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Advantages of coupling a woody biomass cogeneration plant with a district heating network for a sustainable built environment: a case study in Luserna San Giovanni (Torino, Italy).

Chiara Delmastro[a], Guglielmina Mutani[a,*], Laura Schranz[a]

[a]DENERG, Politecnico di Torino,corso Duca degli Abruzzi 24, Torino 10129

Abstract

One of the key strategies towards the European goals is the exploitation of local and renewable energy sources: the paper analyses the benefits and the feasibility of a woody biomass cogeneration plant in Luserna San Giovanni (Torino, Italy).
The first part of the paper presents a graphical method to evaluate the thermal energy use of public and residential buildings. Then, after the selection of the buildings with both higher energy consumption and higher specific energy consumption, a thermal analysis allows the assessment of energy savings potential of these buildings. The results of this first analysis permit to estimate the effective and peak power of the plant considering different scenarios of buildings' renovation and then of heat distribution.
The second part of the paper describes the pre-feasibility analysis of the district heating network supported by a GIS-based tool (Geographical Information System). Main results are the evaluation of the environmental and economic impacts of the biomass plant and of the connection to the district heating network on a short and long term horizon.

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Keywords: biomass, district heating networks, energy signature, buildings.

1. Introduction

A solution, for reaching EU 2020 objectives, for reducing fossil fuel use and improving energy security, is represented by the use of local biomass for district heating power plants. Biomass combined heat and power (CHP) plants connected to district heating (DH) networks are recognized as a sustainable opportunity to increase the share

* Guglielmina Mutani. Tel.: +39-011-0904528; fax: +39-011-0904499.
E-mail address: guglielmina.mutani@polito.it.

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of renewable sources into energy systems. As CHP plants are not optimized for electricity production, their operation is profitable only if a sufficient heat demand is available throughout the year and usually pre-feasibility studies are based on peak power assuming monthly or yearly consumption data [1; 2].

This paper presents a simple and effective methodology that provides accurate estimations of economic, environmental and energetic performances of a CHP plant connected to district heating networks. Based on the developed thermal model and on actual consumption data, different scenarios of energy savings are considered. A model for the district heating network pre-feasibility study in Luserna San Giovanni is used as an application to demonstrate the effectiveness of local biomass exploitation. Potential energy savings and resulting economic and environmental costs are estimated.

2. The case study

Luserna San Giovanni is a little city in the mountain community “Val Pellice”, near Turin, with around 7500 inhabitants (density of 425 inh/km^2, surface of 17.73 km^2). This municipality represents a typical Italian mountain community in which the availability of biomass to produce energy can be a crucial topic for farms economy that can solve: the dependence of energy fuel from abroad and the high use of fossil fuels.

2.1. Climatic data

Luserna San Giovanni belongs to the coldest Italian climatic zone (zone F) with 3065 Degree Days (DD) , with the heating season from October 5th to April 22nd and with no cooling season.

In the last years, during the heating season, the monthly air temperature increases of about 1°C during the heating months and more than 2°C in January. The minimum temperature to evaluate the size of boiler power is -9.3°C [3]; in the last twenty years this temperature arises at -9.0 °C. In Table 1 the monthly temperatures of the last 23 years are compared with the ‘70-‘90s.

Table 1. Average monthly temperature for Luserna San Giovanni (TO) in two different periods 1970-90 and 1991-2013.

Month	1	2	3	4	5	6	7	8	9	10	11	12
1970-1990	-0.9	1.9	6.9	11.4	15.4	19.8	22	21.3	17.5	11.3	5.5	0.7
1991-2013	1.1	2.6	7.2	10.8	15.0	19.2	21.2	20.7	16.4	11.3	5.6	1.6

2.2. Buildings description (Reference Scenario)

The data about the analysed public and private buildings are reported in Table 2. Most of the buildings were built without insulation but some of them have already changed the boiler with a condensing one. Moreover, in the recent years the school has been renovated by placing an insulated layer on the inferior slab; the condominium Airali and the detached house have new insulated roofs.

