Biomass in District Energy Systems: Overview and Perspectives for an Italian Case-Study.

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Abstract. Buildings are one of the major users of energy in the European Union, accounting for almost half of the total consumption. In this scenario, renewable energy sources play a fundamental role in the transition towards a low-carbon society, and promoting their use is vital for the future of Europe. This work focuses on the use of district heating networks supplied with energy from biomass as a form of sustainable development for cities and communities, with attention to the Italian situation. After a first introductory part dealing with the European context of district energy networks, the focus shifts to Italy. It is introduced the diffusion on the national territory of district systems with a description of the most used energy sources that power these systems. To demonstrate how the use of biomasses in district energy networks represents a valid alternative to fossil fuels an analysis of the utilization of forests for wood harvesting in the Italian energy sector is carried out, showing how greenwoods and forests can withstand even greater exploitation for the collection of wood material for energy production. In order to prove the feasibility of the switch, a case study district, representative of the Italian residential building stock, is analysed. The district is firstly studied to evaluate the energy demand for space heating, and subsequently investigated by comparing different strategies for its energy efficiency improvement, all dealing with materials coming from wood processing, and switching from a decentralized energy system based on fossil fuels to a centralized network supplied by biomass. The results of the analysis show interesting results in primary energy consumption savings at least 38%, highlighting the potential of the demonstrated approach. Final remarks explain that, with the correct support of policies and awareness on the status of national forestry ecosystems, benefits are achievable through more intensive use of forests, leading to a higher share of natural feedstock in materials for the energy enhancement and energy production, that will help in reaching European sustainability goals.

Keywords. Solid biomass; Building energy demand; Energy efficiency; Renewable energy sources; Italy.
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1. Introduction

To comply with climate agreements, the European Union (EU) has important goals to achieve by 2030 and 2050, focusing mainly on the penetration of renewable energy sources (RES) in the energy landscape, and increasing the efficiency of buildings to decrease consumption and harmful emissions.

Heating and cooling in industries and buildings represent half of the energy consumption of the EU [1]. European households use 79.2% (222.7 Mtoe) of the total energy they consume for heating and DHW. The largest share of energy used to cover buildings' needs comes from fossil fuels (66%), while just the remaining percentage (34%) is generated using RES [2].

In Europe, natural gas is the most widely used primary fuel for heating, accounting for around 44%. The use of coal, although halved since 1990, is still present in the European residential stock with a share of about 10%. Oil is also still used as a primary energy source, accounting for about 15%. Biomass has seen an increase of about 20% from 1990, but as with oil, about 95% of its supply is used in individual heating systems. The remaining renewables (e.g. solar, wind) only count for 3%. The switching from fossil fuels to less armful sources, coupled with energy efficiency works on buildings, has contributed to a decrease in harmful emissions since 1990, reaching the objectives of the EU of a reduction of at least 20% by 2020 [2,3].

In most European Member States (MS) heating is the largest final energy consumption in residential buildings. To curb energy use and emissions, energy efficiency measures are of paramount importance, but they are often not enough. While policies and directives are strongly implemented by the EU their application is often unsatisfactory. A further way to reach the EU sustainability goals is to improve the

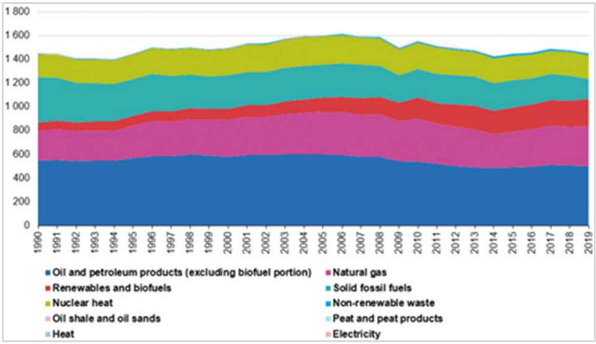

Fig. 1 - Gross inland energy consumption by fuel from 1990 to 2018 for the European MSs (EU-27) in million tonnes of oil equivalent. Data from [4]

efficiency of heat generators. In some cases, by modernizing the existing systems with more performing machines. There are other cases where alternative solutions exist. In areas with high heat density, district heating (DH) networks can be an interesting solution. Their versatility allows exploiting local heat surplus and possible integration with RES, but also more performing and efficient technologies such as combined heat and power (CHP). In favour of this switch towards network solutions, several studies claim that the heat demand in Europe is sufficient for the development and expansion of DH systems, even though currently only 12% of the energy needs are supplied by DH [5,6].

