District heating thermal plant fed by biomass residues in a rural area of Central Italy

M Manni1,*, A Petrozzi1, A Nicolini1,2 and F Cotana1,2
1 CIRIAF – Interuniversity Research Center on Pollution and Environment “Mauro Felli”, Perugia, Italy.
2 Department of Engineering, University of Perugia, Perugia, Italy
* manni@crbnet.it

Abstract. According to the European goals defined in EU Dir. 28/2009, biomass represents a valid alternative to fossil fuels. Combined heat and power (CHP) biomass plants are considered as advantageous in those rural areas which show critical issues regarding the disposal of organic wastes from agriculture and forestry activities. Furthermore, the connection of those villages to the national energy grid requires high operational costs which can be avoided by realizing an autonomous district system exploiting available renewable sources. The hereby study aims at demonstrating all these benefits through the presentation of a pilot project about a district heating system powered by a CHP biomass plant. The intervention has been proposed for a group of buildings located in Perugia, Central Italy. Their connection to the plant would be realized through an underground pipeline. Both the biomass exploitation and the district scale guarantee significant economic and environmental advantages. Indeed, the installing costs can be paid back in less than ten years considering (i) the savings from avoided natural gas exploitation and (ii) incomes from the disposal of wooden organic wastes.

1. Introduction

The environmental impact of the building sector on emissions released in the atmosphere has been constantly raising during the last decades. Buildings are responsible for over 40% of global energy consumption and about 18% of Greenhouse Gas (GHG) emissions [1]. In that context, EPBD (Directive 2010/31/EU) [2] and Energy Roadmap 2050 [3] contributed in promoting the definition of the concept of net-zero energy buildings and Zero Emission Buildings (ZEB) to reduce energy consumption and producing energy from renewable sources to lower GHG emissions.

The ZEBs are characterized by high energy efficiency and can cover the respective yearly energy consumptions by exploiting Renewable Energy Sources (RES). Relevant contributions can be found in the Literature describing the different ZEB categories, presenting pilot projects, and reporting results from monitoring campaigns [4–6]. The zero energy goal can be achieved by applying two clusters of strategies [7–10]: (i) ‘passive strategies’, aiming at increasing solar thermal loads and decreasing energy dispersion through the building’s envelope [11,12]; (ii) ‘active strategies’, to improve systems and technologies for energy generation in order to counterbalance the energy demand [13]. These interventions are integrated during the planning stage to design a responsive architecture.

As far as the ‘active strategies’ are concerned, the introduction of the Zero Emission Neighborhood (ZEN) concept has represented an important step towards the improvement of their efficiency. Considering a larger scale makes it necessary including in the analyses several factors – neglected or not significant in ZEB case studies –such as sustainable transportations, urban spatial qualities, promotion of sustainable behaviors, management of the energy flows in a smart and flexible way [14].

Neighborhood-scale strategies for energy supply were initially developed in the United States of America in the 1880s. The first generation of district heating systems (DHSs) was based on steam power
thermal plants with high operating temperature and low energy efficiency [15,16]. Conversely, the following three generations demonstrated to be more articulated and sustainable. Nowadays, the development of the fourth-generation DHSs is fundamental to realize the Sustainable Development Goals (SDGs) and to achieve a complete de-carbonization of society [17]. Those systems, which can already cover up to 90% of the residential heat demand in Scandinavian countries [18], can recycle low-grade heat from industrial processes and integrate it into the energy generation process from RES.

In this context, the hereby study aims at presenting a DHS case study powered by a combined heat and power (CHP) biomass plant. It is part of a proposal for the Perugia municipality to promote the realization of autonomous energy grids in the remote rural villages whose economy is based on agricultural activities. The ordinary maintenance of public and private greenery produces a high amount of wooden organic waste. In that regard, a survey conducted among people living in these districts shows that they prefer burning these residues instead of disposing in landfills. The main reasons for that behavior can be found on the lack of adequate areas for the disposal in the proximity and in the too little consideration of the impact on the environment of this behavior. Alongside, organic wastes are also produced by some companies making wood chips from the core of the trees’ trunks. In particular, the branches and the cortex layer are removed during the pre-processing stage and disposed.

The research domain covers (i) the exploitation as RES of organic wastes from wood chips’ processing and residues from greenery’s maintenance, as stated by Circular Economy’s principles, (ii) the effectiveness of the CHP biomass plant when applied to a district system, and (iii) the preliminary evaluation of the economic and environmental advantages guaranteed by those interventions.

2. The pilot project
2.1. The current CHP biomass plant
The pilot project is part of a proposal for the rural villages in the Perugia municipality. The case study is a residential zone located in proximity to the main regional road that connects the district to the current storage dock for biomasses.

The storage dock is managed by a private company which produces wood chips for feeding a CHP plant combining a gasifier to a heat exchanger and an engine (Figure 1). The obtained syngas is characterized by a thermal power of 110 kW_t and it is delivered to the 49 kW_e engine (powered by syngas). Finally, the available heat from the exhausted gases is recovered and exploited in the preliminary drying stage of the biomass.

