORC}$	Outlet temperature of the thermal oil from the ORC	254	°C
$T_{Out\_Oil\_HX}$	Outlet temperature of the thermal oil from the HX1	216	°C
~~Q_{HX1}~~$Q_{TH\_Aux\_HX}$	Thermal power exchanged in ~~HX1~~the aux. HX	0-2.4	MW
T_{H_AL}	Hot side temperature of the auxiliary water loop	102	° C
T_{C_AL}	Cold side temperature of the auxiliary water loop	72	°C
~~M_W~~m_{W_AL}	Water flowrate in the auxiliary water loop	72.4	m^3/h
~~m_{Oil_HX}~~M_{ORC}	~~Thermal oil~~Water flowrate ~~deviated~~ in the ~~backup HX1~~ORC water loop	121~~0-132~~	m^3/h
~~Q_{cond}~~Q_{TH_cond}	Thermal power provided by the ORC’s condenser	4.2	MW
Q_{EL_ORC}	Electric power produced by the ORC’s turbine	1	MW
Q_{TH_Evap}	Thermal power absorbed by the ORC’s evaporator	5.3	MW
~~T_{Out_DC}~~T_{In_Cond}	~~Outlet~~Inlet temperature of water ~~from DC~~in the ORC’s condenser	60	°C
T_{Out_Cond}	Outlet temperature of water from the ORC’s condenser	90	°C
T_{In_DC}	Inlet temperature of water in the DCs	60	°C
~~Q_{HX2}~~$Q_{TH\_Aux\_HX2}$	Thermal power provided by the HX2	0-2.4	MW
$T_{Out\_}$~~$_{HX2}$~~$_{HX}$	Outlet temperature of water from HX2	90	°C
~~T_{M_DH}~~T_{S_DHN}	Supply temperature of water in the DHN	90	°C
$T_{R\_}$~~$_{DH}$~~$_{DHN}$	Return temperature of water from the DHN	60	°C
~~m_{DH}~~m_{DHN_tot}	Water flowrate in the DHN	90-400	m^3/h
~~m_{SST1}~~m_{In_SST1}	Water flowrate in substation 1	16-50	m^3/h
~~T_m~~T_{S_SST1}	~~Supply~~Inlet temperature of water in substation 1	90	°C
~~T_r~~T_{R_SST1}	~~Return~~Outlet temperature of water from substation 1	60	°C
Q_{HX_SST1}	Thermal power exchanged in HX of substation 1	0-2	MW

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~~T_{m_USR1}~~$T_{S\_User\_SST1}$	Supply ~~temperature~~temp. of water to users connected to substation 1	90	°C
~~T_{r_USR1}~~$T_{R\_User\_SST1}$	Return ~~temperature~~temp. of water from users connected to substation 1	60	°C
~~Q_{SST1}~~Q_{User_SST1}	Thermal power delivered to users connected to substation 1	0-2	MW

In addition, a set of hypotheses and assumptions have been defined as summarised in the following list:

- The heating demand of users is not dynamically simulated. A simplified method for estimating hourly heat demand from weekly monitored data has been defined, preventing a heavy computational weight. The method is described in the following;
- The distribution losses in the secondary loops and in buildings are neglected. This assumption has been taken into consideration in the definition of the heating demand model, by considering the monitored data measured in the substation HX rather than in buildings;
- The efficiency of the woodchips boiler and HXs is assumed to be constant along the simulation year;
- The control logic has been simplified. While the real operation of the pumping unit is controlled by a differential pressure logic, in the model it has been simplified by implementing a control logic where the flowrate imposed at the pumping unit is the sum of the flowrates needed in each substations to cover the users' the thermal demand.

Further details are reported below, component by component.

Biomass boiler

The biomass boiler has been modelled starting from *Type 700* of the Trnsys TESS library (*Simple boiler with efficiency inputs* [27]). This subroutine calculates the thermal power required to keep a certain mass flow of the carrier, the thermal oil in this case, above a set point outlet temperature. Taking into consideration a constant boiler efficiency throughout the year, the subroutine calculates then the PE used.

ORC Module

Thanks to the availability of performance data at partial load, the ORC module has been simulated as a *black box*, through data interpolation. To this end, the *Type 581 (Multi-dimensional data interpolation* [27]) from the TESS library has been adopted. The available nominal data at partial load, obtained by the producer company, were elaborated to draw a nominal performance map for the ORC module, able to provide thermal and electric efficiencies and the outlet temperatures of oil and water in function of the thermal input at the evaporator (Fig. 6).

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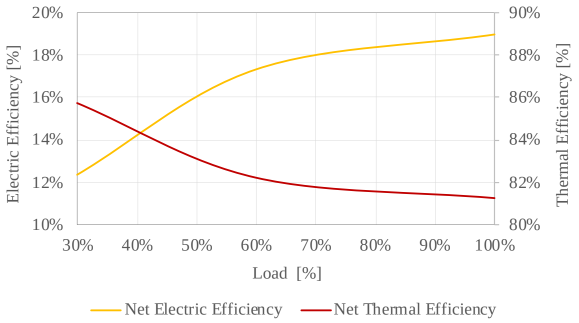

Fig. 6. Nominal net electric and thermal efficiency at partial load of the ORC

Control logic (CL)

The simulation starts at each time-step by calculating, in each substation, the value of water flow rate needed to exchange with the user side's network the amount of heat to match the heating demand of the buildings. In ~~the~~this model, the heat demand of the users is considered to be equal as the heat exchanged into the substation HX, without simulating the distribution efficiency in the user's side (distribution losses on users' ~~buildings.~~

~~The CL modulating the flowrate supplied to DHN is based on a differential pressure control. The amount of water flowing~~loop are already included into ~~each substation is calculated with *Type 512* (*sensible* ~~the heat ~~*exchanger with hot-side modulation* [27]). It simulates the heat exchange in a flat plate HX while calculating a control function to be applied to a modulating pump upstream the HX in order to keep the outlet temperature in the cold side above a defined set-point.~~load data).

The circulating flow rate in the whole network is assumed then to be the sum of the computed substations' flow rates, and it is pumped in the network by the main pump in the central thermal station. Once the flow rate of water requested by the DHN has been heated up to the set temperature by the combination of the ORC's condenser and the auxiliary HX (when needed), it is supplied to the network. At each substation node, a diverter is installed and controlled to convey the proper fraction of the flow rate into the substation in order to satisfy the heat demand of each ~~(Fig. 7).~~

~~When no heat exchange is required at a HX in the substation, a by-pass system diverts the flow rate back into the network in the return pipe.~~

For the simulation of the flat-plate HX in the substations, and the assessment of the amount of water flowing into each substation, the *Type 512* (*sensible heat exchanger with hot-side modulation* [27]) has been adopted. The algorithm of this component computes at each time step a control signal (CSsst,i) between 0 and 1 for regulating the operation of an hydraulic pump placed upstream the HX (source side) in order to satisfy a heat demand on the load side (users' secondary loop). The flowrate that is needed in each substation's HX ($m_{SST,HXi}$) is calculated with Eq. 1 and allow to determine at each time step, according to the supply temperature in previous time step, the amount of heat delivered to each substation.