Heat Roadmap Europe studies, indicate how DH is more efficient than decentralized systems, also allowing higher shares of renewables [2]. Network systems are usually chosen also because a single plant means less maintenance and lower running costs, a reduction of the carbon emissions and improved air quality related to the switch from fossil fuels to RES. This latter aspect helps in the uptake of renewable energy, reduce fuel poverty, and create competitiveness in heating costs [7,8]. The goal of this paper is to provide an example of sustainable renovation for an Italian district located in the historical city of Venice through the development of a replicable methodology accompanied by an application to a case study of the renovation works on buildings' envelopes and the switching from a traditional heating solution based on natural-gas-boilers to a DH network powered by biomass.

1.1. DH networks across Europe and Italy

Although EC's plans for the development of DH systems are quite recent, Europe is one of the places where the highest number of DH networks are located. It is a widespread technology across the whole continent with more than 10,000 different networks installed [9]. Several small systems found application in Germany, mainly in cities where outdated heating systems were replaced by DH systems to reduce fire hazards in historical buildings containing art fortunes [10]. Scandinavian, the Baltic countries, and Central Europe present a higher degree of DH systems expansion because of the high consideration for the environmental and energy independence aspects. The climatic characterization is another important aspect: with its long and cold winter reflected in a high number of heating degree-days (HDD) (above 3,000), Central and Nordic Europe have a high heat demand index, resulting in major investments into expanding and improving the existing DH systems. Contrary to that, DH systems are not so common in southern European regions where the dominant energy sources are gas and fuel oil, and the density of buildings is lower. Exceptions of these considerations are cities: in countries where the climate is more temperate, the majority of DH systems can be found in densely built-up areas [11].

In Italy individual systems, mainly powered by electricity and natural gas, are used to meet heating and cooling needs. The last census shows that in 2018, 368 DH networks were operating, satisfying the thermal needs of 350 million m^3 of built-up spaces These systems are mainly located in the northern part of Italy, with higher concentrations in alpine areas, due to the rigid temperatures. However, since half of the Italian territory is characterized by cold winters (more than 2,000 HDD), is not unusual to find examples of these systems used in the central region of Italy, where the large availability of geothermal heat fuels numerous plants. Cities play an important role in the distribution of DH networks along the Peninsula: almost 200 examples are in contexts where the high density of heat demand made DHs the ideal solution for heating. A mix of different energy sources is used. The most widely used fuel is natural gas representing 64% of the total, RESs are still the smallest fraction, but increasing in recent years, in particular woody biomass-fuelled networks accounts for 13% [12]. Regarding the sizes, on average, small power plants are more common in Italy: 54% are smaller than 6 MW, 31% are in the range of 6 MW to 50 MW, and only the remaining 16 % are bigger than 50 MW [13].

1.2. Woody biomass harvesting in Italy

In the whole EU forests and their ecosystems are growing. In recent years the surfaces covered by woods have increased by about 13 million hectares. About 55% of the forested areas are currently used for harvesting wood for biomass [14]. In Italy, the situation is a bit different. Data from Italian Ministry of Agriculture, Food and Forestry Policies show that after actualizing the data considering the life cycle of the trees, out of a total of 241,800 ha (hectares) available for woody biomass harvesting, only 25% is used for extracting woods for energy reasons [15]. Therefore, it is possible to suppose an increase in the utilization of the available areas for wood harvesting and this scenario is foreseen in the Italian energy strategy (Strategia Energetica Nazionale, SEN): the growth in the use of RES for thermal energy production is acknowledged, but measures to promote and support this development are needed [16]. Optimizing the use of biomass can significantly improve the energy sector. To do so, measures to stimulate the use and gradual expansion of the biofuels are needed.