To achieve the high efficiency required to the gasification thermal process, the inlet biomass has to be pre-treated by removing branches and cortex from the trunk. This operation produces a large volume of organic wastes which could be exploited to feed the biomass plant powering the DHS. Thus, the logistics platform of the district grid is considered adjacent to the pre-treatment area in order to avoid emissions due to the transportation of the residues.

![Figure 1. Main components of the current CHP biomass plant: the gasifier (a) and the engine (b).](image)

2.2. The selected users
The public buildings which will be connected to the DHS are distant up to 1.2 km from the biomass CHP plant. These architectures are (a) the medical center, (b) the public school, and (c) the local sportive arena. The facilities are currently served by natural gas boilers with nominal power values ranging from 150 kW to 332 kW. According to the regulation in force within the municipality, the heating systems in
public buildings are activated from the 1st of November to the 15th of April, and for a maximum of 12 hours per day.

The monitoring campaigns and the evaluation of the yearly energy consumption amounts for the last decade have permitted to estimate the energy demand for heating as equal to 60,000 kWh per year, 180,000 kWh per year and 100,000 kWh per year for building a, b, and c, respectively (Table 1). Thus the new DHS should provide up to 340,000 kWh per year. Initially, another building – the locker rooms of the outdoor football pitch – was considered alongside to the buildings a, b, and c, and included in the monitoring campaign. Nevertheless, the cost-benefit analysis underlined that the cost of the realization of the connection to the DHS would have been higher than the savings because of the building’s low energy consumption.

Table 1. Overview of the energy consumptions estimated for the considered building users.

| ID | Building’s use            | Existing thermal plant       | Thermal power  | Estimated energy consumption for heating |
|----|----------------------------|------------------------------|----------------|-----------------------------------------|
| a  | Medical centre             | Natural gas boilers         | 150 kW + 150 kW | 60,000 kWh/year                        |
| b  | Public school              | Natural gas boiler          | 332 kW         | 180,000 kWh/year                       |
| c  | Local sportive arena       | Natural gas boilers         | 291 kW + 104 kW | 100,000 kWh/year                       |
| d  | Football pitch             | Natural gas boiler          | 30 kW          | 8,000 kWh/year                         |

2.3. The district heating system
The DHSt biomass plant coupled to the DHS represents an efficient strategy to exploit the large volume of organic wastes which are hardly managed by the municipality. In compliance with the principles of the Circular Economy, the biomass is converted into calories and delivered to users connected to the grid. Furthermore, the ashes produced at the end of the process are scattered on the ground as fertilizer.

The DHS layout included the CHP biomass plant, the district grid, and the final users. In addition to those, the current natural gas boilers are maintained in each building to guarantee thermal power during the maintenance of the DHS.

The proposed CHP plant is composed of two boilers with a nominal power of 500 kW for each (1 MW in total). The energy requirements have been quantified considering the contemporaneous utilization from all the buildings; then, the resulting amount has been further increased to take into account the increment of the users’ number in the future. The CHP plant is arranged in the following elements: the outdoor temporary storage platform, the wood chipper (to convert biomass into wood chips), the underground room (where wood chips are dropped off before being loaded through a cochlea), the two 500 kW biomass boilers, and a hot water storage tank.

The grid connecting the CHP plant to final users is characterized by a primary ring made of two insulated pipelines, one to deliver and the other to return the heat transfer fluid (water). The primary ring is 1.3 km long and it follows a linear path along the existing road to reduce the costs for the realization of completely new infrastructures. The buildings are connected to the primary line by secondary thermal stations equipped with plate heat exchangers. Finally, the calorie-counter will be installed on each building to monitor energy consumption.

3. Biomass consumption and preliminary environmental analyses
The exploitation of biomasses as an energy source can be considered sustainable since their combustion does not contribute to incrementing the greenhouse gases in the atmosphere.

The volume of wood chips loaded throughout the year in the thermal plant is estimated with Eq. 1. According to that, the thermal energy delivered to users (E) depends on the product of the wood chips’ low calorific value (LCVwc), the volume of the burnt biomass (Vwc), and the efficiency of the DHS (ηtot).

\[ E = \text{LCV}_{\text{wc}} \cdot V_{\text{wc}} \cdot \eta_{\text{tot}} \]  

(1)

Considering the estimated energy consumption equal to 340,000 kWh per year, while the low calorific value of wood chips and the efficiency of the system are approximately 2.5 kWh/kg and 0.95, the required volume of biomass has been estimated for 140 tons per year. This quantity can be stored in a 4.5 m by 4.5 m by 2.5 m underground room characterized by a total volume equal to around 50 m³.
The biomass (density of about 300 kg/m\(^3\)) will be loaded on this room for nine times per year (15 tons each).