In Fig. 1a, the energy use (kWh) is compared with the specific energy-use (kWh/m^3) of the public and residential buildings with the exception of the Caffarel factory (where the thermal consumption is also used for processes). The average annual energy consumption is of about 366,000 kWh and of 48 kWh/m^3 and the buildings with higher priority for renovation are in the top right quadrant: City Hall (n.3), swimming pool (n.7) and primary school (n.4). Buildings n.3 and n.4 are old and big with high energy consumption, while n.7 has the higher specific energy consumption because of swimming pool services.

To evaluate the buildings’ energy performance, three different methodologies can be used: calculation-based, measurements-based and hybrid approaches [4; 5]. In this work, the energy-use is calculated using a hybrid approach: evaluating the energy-use with a measurement-based approach and supporting the energy savings with supplemental calculations [6; 7]. In this paper, the energy signature (ES) method has been adopted; it correlates powers with outdoor temperatures over the sampling time through a single-variate regression model. The methodology has been implemented in the standard EN 15603:2008 and it is part of the EU regulatory framework on the energy consumption reduction. The ES method has been chosen for this analysis in order to get useful information on building energy performances and to estimate the heat transfer coefficient of buildings.

In Fig.1b and Fig.2a the ES of buildings are represented correlating thermal power versus average temperature over a monthly period considering the last four heating seasons. The differences about energy performance depend mainly on heated volume, efficiency of the system, level of insulation and by the compactness of the building. In Fig.2b the monthly specific power is represented with higher values for the swimming pool, as expected.

Table 2. Heating energy-use for buildings (*combined heating and hot water)

Number	Buildings	Buildings' construction period	Volume m^3	Energy use kWh	Fuel	Boiler type	Boiler power kW
1	Caffarel factory	1980	177,397	5,000,000	Natural gas	Condensing	3500
2	Police station	-	3,150	150,000	Natural gas	-	93
3	City Hall*	< 1945	11,834	875,456	Natural gas	Traditional	1160
4	Primary school*	< 1945	8,415	658,710			
5	Technical Institute Alberti	< 1945	10,152	300,000	Natural gas	Traditional	180
6	Gymnasium	1970	9,115	377,067	Natural gas	Condensing	960
7	Swimming pool	1970	8,071	685,267			
8	Condominium Airali	1968	3,479	173,174	Natural gas	Traditional	244
9	Condominium Palazzo del Sole	1976	4,930	255,300	Diesel oil	Traditional	185
10	Condominium de Amicis 32	1971-1980	4,163	122,000	Natural gas	Condensing	134
11	Condominium de Amicis 28	1971-1980	6,656	214,000	Natural gas	Traditional	215
12	Condominium Lusernese	1968	11,544	356,000	Diesel oil	Traditional	214
13	Condominium Lucerna	1961-1970	10,275	500,000	Natural gas	Traditional	342
14	Condominium Bassotto	1961-1970	12,540	590,000	Natural gas	Condensing	381
15	Condominium Vittoria	1971-1980	16,302	558,000	Natural gas	Condensing	381
16	Condominium Alpi	1971-1980	8,008	260,000	Diesel oil	Traditional	287
17	Condominium Briolera	1946-1961	5,434	150,000	Natural gas	Condensing	105
18	Condominium Giardini	1981-1990	5,900	332,000	Natural gas	Traditional	277
19	Detached house*	1961-1970	401	28,609	Natural gas	Traditional	26

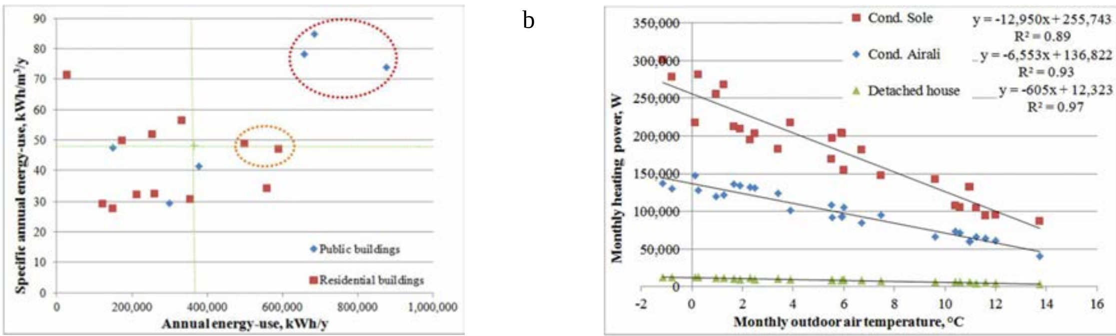

Fig. 1. (a) annual heating energy consumptions for public and residential buildings; (b) monthly heating power for residential buildings [W].