2. Methods

The EC has in recent years supported the development of methodologies for the renovation of the building sector through projects and funding. In particular, the district scale approach is the one in which the scientific community believes most. The aim of this work is to demonstrate how the use of energy from renewable sources, together with improvements in the building envelope, could be a winning strategy to achieve the 2050 targets set by the EC. To do this, the methodology suggested by the IEA EBC Annex 75 project was used [17]. The work begins with the selection of a neighbourhood in desperate need of renovation. The decision fell on the residential neighbourhood of Santa Marta, located in the western part of the historic city centre on the island of Venice. The district was studied and digitally reconstructed through the use of QGIS software [18]. Once the model is digitally reconstructed, the buildings are assigned the thermophysical characteristics of the elements that compose it, the composition and structure of the heating and hot water production systems, and the usage characteristics. The model is then simulated using the City Energy Analyst (CEA) software developed by ETH Zurich [19]. Within the software environment all other settings necessary for the correct functioning of the model are set. A first simulation is carried out to create a baseline corresponding to the actual state. In the following steps, improvement scenarios are simulated by applying previously defined energy conservation measures on the building envelope elements and from the point of view of the plant systems. By comparing the results, it is possible to derive the energy saving potential of each scenario and to define the best of the scenarios in terms of costs, energy or somewhere in between [20].

The developed methodology is applied in the following paragraphs for the aforementioned case study of Venice.

3. Case study

The Italian political class aimed to end the insecure situation in which the low-income population found itself since the turn of the twentieth century. Luigi Luzzatti, an Italian lawmaker, founded the Istituto Case Popolari in 1903. (Public Housing Institute; ICP). The purpose of this organization was to provide low-cost housing that adhered to the most up-to-date sanitary and hygienic laws. In Venice, a chapter of ICP was founded in 1914 with the same goal: to improve the living conditions of the poor. The ICP's name changed several times over the years until it was renamed "Aziende territoriali per l'edilizia residenziale" (Local Agency for Residential Buildings) in the mid-90s.

The district under investigation, known as "Santa Marta IACP housing," was part of this wave of social housing building. It is located in the western portion of Dorsoduro, one of the six districts that make up Venice's old town, towards the city's southwest end. The district is irregularly shaped, but its dimensions are roughly 400 m × 160 m, with a total surface area of 3.78 hectares (ha) (equal to 0.04 km^2). The municipality began construction of the first set of 14 buildings for a total of 148 housing units in this neighbourhood in 1920, with the intention of accommodating low-income workers from adjacent enterprises and nautical workshops. These structures were finished in 1928. A second intervention in the area in 1930 ensured the construction of 365 more units in more than 21 new buildings.

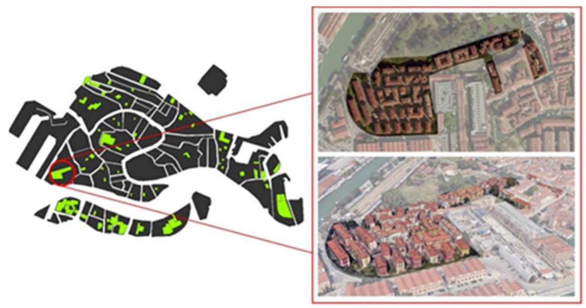

Fig. 2 - Map of Venice's historic centre, showing in green the social housing for low-income families within the Sestrieri. Moreover, satellite view and 3D visualization of the Santa Marta district in Venice

Most of the buildings in the case study are multifamily. The structure may be classified into two groups based on their age, and the geometry of the buildings varies slightly. The first series of buildings, constructed between 1920 and 1928, had a standard rectangular shape with lengths varying from 18 to 50 metres on the long side and a consistent 12.5 metres on the short side. Each building has four stories and two to six flats per floor, depending on the size of the building. The buildings in the second group, finished in 1936, have more complicated and variable geometries: they are typically structured around a central void or in a "C" shape. The sizes of these structures vary greatly, ranging from 170 m^2 footprints to complexes of over 1,500 m^2. The number of floors and flats varies as well, ranging from small two-story cottages with one flat per level to substantial five-story structures with up to 14 flats per floor.

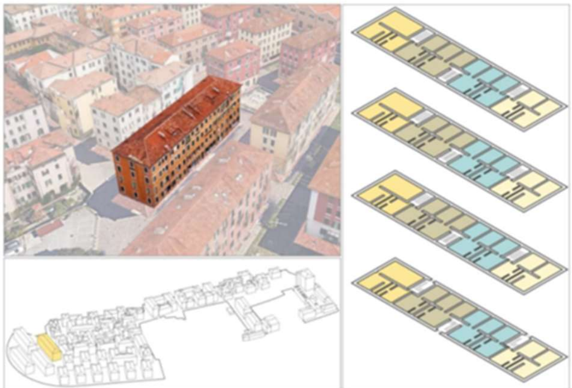

Fig. 3 - Representative building of the first group built between 1920 and 1928, with a regular rectangular shape. Aerial view from Google Earth, 3D map and plans.

