Optimal design and localization of a biomass-fired ORC in DH systems: an energetic, environmental and economic analysis

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ABSTRACT

Hybrid power plants comprising combined heat and power (CHP) integrated with a biomass-fired Organic Rankine Cycle (ORC) represent interesting opportunities for efficient district heating (DH) systems, increasing the level of renewable energy use and producing additional electric power at high efficiency. Nevertheless, in the case of biomass-fuelled plants, there is an increasing necessity for good alignment with the potential of the territory. In this paper, the mountain area of Susa Valley (North-West Italy) is investigated to find an optimal solution for the installation of a 1 MWe ORC unit, exploiting wood chips available in the area. The analysis concerns the simulation of three different thermal plants (two existing DH systems fuelled by natural gas and one at the design stage) characterized by different sizes of demand and percentages of user type (eg. residential, tertiary). The study first analysed real data available for the two existing DH systems (30 minute steps over 5 years), evaluating normalized thermal load. Then, based on climate data and the characteristics of the thermal user, a Matlab model was used to evaluate the new DH system at hourly intervals and to simulate both of the existing configuration plants in order to assess different plant designs. Finally, the Matlab model is used to identify the best solution, in terms of energy, environmental and economic aspects. For each case study, specific KPI (Key Performance Indicators) were evaluated, such as energy efficiency, primary energy consumption, carbon dioxide emissions and SPBT (Simple Payback Time). The study highlights the ORC's role in the Emission Trading System (ETS) scheme in order to reduce total CO_2 emissions of thermal plants and to obtain better economic return with respect to ever-increasing costs of environmental burdens linked to ETS. Due to the profit margin for heat and of electricity in the Italian context, the study found the optimal choice to be the DH system which is characterized by the highest heat sales and the lowest DH network temperatures.

1 INTRODUCTION

The residential sector was responsible in 2018 for a consumption of about 32.1 Mtep, among which 70% was for space heating and cooling. According to the national energy plan, one of the Italian goals is to reduce the global final energy consumption by 0.8%/year of the average consumption 2016-18 triennial by 2030. It's going to be very challenging in particular for "critical" sectors such as the residential sector. Heating and cooling consumption declined rapidly between 2016 and 2017 by 4.2%/year, however it has been increasing by 1.5% in 2018 [9].

District Heating (DH) represents an efficient solution to provide sustainable thermal energy for space heating to final users. This is true in particular if the delivered thermal energy is generated through cogeneration plants and renewable thermal sources. The European Directive 2012/27 introduces the key definition of *efficient district heating and cooling* as a district heating (DH) or cooling system using at least 50% renewable energy [7]. Local biomass fuel, from neighbouring forests, represents one of the promising sources for the integration of renewable energy within DH networks especially in the Northern Italy and alpine areas, where other renewable sources such as solar and geothermal are difficult to integrate into existing high-temperature district heating networks. Some studies investigated the use of wood-fired combined heat and power CHP systems coupled with existing DH [12]. The choice of the best unit to satisfy the DH systems' thermal energy demand is based on a deep knowledge of heat load profiles, that are related to users' behaviour, network performances and control logics. The previous works provide an analysis of existing large-size DH systems, supplied by natural gas CHP units and integration boilers [13]. They show the importance of performing a statistical analysis over various operation conditions. The present article wants to widen the analysis of the historical consumptions comparing three medium-size different DH systems and considers the possible contribution of local wood biomass through 1 MWe ORC unit connected to a thermal oil boiler (OBB). Experimental data are often used to define thermodynamic models capable to predict energy performance and highlight electric efficiency trends under different management strategies of the system [16] [17]. The model defined in this article aims to simulate the ORC not as a single component but by evaluating performance within a system consisting simultaneously of several generation components connected to the thermal utility. The ORC performance is evaluated in each thermal plant not only taking into account energy parameters, but also environmental and economic aspects considering the current ETS scheme. Few articles analyse the influence of EUA (European Emission Allowance) prices [18], that represents interesting topic in this last period. Participation in the EU ETS is mandatory for companies that generate electricity and heat with an installed capacity higher than 20 MW. One of the systems studied is at design stage and it is characterized by installed capacity lower than threshold value. The other two are existing, they participate in the trading phases and are fuelled by natural gas with an installed capacity higher than 20 MW. They have real operational data available that were analysed in order to predict the thermal load for both existing and design systems.