Considering the technological limit of the hydraulic pumps installed in the central unit of the case study (minimum flowrate equal to 90 m^3/h), in each substation a minimum flowrate is set (m_{H_min}). The final value of flowrate for each substation ($m_{sst,i}$) is calculated at each time step with Eq. 2 and Eq. 3 in relation the users heat demand and the minimum flowrate of pumps. If the minimum flowrate is higher than the requested one, the difference between the two is by-passed (Fig. 7).

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$$\dot{m}_{SST,HXi} = CS_{sst,i} \cdot m_{H\_max} \text{ [kg/h]} \qquad \text{[Eq. 1]}$$

$$\dot{m}_{SST,i} = \begin{cases} \dot{m}_{SST,HXi}, & \dot{m}_{SST,HXi} > \dot{m}_{H\_min} \\ \dot{m}_{H\_min}, & \dot{m}_{SST,HXi} < \dot{m}_{H\_min} \end{cases} \text{ [kg/h]} \qquad \text{[Eq. 2]}$$

$$\dot{m}_{bypass} = \dot{m}_{SST,i} - m_{H\_min} \text{ [kg/h]} \qquad \text{[Eq. 3]}$$

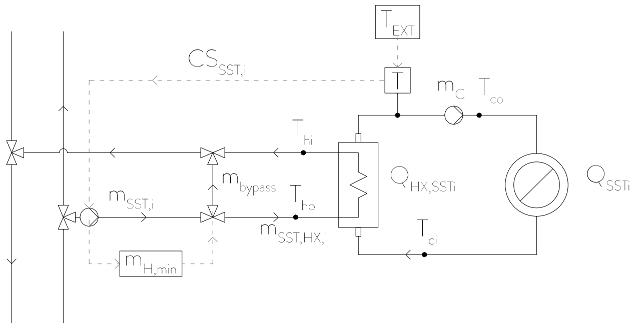

Fig. 7. Scheme of the substation model

Thermal energy storage (TES)

One of the proposed solutions for the improvement of the BDHS energy performance is the adoption of a TES device, currently absent in the real case study. The adoption of a TES in the central unit, at the ORC condenser outlet, enables the absorption of the DHN daily heat load variations, in a way to minimize the amount of heat dissipated. Considering the main features of the case study, the most suitable technology appears to be a steel tank TES filled with water with constant volume, without internal auxiliary heating device, without hydraulic separation of the network and with the storage tank plugged into the primary network in parallel to the respect of the ORC unit and the auxiliary HX. A configuration in series is also tested, but in real condition it would require a complete re-organization of the central unit (higher investment cost)

The sizing process has been carried out through a critical review of the simulation-based daily variations' method described in [28] and [29]. Two main subtasks were accomplished: the definition of the TES volume and its integration within the model. This component is modelled by *Type 158* (*Thermal Storage - Constant Volume Liquid* [30]), representing a cylindrical tank with a vertical configuration, fluid-filled with constant volume.

Distribution network

The heat distribution network consists in a twin pipe trench (supply and return) divided into a main branch and the secondary ones reaching the substations. Heat losses along the network depend on the difference of temperature between the ground and the heat carrier, the surface of the pipes (length and diameters) and the property of the ground and of the pipes.

The distribution network is modelled by *Type 951* from the Trnsys TESS library (*buried twin-pipe* [27]). The heat transfer model is based on the borehole thermal resistance and the fluid-to-fluid thermal resistance. This subroutine basically models a double cylindrical pipe (supply and return) that is filled with liquid and which is buried at a uniform depth below ground. The liquid in the pipe is modelled as an axial series of isothermal liquid nodes.

Heat demand model

Considering the challenge of simulating the whole system's behaviour and the availability of data at weekly level as heat demand in the different substations, an approach based on historical data and external temperatures has been adopted. This approach (Fig. 8) allows to parametrize the heat absorbed by a group of buildings in the substations starting from historical data from the monitoring campaign (daily, weekly or monthly) according to the external temperature of a reference year *x*.

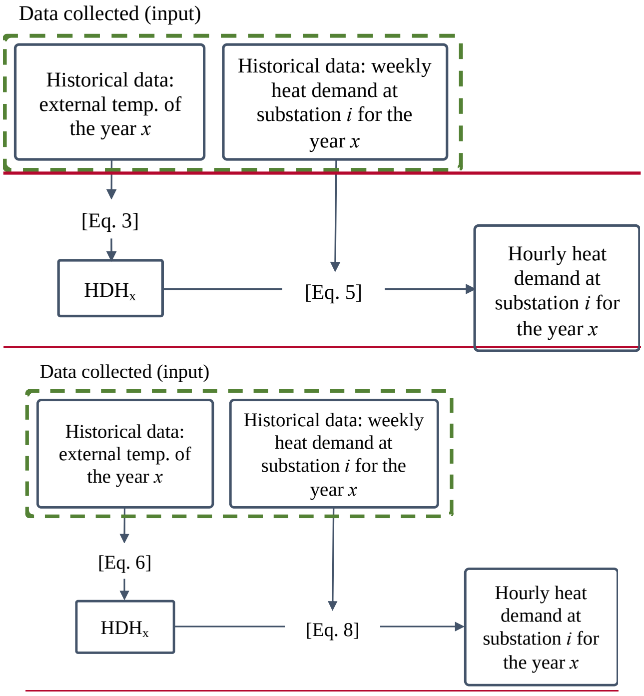

Fig. 8. Scheme of the method adopted for modelling the heat demand of users

In this case the approach results to be quite accurate considering that all the buildings connected to the case study network, a part space orientation, are identical, with same materials, volumes, envelope and age of construction. Indeed, the hourly heat demand for SH of each building can be expressed as [24]:

$$Heating\ demand\ [kWh] = U\left[\frac{kW}{m^2 \cdot K}\right] \cdot A\ [m^2] \cdot HDH\ [K \cdot h] \qquad \text{[Eq. } \cancel{1}\underline{4}\text{]}$$

Where:

- U: thermal transmittance of building's envelope;
- A: building's envelope surface;
- HDH: Heating Degree-Hours related to the geographical location of the building.

Considering that differences of the thermal flows (U·A) values between the buildings of the case study district are negligible, the HDH concept alone has been used to disaggregate the weekly historical data collected at hourly level. This process allows to determine a heat load model for one year with hourly scale, referred to the year in which the data were collected.

The case study BDHS supplies hot water for heating to the residential units during day and night, no DHW or space cooling is provided. The measured data of heat absorbed at the substations' HXs are available with a weekly rate for each of the 5 substations for a several heating seasons.