The construction technologies used for the building envelope were the same in the two phases: two-headed solid masonry and plastered buildings, wooden roofing, hollow core slabs, wooden frame windows and single glazing. There is no insulation. Some differences can be found in the transparent envelope: double-glazed wooden frame windows have replaced some single glazed systems with a wooden frame, depending on the owners' willingness to retrofit the flat. The building's installations are standard and have undergone several updates while remaining faithful to the original supply network. The heating is provided to the flats by a centralized gas boiler installed in each building, although a single system for flat has been installed in some condominiums and in this case the generator is arranged for both heating and DHW. Cooling systems were not foreseen at the time of construction and are not currently present in most buildings. In some cases, a simple monosplit or multisplit air conditioner for one flat has been privately installed over the years by the users (owners or tenants). Domestic hot water (DHW) is provided by an electric water heater installed in each flat which, in the case of condominium heating, only works in summer. For heating, the overall efficiency used to define the boiler characteristics considers the efficiencies of generation, distribution, emission and regulation, provided that the pipes are not commonly insulated due to the age of the building, and that the heat is mainly emitted by cast iron radiators. The overall efficiency of this type of system is 80%.

The main parameters for setting the district model are described in Table 1.

Tab. 1 - Calculation parameters for the type of buildings in the neighbourhood

Parameter	Unit	Building typology
Building information		
number of buildings per typology		54
Construction period		1920-1936
Geometry		
Gross heated floor area (GHFA)	m^2	58,605.96
Net heated floor area (NHFA)	m^2	51,392.86
Heated volume	m^3	138,249.51
Façade area incl. window area	m^2	50,753.28
Roof area if pitched roof	m^2	15,241.27
In case of pitched roof: Is room below roof heated or not?	Yes/No	Yes
Area of windows to North	m^2	1,569.25
Area of windows to East	m^2	2,239.31
Area of windows to South	m^2	1,571.48
Area of windows to West	m^2	2,232.96
Number of floors above ground	-	1-5
Usage		
Type of use		Residential
area per occupant	m^2 / person	30.45
Typical indoor temperature (for calculations)	°C	20
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/(m^2.a)	28
HVAC systems		
Type of existing heating system (boiler, heat pump, etc.)		Boiler
Existing energy carrier (Gas, Electricity, etc.)		Natural gas
Is ventilation system without heat recovery installed?	Yes/No	No
Is ventilation system with heat recovery installed?	Yes/No	No
Efficiency of heat recovery	%	/
Ventilation rate	ach	0.3
Is cooling system installed?	Yes/No	No
Hot water consumption	l/person/day	40

3.1. Calculation parameters and scenarios

A thermal renovation of the selected case study has been proposed, considering five different scenarios of renovation measures on the building envelope.

Tab. 2 – List of the proposed scenarios with their interventions on the envelope of the buildings. Codes M3 to M6 refers to EPS application, M7 to M10 to WF.

Code	Description
M 1	no interventions
M 2	windows replacement
M 3, M 7	façade insulation
M 4, M 8	roof insulation
M 5, M 9	windows replacement and façade insulation
M 6, M 10	windows replacement, insulation of façade and roof

Two different insulating materials have been considered, expanded polystyrene (EPS) panels and wood fibre panels (WF), by application in the inner side of external walls due to the restrictions by Superintendency of Cultural Heritage to preserve the external envelope of buildings in the historical centre of Venice. This action has major repercussions on the price for the initial investments, since no needs for scaffoldings reduce the cost of intervention.

The following table resumes the data for energy performances and a global cost calculation adopted for each scenario.

Tab. 3 - Summary of the measures of intervention on the envelope with performance of the building component and investment and maintenance costs according to the type of insulation material selected. For the intervention in the transparent envelope, only one type with a wooden frame and triple glazing with low emission is intended. The service life is 30 years.