2 METHODOLOGY

2.1 Heat demand dataset

The heat demand model used for the simulations was developed by processing operational data of two existing DH systems with similar climate conditions. Records were collected over two years of operation from the first existing DH system (Ex1) and over five years from the second one (Ex2). The heat supplied to the thermal network, the electric power production and the natural gas consumption have been recorded every 30 minutes.

The thermal demand during the summer season is considered to evaluate the DH network thermal losses and the energy required for hot domestic water. Assuming that it is constant throughout the year, the thermal demand for space heating is obtained.

For Ex1 and Ex2 systems the hourly records are averaged and directly used in the respective location (*direct method*). In addition to achieving an average thermal load suitable for general DH system, for each year the daily thermal energy values, sorted in descending order, are divided by the total heated volume of the final users and the degree-days [kWh /m^3/GG] (Figure 1).

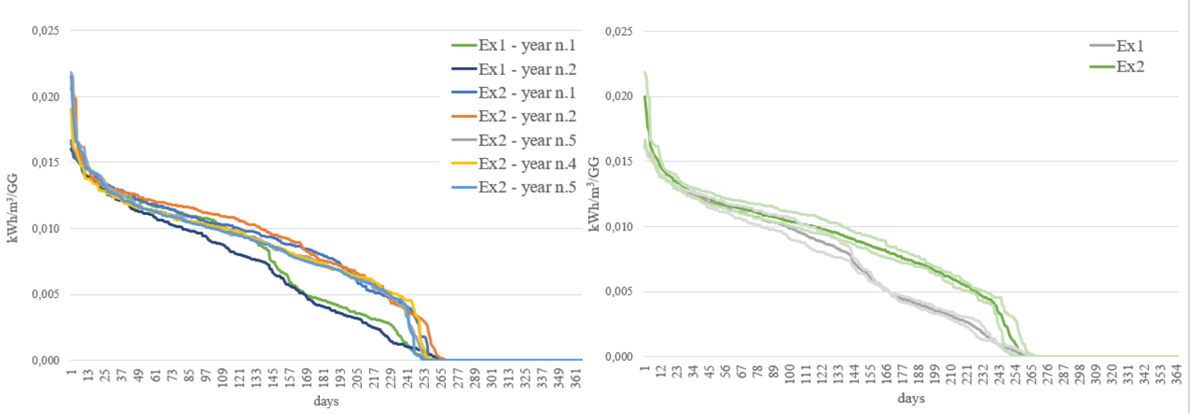


Figure 1: real operational data and average thermal load trends (space heating)

In Figure 2 the Ex1 and Ex2 thermal loads are analysed individually. Analysing data of all available years, the maximum, the minimum and the average thermal load curves were obtained. Comparing the average curve with the maximum and the minimum trends, in both systems the average return value was calculated. The different trend in the final part of the Ex1 curve depends on the high percentage of the hotel industry. The deflection occurs in the off-season.

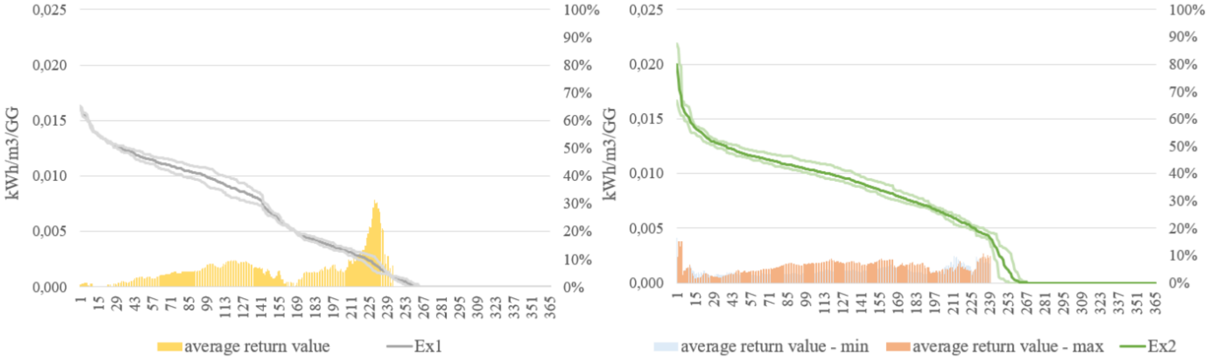


Figure 2: minimum, maximum and average thermal load (space heating)