Since heating is provided also during night (by regulations, in Italy RES' fuelled heating plants have no time restrictions in providing heat to residential users [23]) two different set point temperatures have been adopted to calculate the HDH values.

$$\begin{aligned} \mathrm{T_{set\_day}} &= 20\ ^\circ\mathrm{C} \text{ from 7:00 to 23:00} \\ \mathrm{T_{set\_night}} &= 15^\circ\mathrm{C} \text{ from 23:00 to 7:00} \end{aligned}$$ [Eq. ~~2~~5]

$$\mathrm{HDH} = \begin{cases} \mathrm{T_{set\_day}} - \mathrm{T_{ext}}, & 5:00 < \mathrm{t} < 23:00 \\ \mathrm{T_{set\_night}} - \mathrm{T_{ext}}, & 23:00 < \mathrm{t} < 5:00 \end{cases}$$ [Eq. ~~3~~6]

$$\mathrm{HDH}_{week} = \sum_{i}^{week} \mathrm{HDH}_i$$ [Eq. ~~4~~7]

$$\mathrm{Q}_i = \mathrm{Q}_{\mathrm{week},i} \cdot \frac{\mathrm{HDH}}{\mathrm{HDH_{week}}}$$ [Eq. ~~5~~8]

Where:

T_{set}	°C	Reference set point temperature inside the heated buildings
T_{set}	°C	Monitored hourly external temperature
HDH	K h	Heating Degree Hours
HDH_{week}	K week	Weekly sum of HDH
$Q_{week,i}$	MWh	Monitored weekly value of heat absorbed at the substation i
Q_i	MWh	Simulated hourly value of heat absorbed at the substation i

Despite being quite simplified, this method ensures a sufficient accuracy when historical data are available. A greater accuracy could be obtained by simulating the thermal behaviour of each building of the district analysed; this topic can be faced as further development of the research, after an accurate evaluation of the "costs and benefits" of such alternative approach, by a comparison of the precision achieved in the estimation of the heat demand and of the effects on the whole model to the increased computational weight.

2.3 Approach to the environmental and economic model

The environmental and economic model has been developed in an Excel spreadsheet as a plug-in of the Trnsys energy model. Part of the output is printed in a .csv[6] file that constitute the

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[6] A comma-separated values (CSV) file is a delimited text file that uses a comma to separate values. Each line of the file is a data record. Each record consists of one or more fields, separated by commas.

dynamic input to the environmental and economic model. The environmental analysis is carried out by combining the data of biomass boiler flue gas flow rate, output of the dynamic simulation, and the concentrations of pollutants. The aim is to highlight the main pollutants emissions related to biomass combustion and compare them with the ones of conventional technologies.

The economic model starts from the simulation output and the data collected at the case study (e.g. electricity consumption) and takes into account the price of heat sold, the cost of biomass, the incentives for electricity etc., in a way to obtain a yearly economic balance.

These two parts of the model are integrated in the whole structure of the simulations as summarised by the following scheme (Fig. 9). In tab. 4 the summary of the main assumptions adopted for the evaluations is reported.

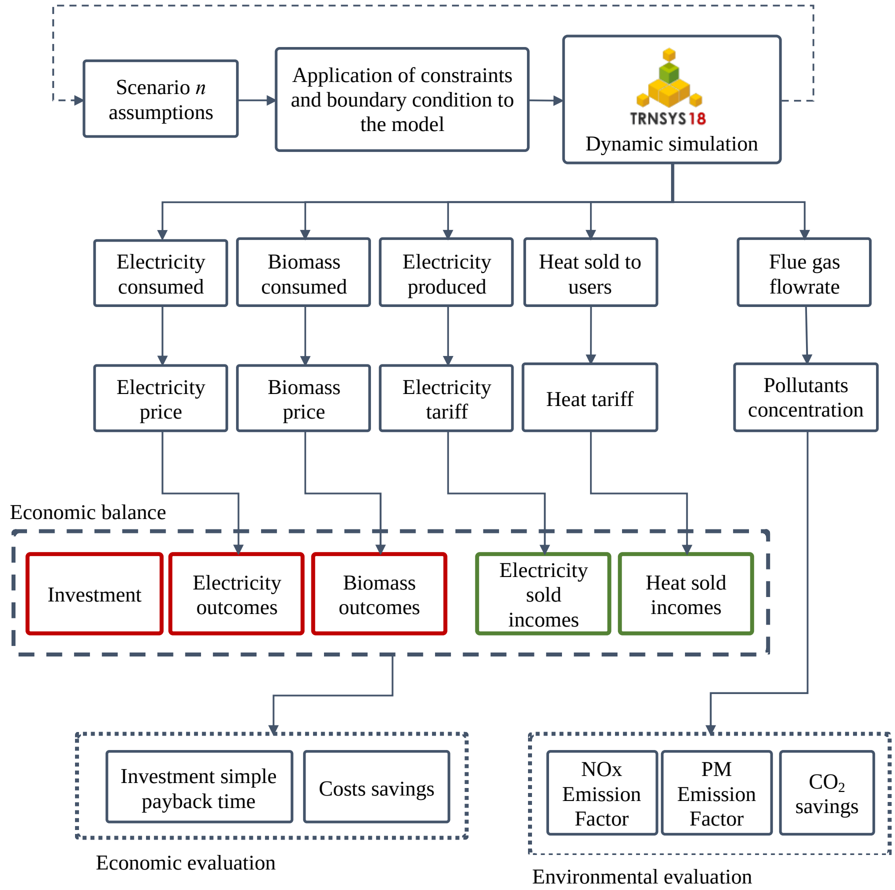


Fig. 9. Approach for economic and environmental evaluation

Table 4. Summary of the main assumptions for the economic and environmental evaluation

Parameter	Unit	Value	Ref.

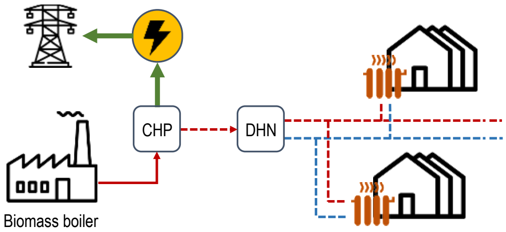
Woodchip’s price	€/ton	42	Available from Camera di Commercio Milano-Brianza [31]
Heat sold tariff	€/MWh	96.27	Statistics from Fiper
Subsidised tariff (feed-in) on electricity sold	€/MWh	280	Feed-in tariff (*Tariffa Omnicomprensiva* [32])
Non-subsidised tariff on electricity sold	€/MWh	F1: 35.65 F2: 39.87 F3: 27.24	Data collected from case study (1)
Cost of investment (TES, 320 m^3)	€	220,000	Market price
Low Heating Value (LHV) of woodchip	kWh/kg	2.84	Statistics from Fiper