WALL	Unit	Reference	EPS	WF
U-values	W/m²K	1.71	0.25	0.25
Investment costs	EUR/m²		38.93	67.02
Maintenance costs	EUR/m²y	1.27	1.52	1.71
ROOF	**Unit**	**Reference**	**EPS**	**WF**
U-values	W/m²K	2.70	0.20	0.20
Investment costs	EUR/m²		119.94	139.70
Maintenance costs	EUR/m²y	2.09	2.87	3.00
WINDOW	**Unit**	**Reference**	**New**	
U-values	W/m²K	5.8	1.00	
Investment costs	EUR/m²		333.8	
Maintenance costs	EUR/m²y	1.60	3.78	

In the present scenario, each flat is equipped with a condensing boiler fuelled by natural gas, with a water-based distribution system. For the purpose of the study, a centralized heat distribution system is planned considering two combined heat and power (CHP) generators, a natural gas fired, and a biomass powered (Table 4) [21]. The selected systems present a difference in costs: the investment costs assumed for gas CHP is 830 €/kW, coupled with 29 €/kW of yearly maintenance, while for a biomass generator the costs are respectively 500 €/kW and 17 €/kW year.

Tab. 4 - Summary of the measures of intervention on the system with sizing referred to the needs calculated for each scenario of intervention on the envelope. The service life is 15 years.

Parameter	Unit	M 1	M2	M 3	M 4	M 5	M 6
I1 - Central heating system 1 (Natural Gas CHP)							
Capacity	kWe	2,241	1,810	1,717	1,797	1,375	1,012
I2 - Central heating system 2 (Biomass CHP)							
Capacity	kWt	604	524	499	521	407	309

All the different heat supply systems are coupled with all the energy efficiency measure scenarios, totalling 21 cases, including the scenarios in which no envelope interventions are foreseen, only the substitution of the heating generators.

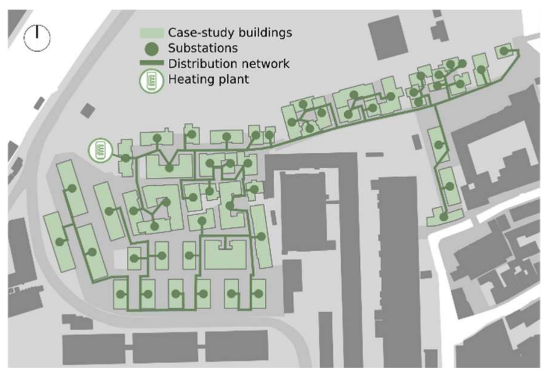

Fig. 4 - Plan of centralized network, CEA elaboration.

The design of the supply network and its substations is considered by using the CEA tool, in which the characteristics of the selected plants are implemented in the model and a district network is calculated.

For the case study of the Santa Marta district, the network is defined as in and extends for 1,782.72 m. The main power plant was located to the east of the area for a number of logistical and feasibility reasons: it is a large port area where the connecting infrastructure network, i.e., road, tram and marine networks with their landing stages, are still in use and would facilitate the storage and transport of materials such as biomass to Venice main island. In addition to dimensioning the length according to the route, each pipe section of the network is dimensioned according to the energy needs for heating and hot water of each building (better each substation). The parameters of length and diameter of the network influence the installation costs. In the present case, parametric costs from literature and professionals are applied, as shown in Table 5. Also costs for the substation installation are adopted at the parametric level, counting 30% of the total pipeline installation cost, white the maintenance costs are evaluated as 10% of the total cost of pipeline and network over the service life period. Therefore, the cost of a centralized system network is a function of the shorter length and smaller diameter, i.e., it is related to the geometric density of the district and the energy needs of the buildings.

Tab. 5 - Supply and placement of the network pipework parameterized according to the length and diameter of the segment.

Diameter [mm]	Cost [€/m]
20	100
25	114
32	123
40	133
50	145
65	226
80	361
100	415
125	471
150	517
200	620
250	700
300	775
350	930
average	402

The scenarios are combined according to the following scheme, in which interventions on the envelope have code M, and installations have code I.

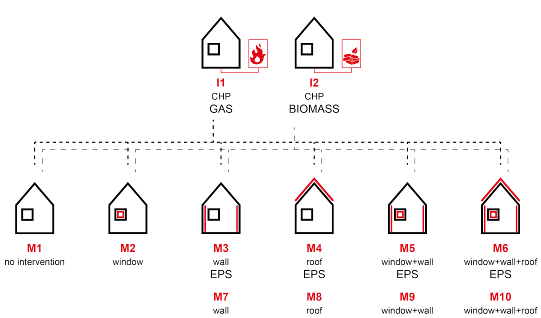

Fig. 5 - Overview of selected scenarios combined by measures of intervention on envelope (M) and new centralized system (I).