Instead if data aren't reliable or during the DH design stage, the *indirect method* will be used. The average thermal load is chosen from the location that well represents the users typology and that is closer to the percentage of residential and tertiary sectors. Values are multiplied by degree-day and by the volume of the building stocks heated in the new DH system site. In order to obtain the hourly heat demand, the daily energy consumption is reallocated following the average daily thermal load trend.
The main characteristics of the thermal plants analysed are summarized in *Table 1*. All DH systems are characterized by the same climate zone (F) with comparable climatic conditions. Moreover, they have similar thermal plants' configurations characterized by internal combustion engines fueled by natural gas with electrical heat pumps (GEHP) and integration back-up boilers (IBB).

Table 1: DH systems' configuration and characteristics

Condition	**Code**	**Degree-days**	**Final users**	**Service sector**	**GEHP P_{th}**	**GEHP P_{el}**	**IBB P_{th}**	**DH network temperatures**
Existing	Ex1	4,370	1,030,000 m^3	38 %	8.7 MW	8.2 MW	30 MW	75 – 55 °C
Existing	Ex2	3,050	1,400,000 m^3	17 %	8.7 MW	6.2 MW	40 MW	90 – 60 °C
Design Stage	DS	4,950	690,000 m^3	15 %	-	-	-	75 – 55 °C

2.2 Thermal plants' component

The base DH thermal plants' configurations require the installation of internal combustion engines fueled by natural gas, electrical heat pumps and integration back-up boilers. The possibility to install the ORC unit was investigated in all scenarios. The simulation model selects each component and changes the working parameters, in order to achieve the combination that maximizes the system's efficiency. It was assumed that the network return water is firstly heated by the ORC unit. If the energy requirement is not completely satisfied by ORC, GEHP first and IBB then are used.
To correctly simulate the working performance and to impose a power limit control, the variation of the components' performance were analysed at partial load.

- ORC unit

A commercial unit has been chosen to study ORC performance at partial load. Table 2 shows its nominal data.

Table 2: ORC and OB nominal parameters [3]

ORC P_{th}	**ORC P_{el}**	**OBB P_{th}**	**OBB η_{th}**	**F**
4.1 MW	1.1 MW	5.3 MW	85 %	6.2 MW

The ORC system keeps high electrical efficiency even when it operates with lower thermal power input. The modulation of the ORC is closely linked to the performance of the OBB at partial load, which is not heavily penalized for a value of up to 65% of the nominal power. Therefore it was supposed to modulate up to 75% of nominal load when electrical efficiency decreases just by 3%. Efficiency also depends on the water outlet temperature from the condenser. The design point given by the manufacturer should be characterized by an outlet temperature of 35°C for which electrical efficiency is 24%. It was assumed that the temperature threshold is equal to 75°C. The maximum flow rate circulating in the condenser of the ORC is 300 m^3/h. When the water flow rate is higher than the ORC threshold value the surplus is directly heated by the IBB.