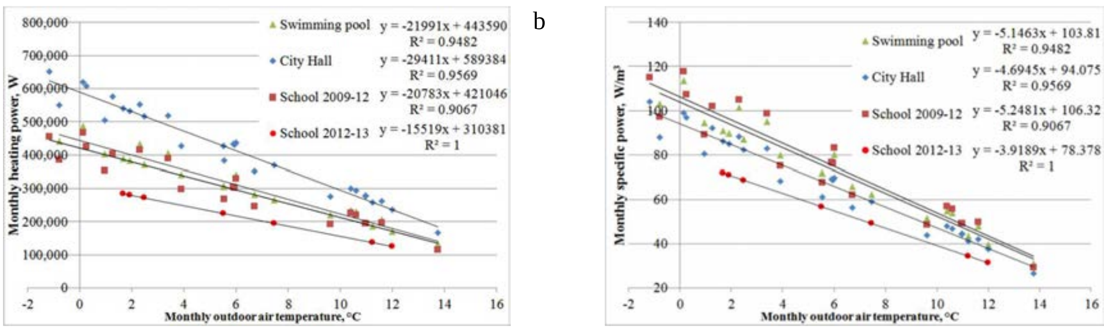

Fig. 2. (a) monthly heating power for public buildings [W]; (b) monthly specific heating power for public buildings [W/m^3].

In the ES method, the slope gives an estimation of the heat transfer coefficient of the buildings (combined with heat gains and considering buildings thermal inertia); as the outdoor temperature decrease, the heat losses and the power increase [7, 8]. The CHP power plant in project will be composed by a biomass boiler for supplying the base thermal load and by an auxiliary gasoline boiler to cover peaks. The installed power of boilers can be used to ensure the peak power, while the heat transfer coefficient has been evaluated in order to evaluate the needed base-load's capacity. The thermal base-load power can be estimated by multiplying the heat transfer coefficients for the average difference of air temperature between indoor and outdoor environments (14.26°C considering the last four heating seasons). In Table 3 can be observed the installed power of boilers and the capacity requested for covering the base-loads: the relative differences of 37%.

Table 3. Installed boilers' power and based -load capacity (kW).

Buildings	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Installed	3500	93	1160		180	960		244	185	134	215	214	342	381	381	287	105	277	26
Base-load	2000	75	420	296	150	182	314	93	155	61	107	178	250	295	279	130	75	166	9

2.3. Buildings' renovation (Retrofit Scenario)

In this section, the possibility of associating buildings renovation together with the DH network connection works has been considered; the purpose is to explore the possibility of connecting more users, to evaluate the new energy demand after the retrofit and to estimate the based-load demand with or without renovation. From the energy audits of the selected buildings (Fig.1a), a thermal model referred to the Italian existing regulations was evaluated to calculate the energy savings. The renovation works concern the thermal insulation of: buildings' facades to reach U = 0.25 W/m^2/K, inferior slab with U = 0.30 W/m^2/K and roof structure with U = 0.23 W/m^2/K; in addition the windows replacement with U = 1.3 W/m^2/K and the boilers' substitution were considered. The values of thermal transmittance U were chosen to achieve national financing; only the City Hall could not be externally insulated (due to historical constraints). The evaluation of the costs considers data from public buildings and recent renovation of schools near Turin [9]. The costs are: boilers' removal 620 €, windows substitution 450 €/m^2, façade and roof thermal insulation 50-70 €/m^2; with a total cost of about 1,150,000 € for the three buildings. The total energy savings is of 43-46% and the based load is reduced by 30% compared to the no retrofit scenario.