4. Results

The proposed scenarios were simulated and analysed in comparison with the Reference case to identify Primary Energy consumption, GHG emissions and Global Costs, as shown in the table below. Some notes can be made on the results obtained. The planned measures lead to energy efficiency that halves primary energy consumption for most scenarios. Among the measures in the envelope, the most efficient are those that consider an insulation intervention of the whole envelope (M6 and M10). Moreover, it should be underlined how the substitution of energy system (M1 code, without envelope intervention) could halve the energy use of Reference case, reducing the Primary Energy from 508 kWh/m² yearly to 313 kWh/m² yearly by adoption of a Natural Gas CHP and 268 kWh/m² yearly for Biomass CHP.

Tab. 6 - Summary of the calculated outputs, highlighting the minimum (in green colour) and maximum (in red colour) values for each parameter. Values are expressed per unit of net conditioned area (NHFA). Global costs is the sum of investment, maintenance and energy costs

Scenario	Primary Energy [kWh/m² y]	GHG Emissions [kg CO2eq/m² y]	Investment [€/m² y]	Maintenance [€/m² y]	Energy Cost [€/m² y]	Global Cost [€/m² y]
Reference	508	118	45	61	709	815
Natural Gas CHP						
I1_M1	313	74	47	97	504	648
I1_M2	281	66	89	99	454	642
I1_M3	271	64	70	94	438	603
I1_M4	291	68	75	96	469	640
I1_M5	232	54	113	98	379	591
I1_M6	192	45	140	99	317	556
I1_M7	271	64	94	99	438	631
I1_M8	291	68	81	98	469	647
I1_M9	232	54	137	103	379	619
I1_M10	192	45	172	126	317	614
Biomass CHP						
I2_M1	268	63	27	81	417	525
I2_M2	236	56	74	88	377	540
I2_M3	225	53	57	84	364	505
I2_M4	245	58	61	85	389	535
I2_M5	187	44	103	90	320	513
I2_M6	146	34	133	93	275	501
I2_M7	225	53	80	89	364	533
I2_M8	245	58	66	87	389	542
I2_M9	187	44	126	95	320	541
I2_M10	146	34	164	99	275	538

The choice of material represents a question of cost as both proposed materials must guarantee the same requirement of equivalent thermal transmittance and therefore the factor that influences is the unit cost, in this case higher for wood fibre. The Global Costs have been calculated with an interest rate of 3% for a service life of 30 years. The best cost-effective solution is given by the scenario in which a centralized grid system is installed with a Biomass CHP generator combined with the insulation of the full envelope (I2_M6). In analytical terms, the table shows that, looking at the energy efficient solutions, the investment and maintenance costs are certainly much higher to be sustained and amortized over time

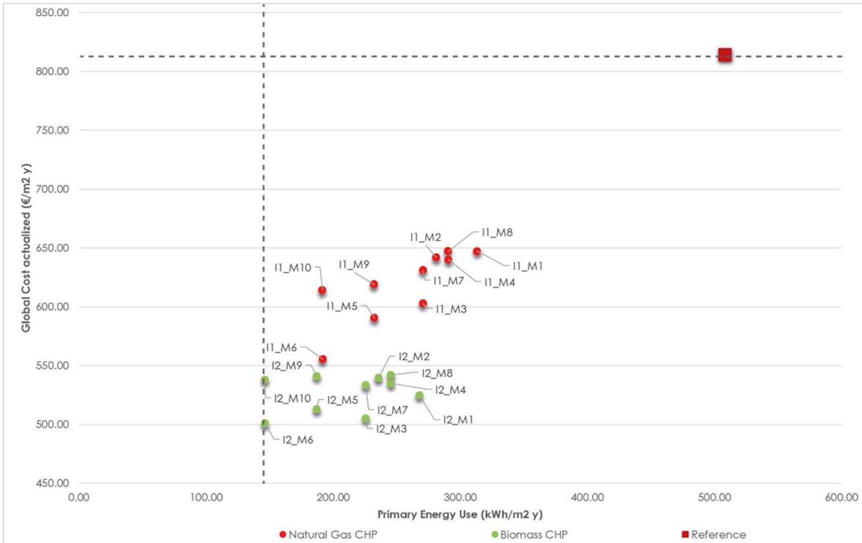

Fig. 6 - Chart Global Cost and Primary Energy to identify the optimal intervention solution: the horizontal and vertical dotted lines indicate respectively the margin downwards of the cost-effective solutions in relation to the Reference and the margin of the most efficient solutions to the left in relation to the optimal solution.