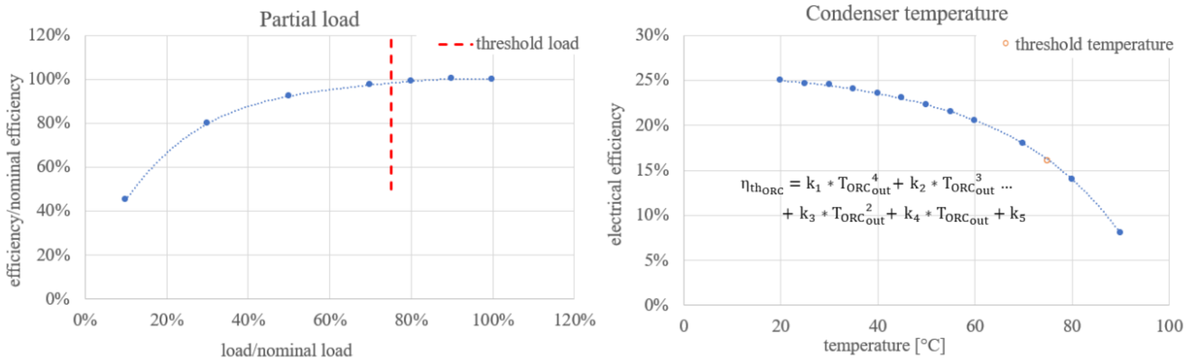


Figure 3: ORC electrical efficiency

The efficiency trends are described by two fourth-degree polynomial functions. These functions are used by the model to simulate the operation of the ORC as explained in the following paragraphs.

- Gas Engine with Heat Pump

Gas Engine with Heat Pump (GEHP) is used in order to enhance the heat recovery exploiting the waste heat from the second intercooler engine and from the exhausting gas at low temperature. It was assumed to cool exhausting gas until 50°C avoiding condensation. In order to simulate through the calculation model the GEHP as a single component, electrical ($GEHP_{\mathrm{el}}$) and thermal power ($\mathrm{GEHP_{th}}$) were recalculated assuming COP equal to 5. Knowing the heat recovery obtained in the evaporator ($\mathrm{Q_{eva}}$), the heat pump electric power was obtained and it was subtracted from the engine electric power (GE_{el}), although the heat generated in the condenser was added to the engine thermal power (GE_{th}). GEHP is characterized by a lower electrical efficiency, but a higher global one.

$$\mathrm{GEHP_{el}} = GE_{el} - \frac{Q_{eva}}{COP - 1} \tag{1}$$

$$\mathrm{GEHP}_{th} = GE_{th} + \frac{Q_{eva}}{COP - 1} * COP \tag{2}$$

- Integration Back-up Boiler

Integration Back-up Boiler (IBB) performance isn't penalized at partial load. The simulation model assumes that integration components are employed only when the heat required by the network is higher than the maximum power that can be generated by principal power-generation modules (ORC and GEHP). The thermal efficiency is considered constant and equal to 90%.

2.3 Simulation model

The model is outlined in Figure 4. Knowing the heat supplied to the network hour-by-hour, the DH network temperatures, the thermal plant's configuration, the number and the nominal parameters of each component, the simulation model allows to determine the electrical power ($\mathrm{P_{el}}$), the fuel power (F), the rate at which each component is working (PL), the thermal/electrical efficiency (η_{th}; η_{el}) and the consumptions of wood biomass (W) or natural gas (NG). The lower heating value ($\mathrm{LHV_{NG}}$) of the natural gas is about 0.035 GJ/m^3 (9.7 kWh/m^3). For the biomass was supposed a LHV$_{bio}$ of about 2.35 kWh/kg assuming a moisture content of 50% wb.

PL is calculated knowing the heat required from the network and the nominal thermal power of the component. First thermal and electrical power of the ORC unit are obtained (Figure 4: I – II). The output temperature from the condenser is calculated (III) and then efficiency is computed in order to obtain the fuel power (V). Using the thermal power generated by GEHP, electrical and fuel power are calculated from the correlations (VIII – IX).

Inputs	Description
n	Number of component
r_{max}	Minimum load percentage
a; b	Constant coefficient
c; d	Constant coefficient
k_i	Constant coefficient
$P_{th_{nom}}$	nominal thermal power of component
$P_{el_{nom}}$	nominal electric power of component
HN	Heat required from the network
Tin; Tout	DH network temperatures

