Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Re-designing district heating networks through innovative CO2 solutions

To cite this article: P Ungar *et al* 2022 *J. Phys.: Conf. Ser.* **2385** 012125

Re-designing district heating networks through innovative CO2 solutions

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Abstract. One of the main problems of current district heating networks is the significant heat losses that occur due to the high temperature of the heat distribution fluid (usually, water in the Italian climate conditions). Moreover, in ORC- or steam-turbine-based cogeneration power plants, the heat distribution fluid is heated directly by the condenser of the ORC cycle resulting in low efficiency of the power production section of the system. Considerable power is also employed for pumping the district heating flow rate through a long distribution ring. In this work, the effect of replacing water with low-temperature CO2 as a working fluid in a district heating network is analyzed. Specifically, a real district heating installation (the Biogenera-Calenzano network) providing at design conditions 850 kW of electricity and 1.7 MW (average) of heat is assessed using an experimental data set, simulating the equivalent working conditions with CO2 distributed through the network.
The proposed innovative solution continues to receive the heat from the condenser of an ORC cycle, but the temperature of the working fluid is significantly lower providing a relevant increase in the power production because of the reduction of the condenser temperature (determining an increase of the expansion ratio of the turbine). The increased power production of the turbine exceeds the power needed by local heat pumps which should be installed near the utilities of the district heating network to provide flexible heat on demand

Keywords: District Heating, CO2, ORC, CHP, Heat pump.

1. Introduction

District heating (DH) coupled with Combined Heat and Power (CHP) production is recognized as a recommended practice for energy and primary resource-saving [1-2]. Accordingly, market incentives are recognized – mainly through recognition of a high price for the electricity produced [3]. The current situation is seeing a progressive shift to low temperature heat distribution [4]: although specially insulated pipes are employed in the heat distribution networks (mainly working with hot water in mild climates), heat losses over the long distribution piping lines represent a relevant energy loss and are smaller in low temperature grids. The shift to low-temperature operation is also beneficial as it allows the integration of centralized heat pumps in the DH network; however, it requires adaptation of the final heat distribution systems in buildings. The use of water also entails a considerable use of power for pumping the heat transfer fluid through the network [5]. DH networks also represent substantial thermal inertial loads: the use of heat is variable during the day (which implies in most cases the installation of large heat storage units, [5]) and in mild climates, during substantial fractions of the year the whole network is not operational: the result is that the grid operation is interrupted, and that substitute cooling loads must be provided for CHP systems to allow year-round power production when heat is not needed for dwellings.

Considering these premises, alternative solutions to reduce the several problems encountered have been proposed: among these, the idea of substituting water with CO_2 as a DH heat transfer fluid is particularly attractive [6]. The innovative system proposed distributes the heat transfer fluid at near-ambient temperature, using pressure-adapted lines for liquid and vapor CO_2. The system was initially developed for a Switzerland case study, in which a lake is used as a heat sink for centralized heat removal (for upgrade) or discharge (for cooling). The users are distributed along with the DH network and are responsible for the heat upgrade to the required temperature (for both heating and domestic hot water). The proposed system allows to cover a flexible demand of heat and can even be operated in the cooling mode inverting the liquid/vapor conditions in the supply/return lines. Moreover, the pipe size of the system is considerably smaller than typical water-operated DH systems. Also, the friction losses are reduced requiring less pumping power to the system [7]. in this work, the original scheme proposed in [6,7] has been revised and adapted to the context of an Italian case study.
The case study is the Biogenera-Calenzano site (Figs.1-2), an ORC plant fuelled by biomass connected with a water-based district heating network. The fuel (13.000 tons/year of biomass) comes from a 70 km radius area and is mainly composed of forestry management residues. The district heating network evolves for an overall length exceeding 6 km in the Calenzano area. The behaviour of the updated network was analysed using the actual heat demand recorded in the DH network in the heating season 2018-2019. The same dataset has been used to reconstruct the design condition of the original system listed in Table 1:

Table 1. Main features of the H_2O plant during the time span 1/10/2018 - 31/03/2019.