(133 €/m² and 93 €/m² respectively for the I2_M6 scenario), but the total energy costs would be lower due not only to the better performance of the system (and therefore lower consumption of primary energy), but also to the lower unit cost of the energy vector. In fact, for this study the applied conversion values are shown in the Table 7 and energy costs and CO_2 emissions are also included.

Tab. 7 - Primary energy conversion factors, prices and emissions of the energy carriers adopted.

Energy Vectors	*Primary Non-Renewable Energy Fp,nren [-]*	*Primary Energy Renewable Fp,ren [-]*	*Total Primary Energy Fp,tot [-]*	*Unit price [€/kWh]*	*CO2 emissions [kg CO2eq/kWh]*
Electricity	1.950	0.470	2.420	0.219	0.483
Natural Gas	1.050	-	1.050	0.081	0.250
Wood pellets	0.200	0.910	1.110	0.067	0.030
Wood chips	0.200	0.910	1.110	0.028	0.032
Oil	1.070	-	1.070	0.170	0.267
DHN electric	1.200	0.300	1.500	0.150	
DHN gas	0.640	0.920	1.560	0.068	
DHN biomass	0.300	1.200	1.500	0.060	

Biomass values are divided by type of wood chips and pellets according to the different cost on the market and the CO_2 emission factor, while for district heating the values certified by plant operators present on the Italian territory have been considered, with relative application of tariffs to the consumer. The prices adopted for the final consumer are referred to the year 2018, for the energy carrier electricity and natural gas they are elaborated from the Eurostat database [22], while for biomass reference is made to the 2018 report of the Italian Agroforestry Energy Association AIEL [23].

Looking at the summary graph (Figure 6) of the results in terms of global costs and primary energy, the cost optimal solution is identified in the I2_M6 scenario, that coincides with the most energy efficient one. Compared to the Reference case, the costs are reduced by 38%, but in general the graph shows the influence of the installation of centralized biomass plants. The scale of the graph may influence the evaluation as the overall costs vary by about 50 €/m² y, but in the case of the district they are equivalent to about 86,000 € per year.

5. Discussion and conclusions

The results of calculation on the presented case study demonstrates the validity to install a DHN with biomass energy vector to reduce energy consumption and GHG emission in comparison to fossil fuels. Even if the simulation shows the cost-effectiveness of intervention both on envelope and energy system, the adoption of Biomass system halves the Primary Energy use and could be the first step to district building refurbishment with the aim to reduce also GHG emissions. The increased use of biomass in the national energy mix is foreseen by Italian energy strategies and is justified by the analyses presented above. Currently only a quarter of the potentially available woody biomass is used for energy purposes. In the transition to a more sustainable future, biomass represents a viable alternative to fossil fuels due to its renewable nature and lower harmful emissions into the atmosphere.

Furthermore, the possibility of creating a district network to replace individual boilers per building is a step towards greater sustainability of the energy sector in the Italian residential sector. However, to achieve even better results it is necessary to optimise the biomass cycle by stimulating its use with ad hoc policies and financial and technical support.

Future developments in this research will focus on defining scenarios in which the entire set of interventions is carried out with wood-based materials. In the case study, the most cost-effective and energy-efficient choice was the use of polyurethane insulation, but with a more careful analysis of the life cycle of the insulation materials it will be possible to make the entire set of interventions on both the building envelope and the energy supply wood-based.

6. References

[1] Review of Available Information on an EU Strategy for Heating and Cooling, (2016).

[2] F. Tobias, R. Elsland, M. Rehfeldt, J. Steinbach, U. Reiter, G. Catenazzi, M. Jakob, C. Rutten, R. Harmsen, F. Dittmann, P. Rivière, P. Stabat, Profile of heating and cooling demand in 2015, (2020).

[3] Odyssee-Mure, Odyssee 2017, (n.d.). http://odyssee.enerdata.net/home/ (accessed December 27, 2019).

[4] Eurostat, Gross inland energy consumption by fuel, EU-27, 1990-2018, (2019). https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_statistics_-_an_overview.

[5] BloombergNEF, Sector Coupling in Europe: Power Decarbonization, 2020.