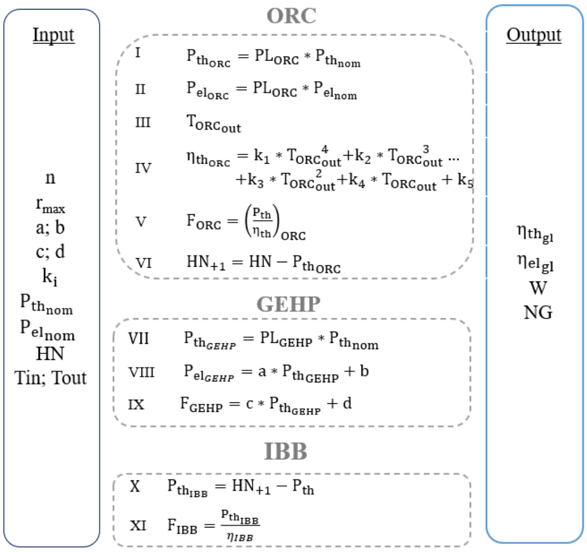


Figure 4: simulation model’s block diagram

The energy output of different components are calculated using coefficients of a polynomial obtained by empirical correlations (section 2.2). As an example, coefficient values are shown for the ORC unit [4].

Table 3: Model's coefficients

k_1	k_2	k_3	k_4	k_5
- 1.08e-06	1.85e-04	- 0.0135	0.357	21.74

2.4 Definition of environmental indicators

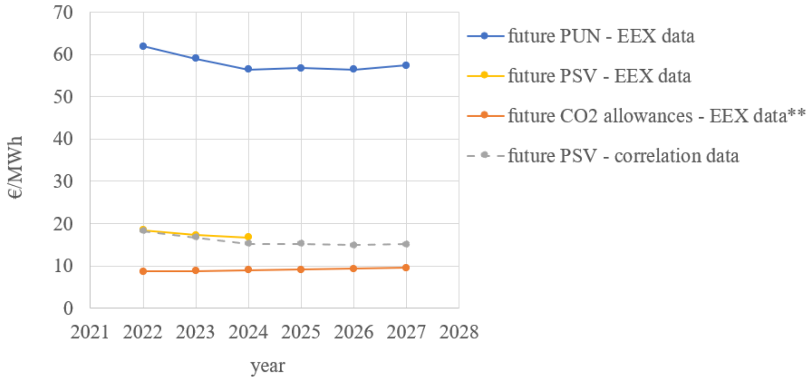
In order to determine the carbon dioxide emission, it was assumed internal combustion engines and integration boilers’ emission factor (EF) of 56.2 kg$_{CO2}$/GJ [10]. Knowing the annual natural gas consumption for each thermal plant’s configuration, carbon dioxide emissions have been evaluated. Biomass is a carbon neutral fuel, meaning that the carbon emitted by biomass burning won't contribute to climate change if it is grown in a sustainable way.

2.5 Definition of economic indicators

The cost of heat and of electricity (in the Italian context) are closely dependent on the cost of the natural gas. Therefore changes in market price from 2014 to 2019 were analysed in order to obtain a correlation between the electricity price at national market (PUN) and the natural gas cost at national market (PSV) [5]. The study was extended to the historical trend cost of CO_2 allowances [6]. The analysis showed that until 2017 the maximum cost was about 7 €/ton. In the following years CO_2 price has increased rapidly. Nowadays the maximum cost of 45 €/ton has been reached. As a consequence of this study, it was assumed that the future PUN will be also linked to CO_2 allowances.

Assuming the EEX future market prices prevision [8] of the cost of electricity (PUN) and CO_2 allowances, the cost of natural gas (PSV) was obtained and it was compared with the predicted value.

The average values for each market price are shown in Figure 5 and are used for the economic considerations in the next paragraphs.



**value related to 1 MWh produced by natural gas power-unit characterized by EF of 56.2 kg_{CO2}/GJ and LHV of 0.035 GJ/m^3 (9.7 kWh/m^3).

Figure 5: comparison between EEX data and PSV value obtained from the correlation

For the purposes of an economic analysis, for each scenario the economic revenues concerning electricity and heat sold to customers and the economic cost related to the market prices of combustion fuel, CO_2 allowances and O&M cost were calculated. CHP systems electrical power will be reduced by the percentage of self-consumption (10% for ORC system and 2% for GEHP). The cost of heat was obtained considering an additional cost for services and excise duties equal to the average cost from 2014 to 2019 (45 €/MWh).