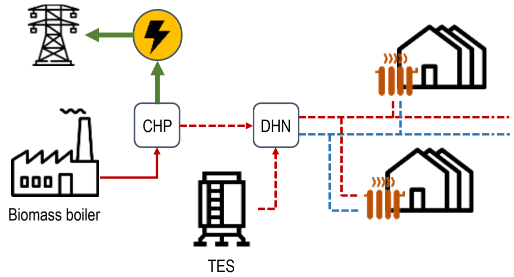
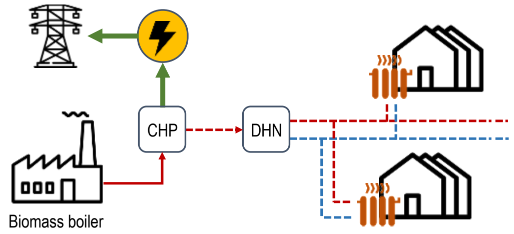
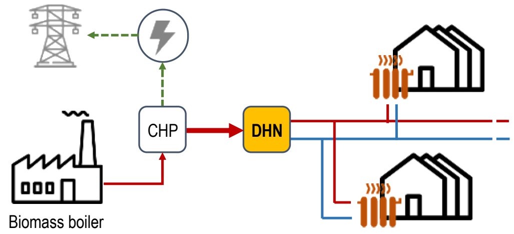
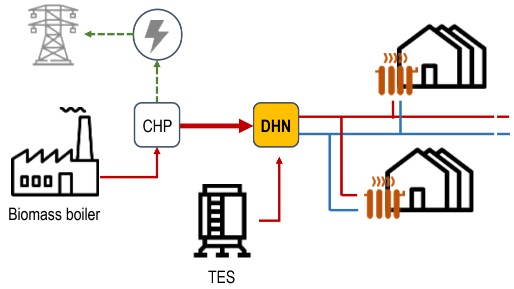
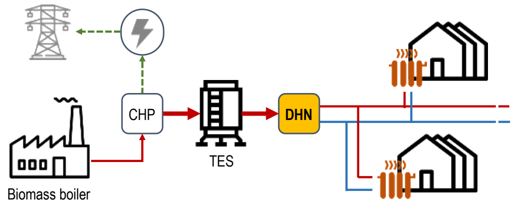
(1) F1, F2, F3 contract typology based on time bands depending on the hour of the day

2.3.1 Definition of scenarios

The developed model is not only adopted to investigate the current performance (i.e. the baseline, called SC_0), but is can be adopted also as optimization tool in order to overcome eventual criticalities, to catch the effects of possible challenging evolutions and measures to enhance the energy performance and the economic appeal of these systems. To that end, based also to the expertise acquired on the DH and on the Italian BDHS sector, for the investigated real case the most promising energy efficient solutions have been individuated and several improving scenarios have been defined accordingly. Main solutions fostered are the integration of TES and a shift in the CL. The scenarios developed, simulated with the same weather file used for the baseline scenario, have been then compared under the energy and environmental point of view. A further analysis on the economic effectiveness of the solutions proposed is provided in terms of simple payback time of the investment involved. The scenarios have been defined following an iterative logic, by adding/varying one property at a time, as described in table 5.

Table 5. Summary of the scenarios defined and simulated

	Layout	**CL**	**TES**	**Support scheme**
SC_0		ED	No	Current (feed-in tariff)

SC_1		ED	Yes (in parallel)	Current (feed-in tariff)
SC_2		ED	No	Absent
SC_3		TD	No	Absent
SC_4		TD	Yes (in parallel)	Absent
SC_5		TD	Yes (in series)	Absent

Scenarios without incentives represent the extreme condition of potential future regimes where the current support scheme would be drastically changed; this will probably implies a shift toward a thermal driven (TD) logic. To this end, SC_3, SC_4 and SC_5 have been defined considering a TD approach, in which the heat production follows the heat demand from users. In these cases, the electricity production is considered as a by-product of the heat produced and is considered to be entirely sold to the grid at the price regulated by the current market. In SC_3 and SC_4, a storage device is added to the model in two different configurations in order to evaluate its effectiveness with a TD approach and the difference between the two configurations.

Through the economic model, a simple payback time for the investment related to storage is calculated in order to evaluate whether the integration of this component could be sustainable or not, under the above-described boundary conditions.

2.4 Key energy, environmental and economic indicators

The energy performance of the case study BDHS has been mainly evaluated through the analysis of the simulation output. However, a set of indicators, listed below, have been defined and calculated for each time step and averaged on the year and the heating season in order to evaluate and compare the different scenarios simulated, where *ex-ante* refers to the energy system substituted by the BDHS and *ex-post* refers to the actual BDHS.

- Thermal Efficiency ($\mathrm{Eff_{th}}$):

$$Eff_{th} = {Q_{th_{sold}}}\Big/{PE_{biom}} \ [\%_{\mathrm{PE}}]$$ [Eq. ~~6~~9]

- Electric Efficiency ($\mathrm{Eff_{el}}$):

$$Eff_{el} = {Q_{el_{sold}}}\Big/{PE_{biom}} \ [\%_{\mathrm{PE}}]$$ [Eq. ~~7~~10]

- Primary Energy Factor (PEF) [33]:

$$PEF = {Delivered\ energy}\Big/{Primary\ energy} = \frac{(Q_{th_{sold}} + Q_{el_{sold}})}{PE_{biom}} \ [\%_{\mathrm{PE}}]$$ [Eq. ~~8~~11]

- DHN losses:

$$DHN\_losses = {Q_{th_{losses,DHN}}}\Big/{Q_{th_{prod}}} \ [\%_{\mathrm{Q,th\_prod}}]$$ [Eq. ~~9~~12]

- Heat dissipated in dry coolers (DC):

$$DC\_diss = {Q_{th_{diss,DC}}}\Big/{Q_{th_{prod}}} \ [\%_{\mathrm{Q,th\_prod}}]$$ [Eq. ~~10~~13]

- Fossil Primary Energy savings (fPES):

$$fPE_{savings} = \frac{(fPE_{ex-ante} - fPE_{ex-post})}{fPE_{ex-ante}} \ [\%]$$ [Eq. ~~11~~14]

$$fPE_{ex-ante} = Q_{th_{sold}} \cdot \frac{1}{\eta_{th,NG}} \cdot f_{p,nren,NG} + Q_{el_{sold}} \cdot \frac{1}{\eta_{el,NES}} \cdot f_{p,nren,NES} \text{ [MWh]}$$ [Eq. ~~12~~15]

$$fPE_{ex-post} = PE_{biom} \cdot f_{p,nren,biom} \text{ [MWh]}$$ [Eq. ~~13~~16]

Where:

- $\eta_{th,NG}$: Thermal efficiency of NG boilers
- $\eta_{el,NES}$: Electric efficiency of the national electric system
- $f_{p,nren,i}$: Conversion factor in non-renewable PE for the source *i*

The evaluation of the environmental impact is addressed by the comparison between the simulated configurations and the *ex-ante* scenario, in terms of two relevant macro-pollutants emissions. The *ex-ante* scenario is defined according to the geographical location of the case study and consists in natural gas (NG) boilers for SH and the national electric grid for the electricity production. For the EF, an alternative calculation is proposed. This KPI is normally provided in relation with the source of PE. With the aim of comparing EF of the scenarios simulated with conventional technologies, according to the complexity of a BDHS in relation to individual heating devices, the emissions of PM and NOx have been evaluated on the heat sold.