Similarly, the Eq. 1 can be used to quantify the savings in terms of natural gas which are achieved by realizing the DHS. The lower calorific value for natural gas is estimated equal to 10 kWh/m\(^3\), whereas the yield of the current boilers is averagely 0.85. Thus, the volume of burnt natural gas turns to fit the same energy requirements (340,000 kWh per year) turns out to be 40,000 m\(^3\) per year. A CO\(_2\) emission factor of around 0.056 kgCO\(_2\)eq/MJ was used for natural gas (epa.gov) to estimate the environmental impact of the technology. Since the higher calorific value is around 40 MJ/m\(^3\), the CO\(_2\) emission factor for the natural gas is equal to 2.2 kgCO\(_2\)eq per m\(^3\), without including the emissions associated with extraction and delivery stage in the estimation. Thus, exploiting biomass instead of natural gas allows the emission of 80 tons of CO\(_2\) per year to be avoided.

4. Costs assessment
This section is arranged in two parts where the installing and the operation costs (sub-section 5.1), and savings and incomes for the public administration (sub-section 5.2) are reported. In particular, the installing costs for the DHS and the CHP biomass plant are counterbalanced by economic savings from the avoided consumption of natural gas. Furthermore, the biomass is characterized by a null cost since it is derived from processing wastes and from residues of ordinary maintenance activities.

4.1. Installing and operation costs
The initial investment was estimated equal to 450,000 € by considering the cost categories reported in Table 2. The categories with the highest costs are the ‘purchase and setup’ of boilers, and the ‘pipeline’ (1.3 km long linear ring) of the DHS. The sum of these two quantities accounts for almost 90% of the whole installing cost.

| Element           | Intervention          | Cost    |
|-------------------|-----------------------|---------|
| Boiler            | Purchase and setup    | 200,000 €|
|                   | Hot water tank        | 20,000 €|
|                   | Equipment room        | 8,000 € |
|                   | Wood chips’ storage room | 6,000 € |
| District system   | Excavating            | 8,000 € |
|                   | Pipeline (1.3 km linear ring) | 200,000€ |
|                   | Thermal stations      | 6,000 € |
| Other             | Certifications and bureaucracy | 2,000 € |
| Total             |                       | 450,000 €|

As far as the operational costs are concerned, the ones regarding natural gas boilers are not included in the present economic analysis (Table 3), although the boilers are not dismissed. The operational costs which refer to the DHS account for 7,000 € per year and they are mainly due to fuel for the wood chipper and its maintenance (4,000 €).

| Category                                      | Cost      |
|-----------------------------------------------|-----------|
| Fuel for the wood chipper and its maintenance | 4,000 €   |
| General managing costs                        | 1,000 €   |
| Disposal on fields of the ashes               | 2,000 €   |
| Total                                         | 7,000 €   |

4.2. Savings and incomes for public administration
The collection of organic wastes and the management of the DHS can guarantee several incomes to the public administration. From the disposal of the residues, it is possible to earn up to 17,000 € per year which corresponds to 0.12 € per kilogram of organic waste delivered by citizens to the storage dock.
The calculation has been conducted considering that all the biomass (140 tons per year) is obtained in this way. Thus, the incomes would be reduced in case the municipality collects biomass from other sources which do not guarantee any earning such as the maintenance of public green areas.

In addition to that, the connection of private users to the DHS in the future can guarantee potential incomes which would be proportional to the building’s energy consumption (around 0.06 € per kWh).

When it comes to the estimation of the economic savings, up to 32,000 € per year are saved from the avoided exploitation of natural gas. This amount is obtained by multiplying the volume of natural gas that is burnt every year in the current boilers (40,000 m³ per year) by the total price of natural gas in the bill (about 0.80 €/m³).

5. Conclusions

The proposal for the municipality of Perugia, that is based on the principles of the Circular Economy, represents an element of innovation for the rural villages in Central Italy. The conducted analyses demonstrate that exploiting local RES such as wooden organic waste can be advantageous also in contexts which are distant from the main urban areas. Furthermore, the outcomes underline the suitability of the intervention and its environmental and economic sustainability. The installing costs can be paid back in less than ten years considering the saving from avoided exploitation of natural gas and the incomes from the disposal of organic wastes.

The main benefits which are guaranteed by the proposed district heating plant are summarized on the following lines:

- Creation of a logistic platform for the management of both processing wastes (from wood chips industry) and residues (from the maintenance of public and private greenery);
- Substitution of the fossil fuel energy source with biomass to supply thermal energy to the main public buildings of the district;
- Demonstrating the suitability and the benefits related to the intervention in order to encourage the repeatability of this best practice;
- Promoting new opportunities of working for private companies within the complementary activities such as the ordinary maintenance of private greenery.

The present study represents a part of a wider research activity aiming at developing best practices about ZEN for low-populated areas in the rural zones of Central Italy. The next stage of the research will focus on the integration in the district system of absorption chillers to guarantee the adequate level of comfort indoor also during the warm season.

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