Table 4: incomes, expenses, O&M costs

Incomes		**Expenses**			**O&M costs**		
Electricity	**Heat**	**Natural Gas**	**Wood Biomass**	**CO_2 allowances**	**ORC**	**OBB**	**GEHP**
58 €/MWh_{el}	61 €/MWh_{th}	18 €/MWh	32 €/MWh	45 €/ton	5.4 €/MWh_{el}	4.0 €/MWh_{th}	20 €/MWh_{el}

3 RESULT AND DISCUSSION

3.1 Description of DH systems

Using the *direct method* described in the previous paragraph, the hourly average thermal loads for the Ex1 and Ex2 systems were obtained. In order to obtain DS' thermal load the *indirect method* was applied using the characteristic curve of Ex2 and calibrating on the different volume of final users and different degree-days. Ex2 was chosen because it well represents the design case regarding users typology. Considering the average daily thermal trend for space heating and hot domestic water, DS' hourly thermal load was obtained in Figure 6.

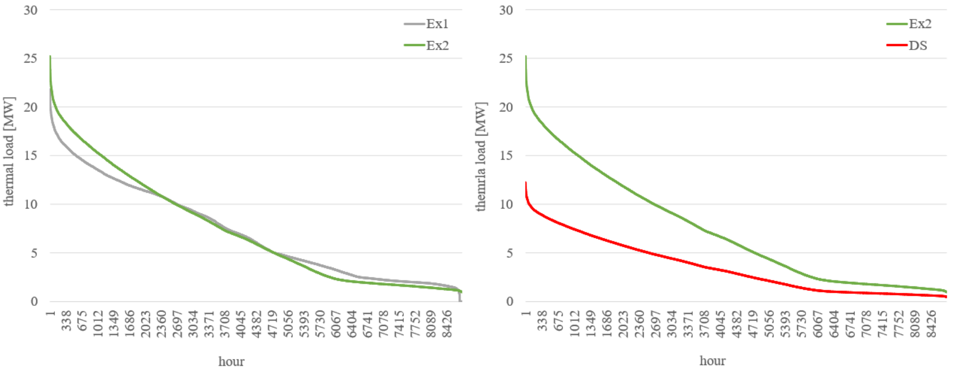


Figure 6: DH systems' average thermal load (space heating + hot domestic water + thermal losses)

3.2 Performance analysis

In all scenarios the ORC unit installation allows the DH system respects the definition of *efficient district heating* reducing the energy contribution of natural gas-fired components (Figure 7).

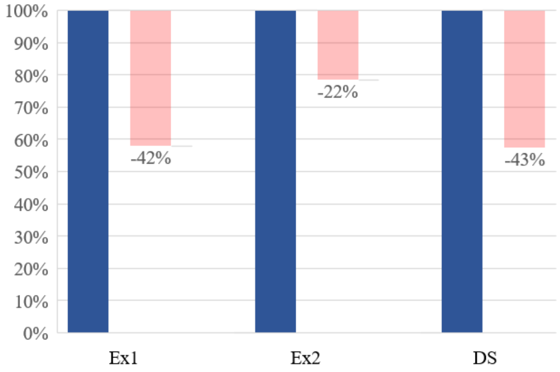


Figure 7: Reduction of energy contribution of IBB and GEHP

The DS' annual thermal energy demand is about half that exiting DH systems. In the design case ORC unit is able to cover the highest percentage with about 48% of the annual thermal load even if the operating hours are lower with respect the existing cases (Figure 8).