The KPIs considered are the following:

- CO_2 emissions savings ($CO_{2\_savings}$):

$$CO_{2_{savings}} = \frac{(CO_{2\_ex-ante} - CO_{2\_ex-post})}{CO_{2\_ex-ante}} \text{ [\%]}$$ [Eq. ~~14~~17]

$$CO_{2\_ex-ante} = Q_{th_{sold}} \cdot \frac{1}{\eta_{th,NG}} \cdot EF_{CO_2\_NG} + Q_{el_{sold}} \cdot \frac{1}{\eta_{el,NES}} \cdot EF_{CO_2\_NES} \text{ [tons]}$$ [Eq. ~~15~~18]

$$CO_{2\_ex-post} = PE_{biom} \cdot EF_{CO_2\_biom} \text{ [tons]}$$ [Eq. ~~16~~19]

- Emission Factor (EF), based on PE:

$$EF = {\dot{v}_{fluegas} \cdot c_i} \Big/ {Q_{th_{sold}}} \text{ [mg}_i\text{/kWh]}$$ [Eq. ~~17~~20]

Where:

- $\dot{v}_{fluegas}$: yearly volumetric flowrate of flue gas [Nm^3]
- c_i: average concentration of the macro-pollutant *i* [mg_i/Nm^3][7]

In the economic evaluations, in order to estimate the impacts only related to the energy fluxes, the investment costs, O&M and interests have been neglected, therefore the yearly cash-flows (Eq. ~~18~~21) calculated do not represent the actual balance of the plant. Nevertheless, considering that the other costs are more or less constant for all the scenarios, the comparison of the net

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[7] Data of macro-pollutants' concentration was provided by the case study manager and are referred to the optimal abatement technology, obtaining concentrations far below the law limits

cash-flows allow to estimate cost savings and payback time, respectively defined in Eq. ~~19~~22 and Eq. ~~20~~23. The comparison among different scenarios is divided into two groups, one considering the subsidised tariff on the electricity sold and the other with the non-subsidised one.

- Net cash-flow (CF_{net}):

$$CF_{net} = \left(profit_{heat} + profit_{electricity}\right) - \left(cost_{electricity} + cost_{biomass}\right) \text{ [€]}$$

[Eq. ~~18~~21]

- Cost savings (c_{sav}):

$$c_{sav} = \frac{CF_{SC_i} - CF_{SC_b}}{CF_{SC_b}} \text{ [\%]}$$

[Eq. ~~19~~22]

- Simple Payback-Time (PBT):

$$PBT_i = {}^{Investment}/_{CF_{net,i}} \text{ [years]}$$

[Eq. ~~20~~23]

Where:

- SC_i: Scenario *i*
- SC_b: Baseline scenario

3 Results and discussion

The results obtained on the basis of the current operative conditions (SC_0) can be resumed as it follows:

- The BDHS, with around 18,021 tons of wooden biomass, is able to distributes 11,699 MWh for SH to the users during the heating season and to provide to the national grid 8,394 MWh of renewable electricity;
- The main benefit is expressed by the fossil PE savings, quantified in the 73% on yearly basis with the respect of the mentioned *ex-ante* scenario;
- Fossil PE savings is mainly related to the heat sold; outside the heating season it depends only by renewable electricity production and, despite the large amount of by-produced heat is dissipated on yearly basis, compared to the national electric grid, it is averagely the 65%.
- The distribution losses through the network account, on yearly basis, to the 12.6% of the heat produced;
- The BDHS enables a 52.3% of annual CO_2 savings with the respect of the *ex-ante* scenario;
- The adoption of best available technologies (BAT) for flue gas treatment enable to limit the emissions of PM and NOx within levels that are suitable also for compromised urban areas.

In addition, the high amount of heat dissipated along a year affects the thermal efficiency and most of the indicators calculated. Therefore, the combination of ED approach and size based on peak is not optimal under the energy and environmental point of view. In fact, the average thermal efficiency on the heating season only is around 47%, far from the one of alternative and conventional heating devices (e.g. individual NG boiler), while the yearly average is around 22%.

3.1 TES integration

The integration of TES represents a valid solution for energy improvement of DHS, well suitable for biomass system (high thermal inertia) and even more suitable when a CHP unit is foreseen. The integration of storage is tested both under ED and TD approach and, in both cases, benefits under the energy point of view are evident.

The TES design has been carried out to absorb the daily variations in the heat load. The storage capacity is designed to be enough to absorb only the positive variations of the load with the respect of the available thermal power at the ORC and not all the variations with the respect of the average daily load (procedure advised for non-CHP plants). Considering the peculiar characteristics of the case study, a volume of 320 m^3 has been assessed as the most suitable for absorbing the daily load peaks.

3.2 Key energy considerations

The main effect on the energy performance related to the integration of a properly sized TES and the shift toward a TD approach is an improved management of the energy fluxes and, as a consequence:

- An overall reduction of the heat dissipated (storage load shifting);
- A slight reduction of the heat losses along the DHN (optimized supply temperature).

In order to appreciate such improvement, in the following table, the main energy KPIs are provided with seasonal and yearly scale for all the configuration simulated.

Table 6. Summary of the environmental KPI for all the configurations simulated

	SC_0 (baseline)	SC_1 (baseline)	SC_3 (baseline TD)	SC_4 (TD+TES-parallel)	SC_5 (TD+TES-series)
fPE savings	72.9%	73%	80.6%	78.5%	83.5%
Eff_{th_y}	22.5%	22.7%			
Eff_{th_hs}	44.7%	45.3%	47.9%	51.4%	56.1%
Eff_{el}	16.8%	16.8%	15.1%	14.9%	16.3%
PEF_y	39.3%	39.6%			
PEF_{hs}	61.3%	62.1%	63%	66.3%	72.4%
DHN_{losses_y}	12.6%	11%			
DHN_{losses_hs}	11.7%	10.4%	12.6%	13.2%	13.5%
DC_{diss_y}	56.7%	57.4%			

DC_{diss_hs}	27.3%	26.9%	19.3%	0.3%	4.5%

As a result of the energy evaluation on the scenarios simulated, considering an existing BDHS with a CHP module, a TD approach coupled to the integration of a TES properly sized is resulted to be the optimal configuration among the one tested. For the case study analysed, the shift toward TD logic and the TES in parallel (SC_5) has provided a consistent improvement in terms of thermal efficiency and PEF, respectively increased by the 137% and the 76% with the respect of the baseline scenario.