a b c

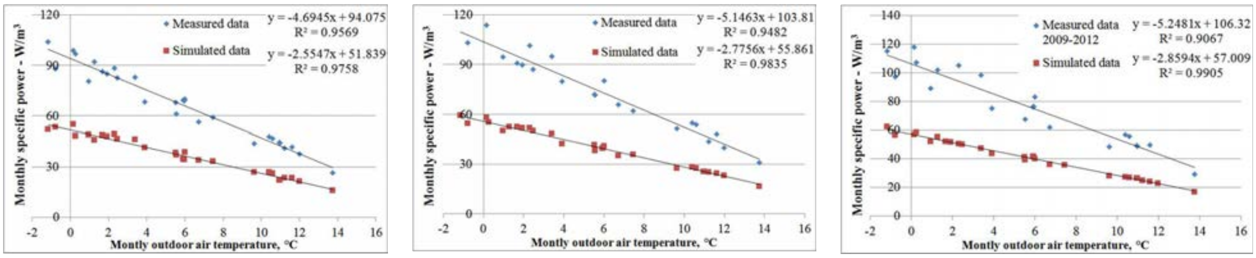

Fig 3. Energy signatures before (measured data) and after renovation (simulated data) for (a) City Hall; (b) swimming pool; (c) primary school.

3. Pre-feasibility study of the district heating (DH) network

By considering the size, the use, the presence of centralized energy systems, the location and physical constraints of the buildings, the plant and the streets, all the analyzed buildings are suitable to be district heated, except the detached house (Fig. 4). Two scenarios have been considered: the Reference Scenario (energy-use of 11.6 GWh/y) and the Retrofit Scenario (energy-use of 10.5 GWh/y). Moreover, 1250 MWh/y is the energy required for the exsiccation (water content 35-25%) of about 4000 t/y of chips. Due to the commercial availability of Organic Rankin Cycle (ORC), for both scenarios will be installed a biomass boiler of about 5 MW, an ORC of 3,1 MW plus an auxiliary Diesel Oil boiler of 3.7 MW (Table 4).

By applying the same procedure of [10], a network layout cost-optimization procedure, based on the Steiner algorithm, is performed. Since for a district heating network the shortest path does correspond to the lowest cost, a parameter to modify branches' lengths - called ''importance of the i-th branch''- has been introduced. The "importance" depends on length of the branch, source position and power, users' peak power and urban constraints [10] and it associates a cost information to all the branches. The relative positions users- power plant and urban constraints strongly influence the paths of the network. Considering network loads of about 11% and the temperature levels showed in Table 4, the resulting DH network is represented in Fig. 4. The total length is of 2.3 km with an investment cost for pipers of 320,000 € (Retrofit) and 340,000 € (Reference), excluding the power plant. In such conditions, about 7850 t/y of chips must be supplied every year and 3.6 GWh/y of electricity will be generated.

Table 4. The power plant.

Biomass power plant information TURBODEN 7CHP	
Biomass Boiler Power	5 MW
Power plant size, storage included	1,600 m^2
Storage of biomass	600 m^2
ORC thermal power - thermal oil circuit	3.5 MW
ORC thermal power – hot water circuit	3.1 MW
Nominal temperature of thermal oil	302-241 °C
Nominal temperature of hot water	60-80 °C
Electric net power - D.Lgs 152-06	702 (kWe)
Net electric efficiency	18 %
Availability factor (assumed)	4500/8760

Fig 4. DH network.

3.1. Economic feasibility

The economic feasibility is evaluated by considering the investment costs of ORC, boilers, heat exchangers, heat sink and DH network; project, connections and installation; operation and maintenance (O&M); fuel; refurbishment costs and national subsidies (for 15 years); electricity generation's profits and electricity consumption savings; thermal energy production's profits [11]. It is supposed to pay the investment costs of both renovation works, the network and the power plant in 15 years with an interest rate of 4.5%. Concerning the Retrofit Scenario it is supposed that the farmhouse owner pays the refurbishment costs and that for 15 years the City Hall, the swimming pool and primary school will continue to pay the presently supplied heat. The considered state subsidies for refurbishment are equal to 24%, 26% and 34% of investment costs respectively for building 7, 4 and 3.