Table 5: ORC performances

Scenario	ORC Electric Energy	ORC Thermal Energy	ORC Global Efficiency	ORC operating hours
Ex1	6 GWh/year	22 GWh/year	74 %	6,200 h/year
Ex2	4 GWh/year	16 GWh/year	69 %	4,300 h/year
DS	4 GWh/year	15 GWh/year	72 %	4,100 h/year

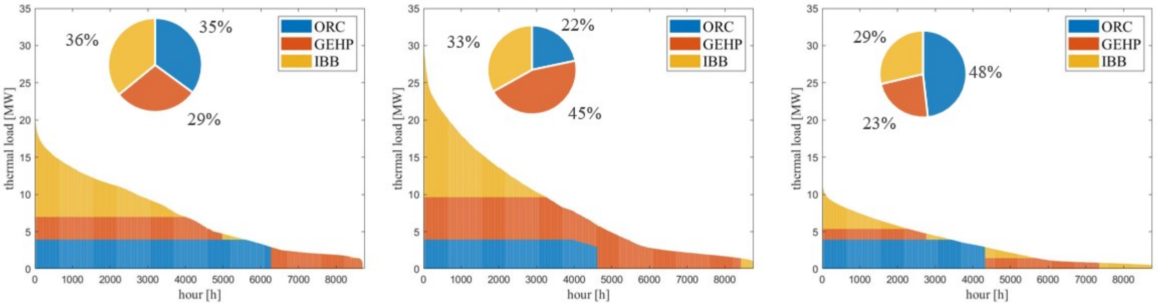


Figure 8: from left: Ex1, Ex2, DS' thermal loads

ORC performance changes from case to case since operating conditions are different in terms of DH network temperatures and energy requirements. The Ex1 DH system is characterized by DH network temperature lower than the other two case studies, this allows ORC to reach a higher value of operating hours.

3.3 Environmental analysis

The percentage of energy derived from renewable sources is higher in the DS system. This reduces carbon dioxide emissions by around 40% compared to the case with only natural gas-fired components. The DS system is not affected by the ETS regulation scheme because its installed capacity is lower than threshold value. Ex2 thermal plant represents the worst case in terms of carbon dioxide emissions, but consumes an annual quantity of wood-biomass suitable for the mountain area of Susa Valley resource availability that was estimated about 14700 t/year. Comparing the thermal plant configurations in which it is supposed to install the ORC unit with the base thermal plants (GEHP + IBB) it is possible to calculate the CO_2 emissions avoided and the corresponding cost savings (Table 6).

Table 6: fuel consumption and CO2 emissions

Scenario	**W**	**NG**	**CO_2**	**ORC avoided NG**	**ORC avoided CO_2**	**ORC avoided CO_2 costs**
	t/year	k(m)^3/year	t/year	k(m)^3/year	t/year	k€/year
Ex1	15,900	6,030	12,000	4,370	8,600	390
Ex2	12,400	8,940	17,700	2,460	4,900	220
DS	11,100	2,450	4,900	1,820	3,600	0

3.4 Economic analysis

The total capital cost for the installation of an ORC is supposed equal to 4,300 k€ considering an ORC unit complete with thermal oil biomass fired boiler, the simple payback time (SPBT) was obtained. In Figure 9 the total economic balance is shown for each scenario. First SPBT was calculated considering the total gross operating profit (GOP). The largest extension of DH network allows the Ex2 system to sell a higher quantity of heat and electric energy to the consumers. This aspect greatly affects the thermal plant's incomes which allows it to reach high GOP and a lower SPBT. Not to consider the influence of the network extension, SPBT was calculated considering only the ORC's incomes and then taking into account the ORC avoided CO_2 costs.

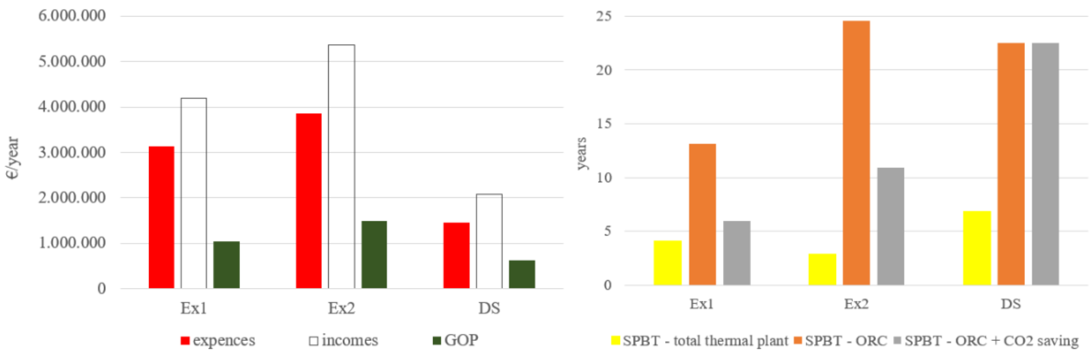


Figure 9: Economic results

In Figure 10 all specific expenses are shown for each scenario.