By analysing the fPE savings at monthly level it is possible to notice that the magnitude of this variable is strictly related to the heat sold: the more the heat produced at the ORC condenser is valorised, the more the plant is able to save fossil PE with the respect of the *ex-ante* scenario. Outside the heating season the value of fPE savings is only given by renewable electricity production and, despite the large amount of by-produced heat through co-generation is dissipated, compared to the national electric grid the case study is able to save averagely the 65% of fPE consumption.

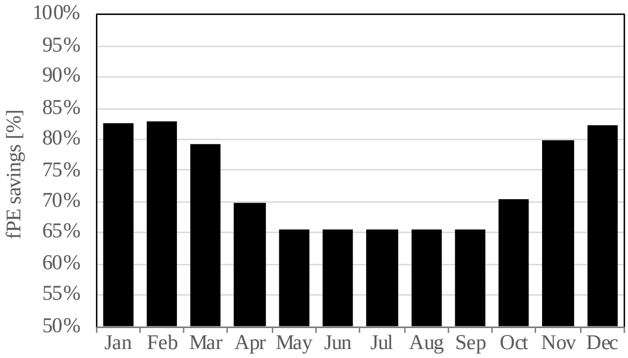

Fig. 10. Monthly distribution of fPE savings for SC_0

In terms of heat losses and dissipation, considering the comparison between SC_0 and the optimal one (SC_5), it is possible to notice that the yearly and seasonal heat dissipation in DC is improved respectively by the 74% and the 54%.

With TD configuration (SC_3), in which the plant operates for only half year i.e. during the heating season, the BDHS case study, in view of an annual consumption of around 8,400 tons of woodchips, is able to produce 3,500 MWh of electricity and to provide to DH users 11,700 MWh for SH.

In the comparison of TES with TD logic to baseline TD, while providing to users the same amount of heat as all the other scenarios (11,700 MWh), the configuration involving TES consumes 7,590 tons of woodchips while dissipating only 33 MWh, the 98% less than SC_3, producing also 3,300 MWh_{el}.

Due to the improved energy fluxes' management given by load shifting, the scenario with TES in TD logic shows an overall higher PEF during the whole heating season.

In order to better understand how the case study works in the different configurations simulated, in the following picture the main energy fluxes are represented for a winter and a mid-season reference day.

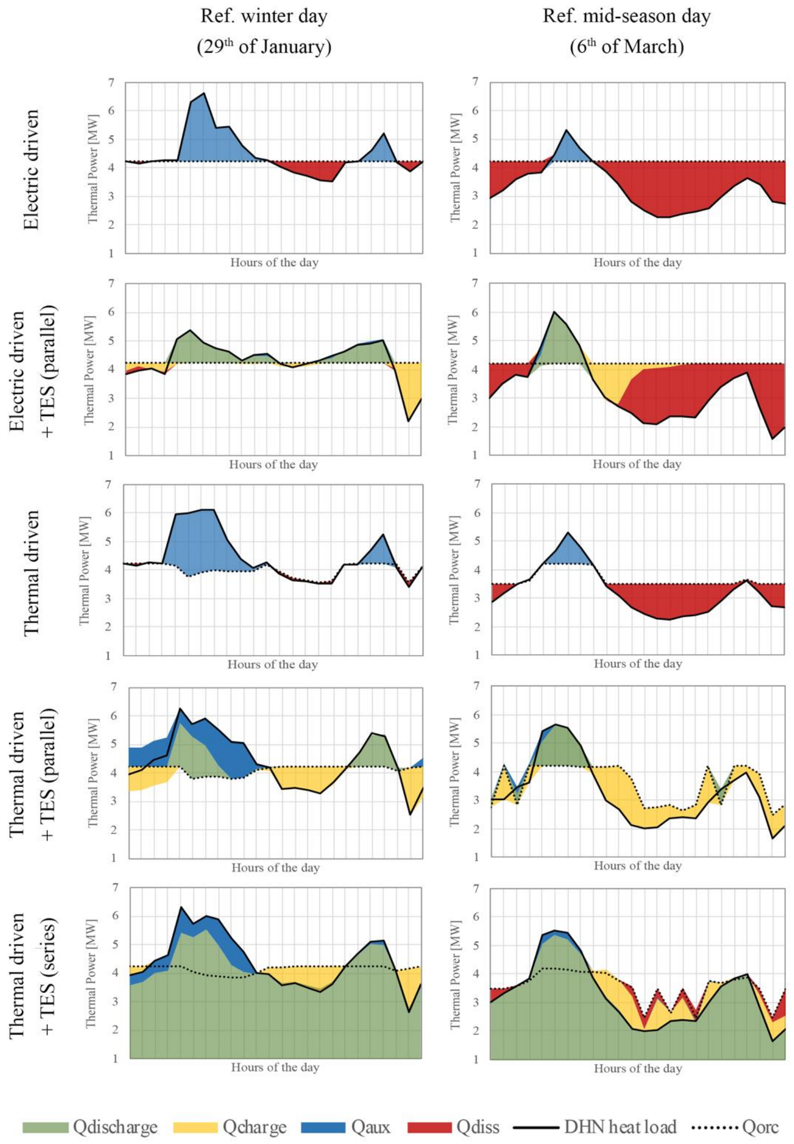

Fig. 11. Main energy fluxes in the high and mid-season reference day. Where Qdischarge is the heat discharged by TES, Qcharge is the heat charged in TES, Qaux is the heat provided by the auxiliary HX, Qdiss is the heat dissipated in DC, DHN heat load is the load at the central unit (users demand + DHN losses) and Qorc is the heat provided by ORC.

3.3 Key environmental indicators

Similar to fPE savings, the baseline in SC_0 shows promising performance in terms of CO_2 savings, with a yearly average of 52.3% in comparison with the *ex-ante* scenario, reaching values of 76,4% for the optimal scenario (SC_5).

On the side of NOx and PM emissions, the comparison between the simulated scenarios and the *ex-ante* scenario highlights a more critical situation, but also in this case best results are achieved for SC_5 (Tab. 7). For the optimal scenario (SC_5), the EF for thermal production calculated for NOx and PM amounted to 305 mg_{NOx}/kWh_{th_sold} and 11.4 mg_{PM}/kWh_{th_sold}, respectively. While the corresponding indicators for a NG boiler amount respectively to 161.2 mg_{NOx}/kWh_{th_sold} and 0.85 mg_{PM}/kWh_{th_sold} according to [19]. This gap between the technology analysed and the reference ones, is mainly due to the nature of the resource used. Indeed, if one hand the use of biomass allows to exploit a widespread and mostly untapped renewable resource allowing high CO_2 and fPE savings, on the other hand considering that biomass is a solid resource, the comparison in terms of NOx and PM emissions with NG technologies, a gaseous resource, is inevitably in favour of NG.