From Table 5 results that the investment is economically advantageous in both cases. The investment results advantageous particularly thanks to the national subsidies for the electricity production. The energy savings related to the Retrofit Scenario allow to connect to the DH network three other condominiums with a total consumption of about 1 GWh/y. The differences between Reference and Retrofit Scenarios are of +6% in the first 15 years, +22 % in the next decade. Thanks to the local availability of woody biomass the fuel cost is acceptable.

Table 5. Economic feasibility in 15 years and benefits from 15 to 25 years (- cost, + benefit).

Type of Costs	Reference Scenario		Retrofit Scenario	
	0-15 y (€/y)	15-25 y (€/y)	0-15 y (€/y)	15-25 y (€/y)
Power Plant + construction works	-322,000	/	-322,000	/
Network, project and connections	-75,000	/	-73,000	
Refurbishment actions with subsidies	/	/	-91,000	/
Fuel Cost	-391,000	-391,000	-391,000	-391,000
O&M and staff	-50,000	-50,000	-50,000	-50,000
Electricity generation and self- consumption	+206,200	+206,200	+206,200	+206,200
Thermal Energy generation	+797,000	+706,100	+797,000	+706,100
Thermal Energy for 3 other condominium	/	/	+90,900	+90,900
State subsidies	+284,300	/	+284,300	/
TOTAL	**+449,500**	**+471,300**	**+451,400**	**+562,200**

4. Environmental impacts

It is possible to identify two main positive aspects of biomass CHP plant on environmental impacts: the use of biomass and the related reduction of fossil fuel consumption; the substitution of individual inefficient boilers with a single controlled and efficient plant. In contrast, pollution related to biomass combustion and transport (this last neglected due to biomass local production) is added in the territory. By considering the reference emission factors of the “Environmental Plan Area” of the Province of Turin (with more restricted emission target) it results that all the emissions’ limits of the new CHP plant are complied (Table 6). The impact of the CHP plant has effects both on local and global level; in fact PM10 and CO emissions are growing, while NO_x are decreasing compared to the existing situation. CO_2 emissions from biomass combustion are zero for the closed carbon cycle; 1670 t_{CO_2}/y are saved with respect to the production of electricity with conventional power plants and 2361 t_{CO_2}/y are saved from the substitution of individual natural gas and diesel oil boilers. Anyway, the heat supplied by the auxiliary diesel oil boiler is responsible for 1493 t_{CO_2}/y, so the global total t_{CO_2} saved are 2538 t_{CO_2}/y.

Table 6. Emission balance (emission factors, D.G.R.98-1247/07).

Scenario	PM10 (t/y)	NO_x (t/y)	CO (t/y)	CO_2 (t/y)
Individual Gas and Diesel Boiler	-0.95	-13.1	-1	-2361
Biomass CHP Plan + auxiliary boiler	+1.86	+12.4	+12.4	-1670 + 1493

5. Conclusions

In this paper, the feasibility of a biomass CHP power plant for providing heat and electricity to buildings in a Mountain Community has been evaluated. In the first part of the paper, the ES method has been used to get information on the energy performances of buildings to be connected to the DH networks. In the second part, renovation works on buildings have been simulated for estimating possible energy savings compared to actual consumptions and for evaluating the new base thermal load after buildings’ refurbishment.

The third part of the work focuses on the economic feasibility of the power plant and the network, its dimensioning and its performance evaluation. From an economic and environmental analysis it results that the buildings’ renovation implies positive effects, especially over a long term horizon; it permits to connect more users to the DH network, to improve the energy efficiency of the system, to reduce pollutants’ emission and to bring local social benefits. The local use of biomass and the advantages of CHP itself represent an opportunity to increase the share of renewable energy sources. Moreover, it allows to reduce fossil fuel dependence and GHG emissions at global level. Anyway, biomass is a limited resource and its potential use is strictly related to the local availability.

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