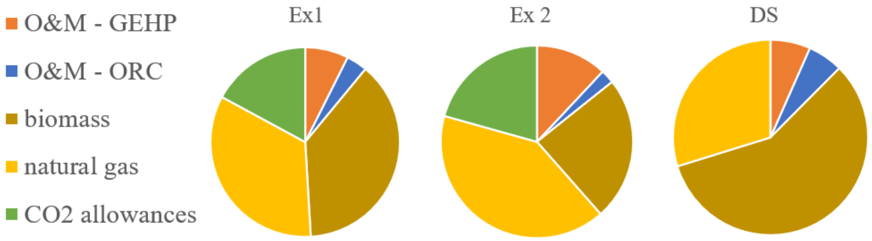


Figure 10: specific costs

CONCLUSIONS

This study presents a comprehensive methodology for assessing the sustainability of integrating ORC plants into district heating networks. An analysis scheme is provided for existing plants and a methodology is presented for new DH networks, on the basis of specific climate conditions and reference to thermal needs.

A detailed analysis was made of existing district heating plants characterized by the integration of several generation systems. From the results it is clear that ORC technology within existing networks powered by natural gas represents an excellent lever with which to exploit local energy resources such as biomass. In order to decarbonize both the thermal and electrical sectors, ORC technology is a great alternative to hybrid DH systems in which internal combustion engines are installed. The use of biomass energy integration with ORC systems also allows gas-fired plants to obtain a better economic return, counterbalancing the ever-increasing costs of environmental burdens of ETS. It is important to bear in mind that in Italy, income in €/MWth is higher than income for the electricity sold (€/MWe), and therefore ORC technology is not economically favourable for non-ETS plants. In fact, the majority of installations occurred during periods when feed-in-tariff for electricity from biomass was adopted in the Italian incentive scheme.

Concerning the optimal solution, the paper shows how from an energetic, economic and environmental point of view the case study Ex1 could represent the optimal solution for the ORC installation, due to its lower SPBT and also because of the ETS system economic integration. The case study suggests that investment in this technology is profitable. This is due to the fact that in the case study, the ORC operating hours are the highest, the DH network extension is large and the profit margin for heat is high. Comparing the Ex2 and DS scenarios, the best solution considering both economic and environmental points of view is the Ex2 solution. Taking into account the ORC SPBT calculation and the economic savings from avoiding emissions due to the biomass-fired cogeneration unit lead to a reduced payback time compared to the DS unit: this unit is not affected by the ETS regulation system, due to its installed capacity.

NOMENCLATURE

PL	working rate	(%)
P_{th}	thermal power	(MW)
$P_{th\ ave}$	average daily thermal power	(MW)
P_{el}	electric power	(MW)
F	fuel power	(MW)
LHV_{NG}	lower heating value	(GJ/m^3)
LHV_{bio}	lower heating value	(GJ/kg)
EF	emission factor	(kg$_{CO2}$/GJ)
η_{th}	thermal efficiency	(%)
η_{el}	electrical efficiency	(%)
W	wood-biomass consumption	(kg)
NG	natural gas consumption	(m^3)
COP	coefficient of performance	(–)
PUN	electricity price at national market	(€/MWh)
PSV	natural gas price at national market	(€/MWh)
GOP	gross operating profit	(€/year)
SPBT	Simple Pay-Back Time	(year)
GE	internal combustion gas engine	
GEHP	gas engine with heat pump	
IBB	integration and back-up boiler	
OBB	oil biomass boiler	
Ex1	Existing DH system n.1	
Ex2	Existing DH system n.2	
DS	DH system at Design Stage	
ETS	Emission Trading System	
KPI	Key Performance Indicators	

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