[6] A. Volkova, V. Mašatin, A. Siirde, Methodology for evaluating the transition process dynamics towards 4th generation district heating networks, Energy. 150 (2018) 253–261. https://doi.org/https://doi.org/10.1016/j.energy.2018.02.123.

[7] L. Liu, P. Rohdin, B. Moshfegh, Investigating cost-optimal refurbishment strategies for the medieval district of Visby in Sweden, Energy Build. 158 (2018) 750–760. https://doi.org/10.1016/j.enbuild.2017.10.002.

[8] X. Zhang, G. Strbac, N. Shah, F. Teng, D. Pudjianto, Whole-System Assessment of the Benefits of Integrated Electricity and Heat System, IEEE Trans. Smart Grid. 10 (2019) 1132–1145. https://doi.org/10.1109/TSG.2018.2871559.

[9] Euroheat & Power, District Heating and Cooling Country by Country - 2015 Survey, 2015.

[10] S. Frederiksen, S. Werner, District Heating and Cooling Development, in: Dist. Heat. Cool., Studentlitteratur AB, 2013: pp. 541–560.

[11] M.A. Sayegh, J. Danielewicz, T. Nannou, M. Miniewicz, P. Jadwiszczak, K. Piekarska, H. Jouhara, Trends of European research and development in district heating technologies, Renew. Sustain. Energy Rev. 68 (2017) 1183–1192. https://doi.org/10.1016/j.rser.2016.02.023.

[12] AIRU, Il Riscaldamento urbano Annuario 2018, AMARC DHS Srl. (2018) 375.

[13] A. Grossi, Stato e prospettive della regolazione del settore del teleriscaldamento e teleraffrescamento Introduzione al seminario, (n.d.).

[14] M. Mikoláš, K. Ujházy, M. Jasík, M. Wiezik, I. Gallay, P. Polák, J. Vysoký, M. Čiliak, G.W. Meigs, M. Svoboda, V. Trotsiuk, W.S. Keeton, Primary forest distribution and representation in a Central European landscape: Results of a large-scale field-based census, For. Ecol. Manage. 449 (2019) 117466. https://doi.org/10.1016/j.foreco.2019.117466.

[15] Ministero delle Politiche Agricole Alimentari e Forestali Ispettorato Generale - Corpo Forestale dello Stato, CRA - Unità di Ricerca per il Monitoraggio e la Pianificazione Forestale, INFC 2005 - Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio, 2007.

[16] Ministero dello Sviluppo Economico, Ministero dell'Ambiente e della Tutela del Territorio e del Mare, Strategia energetica nazionale (SEN) 2017, 2017. http://www.enea.it/it/seguici/le-parole-dellenergia/glossario/parole/strategia-energetica-nazionale-sen (accessed April 4, 2019).

[17] J.M. Hidalgo-Betanzos, IEA Annex 75 | Cost-Effective Building Renovation at District Level Combining Energy Efficiency & Renewables - Workshop document, 2019. https://annex75.iea-ebc.org/ (accessed February 19, 2021).

[18] QGIS - A Free and Open Source Geographic Information System, (n.d.). https://www.qgis.org/en/site/ (accessed February 27, 2020).

[19] J.A. Fonseca, T.A. Nguyen, A. Schlueter, F. Marechal, City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts, Energy Build. 113 (2016) 202–226. https://doi.org/10.1016/j.enbuild.2015.11.055.

[20] T. Dalla Mora, L. Teso, L. Carnieletto, A. Zarrella, P. Romagnoni, Comparative Analysis between Dynamic and Quasi-Steady-State Methods at an Urban Scale on a Social-Housing District in Venice, Energies. 14 (2021) 5164. https://doi.org/10.3390/en14165164.

[21] L. Carnieletto, S. Graci, M. De Carli, Hypothesis for a more efficient and sustainable development of a district heating in Padova, integrating renewable energies and existing generation plant, E3S Web Conf. 111 (2019) 6021. https://doi.org/10.1051/e3sconf/201911106021.

[22] Prices - Energy - Eurostat, (n.d.). https://ec.europa.eu/eurostat/web/energy/methodology/prices (accessed January 10, 2022).

[23] AIEL Associazione Italiana Energie Agroforestali, Mercati & prezzi, 12 (2020) 1–8. https://www.aielenergia.it/public/pubblicazioni/162_M_P_1-2020.pdf.