Nevertheless, the results have been also compared to biomass domestic devices (respectively 633.3 mg_{NOx}/kWh_{th_sold} and 686.6 mg_{PM}/kWh_{th_sold} according to [19]: considering the use of biomass for thermal purposes, large plants such as the case study evaluated, allow a more environmentally sustainable use of biomass in comparison of domestic devices. It is important to stress that these comparisons do not take into account the environmental benefits deriving from the electricity generation due to CHP in the *ex-post* scenarios.

Table 7. Summary of the environmental KPI for all the configurations simulated

		SC_0 (baseline)	SC_1 (baseline)	SC_3 (baseline TD)	SC_4 (TD+TES-parallel)	SC_5 (TD+TES-series)
CO_2 savings	%	52.28%	52.34%	71.08%	67.67%	76.40%
EF_{Th_PM}	mg_{PM} / kWh_{th_sold}	28.6	28.5	13.4	12.1	11.4
EF_{Th_NOx}	mg_{NOx} / kWh_{th_sold}	761.9	759.5	356.2	323.1	305.0

3.4 Key economic indicators

For each scenario, the economic impacts are estimated in terms of cost savings and simple payback time. The scenarios have been divided into two groups depending on the adoption or not of the current subsidised tariff for renewable electricity production.

The baseline scenario has been analysed as it is (with ED logic) but considering the tariff for selling the electricity produced equal to the ones applied to the electricity bought. In this case, outside heating season, the cash flow is negative, even during April and October, when the heat is sold for half a month. Considering that a shift toward a TD approach is evidently needed in this case, a TD control has been simulated. The resulting scenario represents the baseline of the group of scenarios evaluated without the current subsidization scheme in order to assess the economic impact of TES integration with TD approach. The main source of incomes is represented by the heat sold; net incomes are quite reduced in this case, but on yearly level the economic balance result to be still important, around 730 k€. If the yearly cash flow of this scenario is compared to the one of SC_2 (Fig. 12), the net incomes result to be the 140% higher, confirming that without the current subsidization program, an ED approach is no more sustainable.

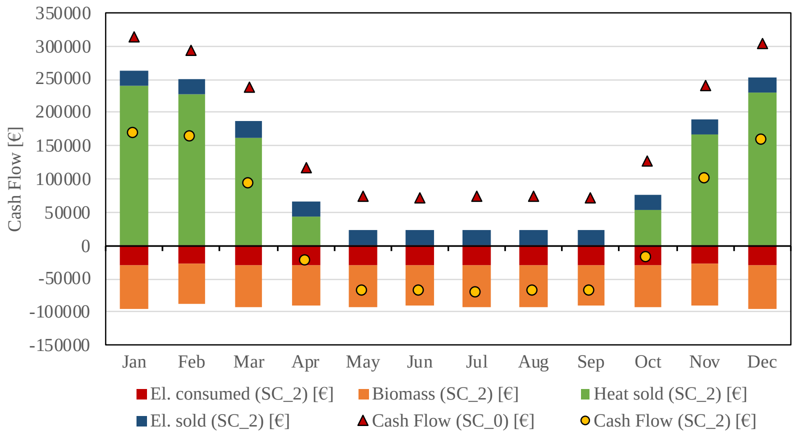

Fig. 12. CF_{net} comparison of SC_0 and SC_2

The comparison between SC_5 and SC_0 shows similar values of biomass valorisation in view of an almost halved biomass consumption. For each ton of biomass burnt the plant is able to generate yearly incomes of about 107 € (112 €/ton for SC_0). More in general the plant in this configuration proved to maintain a certain profitability, 1.69 € of incomes generated for each € spent for plant operations.

The integration of TES, and in particular the configuration in series, results in an improved cash flow. Compared to SC_3, the yearly outcomes increase by the 4% with SC_4 (TES in parallel) and by the 6.3% with SC_5 (TES in series). Accordingly, the simple PBT of the thermal storage calculated for both configurations is around 7.5 years for SC_4 and 4.8 years for SC_5. These features make SC_5 the optimal one.

4 Conclusions and further developments

Currently DHS have a marginal role in satisfying SH in buildings in Italy. In particular, despite the large availability of wood from forests, BDHS satisfy less than 1% of the national SH demand.

However, DHS fuelled by renewable sources or waste heat are constantly increasing and drivers for busting this trend should be activated [34], also toward the achievement of defined targets on thermal renewable sources. To that end, the adoption of innovative methodologies or tools, such as the one proposed in the present paper, could support the design and diffusion of new BDHS. Indeed, as estimated in [19] for the Italian territory, a potential of about 0.8-1.5 GW of power could be installed.

According to [19], the main detected pros of BDHS are related to the possibility of exploiting an almost renewable source, programmable and suitable for thermal purposes, with positive effects in terms of environmental protection, climate change reduction and saving of fossil PE. In addition, despite the difficulties related to the high investment costs (mainly related to the realisation of the networks), benefits on the local economy are evident, also due to the creation of local enterprises. Conversely, the main detected cons of BDHS are related to the economic and normative instability (variation of price of fuels and changes or drastic reduction of the supporting mechanisms), to the new regulatory policies aimed at the standardization of the management and monitoring conditions of DHS also in case of small size systems, and to other non-technical barriers, including eventual preconceptions to biomass combustion for air pollutants reasons. The reduction of heat lost and dissipated between heat generation and final users seems to be the most important driver to improve the efficiency of these systems. And this can be achieved also by an optimization of the coupling between thermal needs of users and thermal production. To this end, it is also important to underline the need of a review of the actual subsidization mechanism for the heat sold through BDHS, currently in favour of users only.

In order to deep these issues, a simulation model has been developed, tested and validated with the capability to explore the technical features and the energy, environmental and economic performance.

From the different results achieved and discussed, lessons have been learnt:

1. Considering the peculiar characteristics of CHP modules (instability, low partial load performance, etc.) and biomass combustion technologies (high thermal inertia, long time delay etc.), the adoption of thermal storage devices is a promising solution thanks to the ability of “decoupling” heat demand and heat production, allowing an improved and more efficient energy management. This feature is extremely important if considering the highly fluctuating nature of heat load profiles the central unit of DHS. For the case study analysed the integration of TES in TD logic allowed to increase the thermal efficiency of the plant by the 20%;
2. The sizing of CHP units should be designed to satisfy the base thermal load from users instead of peaks, in order to guarantee full load conditions for the highest possible number of hours along the year;
3. CHP cogeneration can help in maximizing benefits related to the energy exploitation of biomass. In order to reduce the risk of perverse effects that compromise thermal efficiencies, supporting mechanisms for heat generation should be developed both at local and national level;
4. Despite from the environmental point of view the application of BDHS in urban context remain a delicate issue, if local biomass basins are available, small-medium size systems represent an interesting opportunity toward RES DHC, enhancing also the implementation of circular economy paradigms;
5. Even if the research does not include a systematic economic analysis based on forecasts and alternative scenarios for evaluating the actual evolution of the markets, the economic impact of the feed-in tariff expiration is evaluated; results demonstrate the appropriateness of TES and TD logic.

Further developments of the research could concern the integration of other local renewable sources, taking into account the evolution of the energy market, of the building stock performance, of the climatic conditions, and therefore referring to DHC able to provide both heating and cooling and to adopt cascade heat management, even with low-temperature systems, according also to recent research such as [10]. Moreover, different scenarios of thermal needs (DHW and commercial dwellings) and network extensions could be integrated and evaluated through the model.

In conclusion, this research is a basis for the analytic and systematic identification the future challenges of BDHS in the framework of the path towards sustainable energy systems able to combine energy efficiency and exploitation of local sources, stimulating the diffusion of BDHS in a reasonable and sustainable way.

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References

1. Intergovernmental Panel on Climate Change (IPCC) (2014) Climate change 2014: mitigation of climate change. Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
2. Papadis, E., & Tsatsaronis, G. (2020). Challenges in the decarbonization of the energy sector. Energy, 118025.
3. UNFCCC, Paris Agreement, 12 December 2015. https://unfccc.int/sites/default/files/english_paris_agreement.pdf [last access: 10/5/21]
4. Mathiesen, B. V., Bertelsen, N., Schneider, N. C. A., García, L. S., Paardekooper, S., Thellufsen, J. Z., & Djørup, S. R. (2019). Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. Aalborg Universitet
5. T. Fleiter et al., “Profile of heating and cooling demand in 2015” (2017) Heat Roadmap Europe Deliverable 3.1.
6. IEA (2020), CO2 Emissions from Fuel Combustion: Overview, IEA, Paris
7. Bloomberg NEF. Sector Coupling in Europe: Powering Decarbonization. Potential and policy implications of electrifying the economy. https://www.eaton.com/gb/en-gb/company/news-insights/energy-transition/sector-coupling.html
8. Lund H, Alberg P, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating : Research and results 2018;164. https://doi.org/10.1016/j.energy.2018.08.206.
9. Lund H, Möller B, Mathiesen B V., Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. https://doi.org/10.1016/j.energy.2009.11.023.
10. Caputo, P., Ferla, G., Belliardi, M., & Cereghetti, N. (2020). District Thermal Systems: State of the Art and Promising Evolutive Scenarios. A focus on Italy and Switzerland. Sustainable Cities and Society, 102579.
11. Buffa, S., Cozzini, M., D’Antoni, M., Baratieri, M., & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. Renewable and Sustainable Energy Reviews, 104, 504-522.
12. Lund, H., Østergaard, P. A., Nielsen, T. B., Werner, S., Thorsen, J. E., Gudmundsson, O., Arabkoohsar A., Mathiesen, B. V. (2021). Perspectives on fourth and fifth generation district heating. Energy, 227, 120520
13. AIRU (Italian association of urban heating), 2020 Annual report, Alkes Editrice, 2021 (in Italian).

14. Aste, N., Buzzetti, M., Caputo, P., and Del Pero, C. (2018). Regional policies toward energy efficiency and renewable energy sources integration: Results of a wide monitoring campaign. Sustainable Cities and Society, 36, pp. 215-224
15. Sami, S., & Marin, E. (2017). Simulation of solar photovoltaic, biomass gas turbine and district heating hybrid system. International Journal of Sustainable Energy and Environmental Research, 6(1), 9-26.
16. Sartor, K., Quoilin, S., & Dewallef, P. (2014). Simulation and optimization of a CHP biomass plant and district heating network. Applied Energy, 130, 474-483.
17. Uris, M., Linares, J. I., & Arenas, E. (2015). Size optimization of a biomass-fired cogeneration plant CHP/CCHP (Combined heat and power/Combined heat, cooling and power) based on Organic Rankine Cycle for a district network in Spain. Energy, 88, 935-945.
18. Italian federation involving the most part of the Italian BDHS. https://www.fiper.it [last access: 10/5/21]
19. Caputo, P., Ferla, G., & Ferrari, S. (2019). Evaluation of environmental and energy effects of biomass district heating by a wide survey based on operational conditions in Italy. Energy, 174, 1210-1218.
20. Italian Ministry of Economic Development (MiSE) with Ministries of Environment and Protection of Territory and Sea, of Infrastructures and Transports, of Health and of Defence. Inter-ministerial Decree 26/06/2015 - Application of the energy performances calculation methodologies and definition of previsions and minimum requirements of buildings. Official Journal of the Italian Republic, 2015 (in Italian).
21. Ferla, G., Caputo, P., Colaninno, N., & Morello, E. (2020). Urban greenery management and energy planning: A GIS-based potential evaluation of pruning by-products for energy application for the city of Milan. Renewable Energy, 160, 185-195.
22. ASHRAE, ASHRAE Guideline 14-2002: Measurement of Energy Demand and Savings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2002.
23. President of the Republic Decree (DPR) 26 August 1993, n. 412, Regulations for thermal plants design, installation, operation and maintenance aimed to the energy consumption control, actuating art. 4, comma 4, of the Law 9 January 1991, n. 10. (In Italian)
24. Talebi, B., Mirzaei, P. A., Bastani, A., & Haghighat, F. (2016). A review of district heating systems: modeling and optimization. Frontiers in Built Environment, 2, 22.
25. http://www.trnsys.com [last access: 10/5/21]
26. http://www.tess-inc.com/trnsys/trnsys.html [last access: 10/5/21]
27. http://www.trnsys.com/tess-libraries/TESSLibs17_General_Descriptions.pdf [last access: 10/5/21]
28. Gadd, H., & Werner, S. (2013). Daily heat load variations in Swedish district heating systems. Applied Energy, 106, 47-55.
29. Pakere, I., Purina, D., Blumberga, D., & Bolonina, A. (2016). Evaluation of thermal energy storage capacity by heat load analyses. Energy Procedia, 95, 377-384.
30. http://www.trnsys.com/assets/docs/03-ComponentLibraryOverview.pdf [last access: 10/5/21]
31. https://www.milomb.camcom.it/rilevazione-prezzi [last access: 10/5/21] (In Italian)
32. Italian Ministry of Economic Development (MiSE) with Ministries of Environment and Protection of Territory and Sea. Law Decree 24/12/2008 - Incentives for the production of electricity from renewable energy sources. Official Journal of the Italian Republic, 2008 (in Italian).

33. Latõšov, E., Volkova, A., Siirde, A., Kurnitski, J., & Thalfeldt, M. (2017). Primary energy factor for district heating networks in European Union member states. Energy Procedia, 116, 69-77.
34. Brückner, S., Schäfers, H., Peters, I., & Lävemann, E. (2014). Using industrial and commercial waste heat for residential heat supply: A case study from Hamburg, Germany. Sustainable Cities and Society, 13, 139-142.