Design Electrical Power	Mean Heat duty to the DH network	H_2O in/out Temp DH network
850 kW	1700 kW	90/70 °C

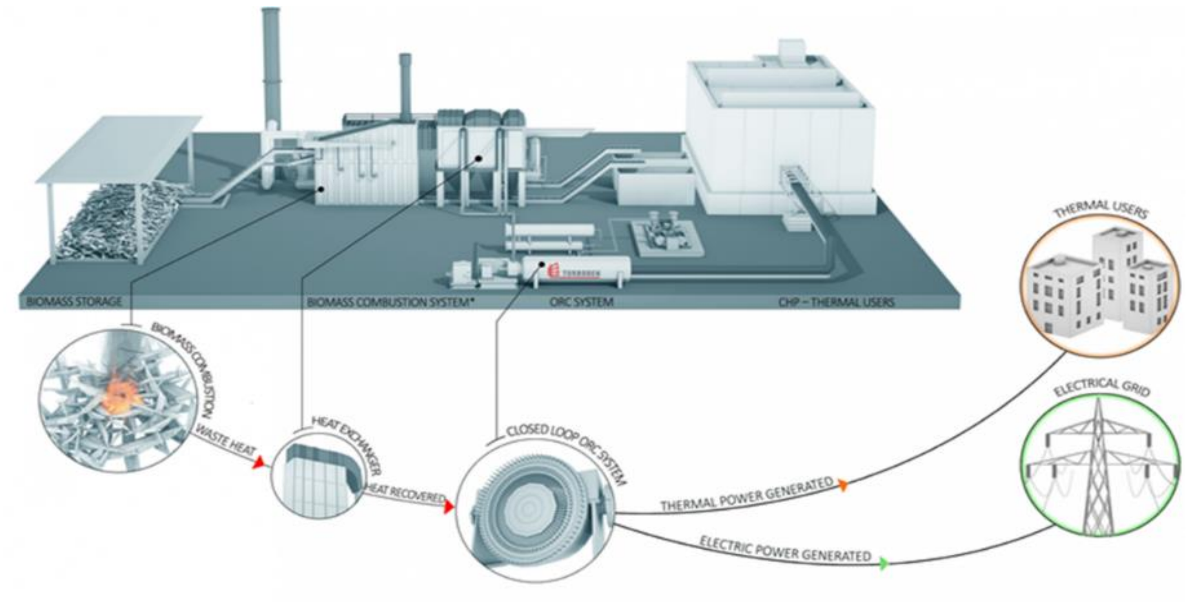

Figure 1. Artist view of the Biogenera cogeneration power plant [8]

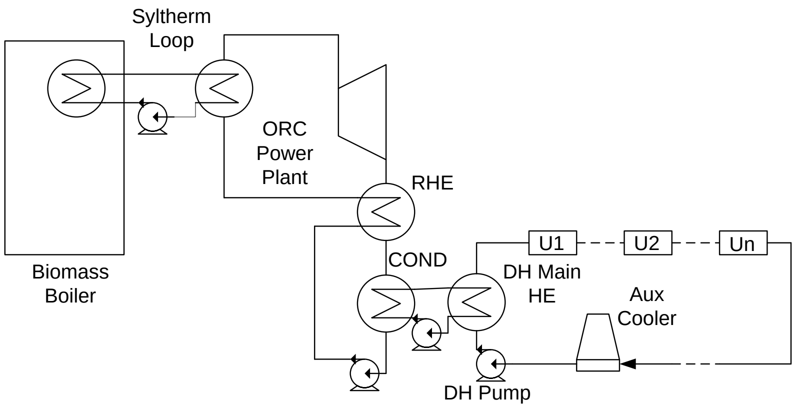

Figure 2. Biogenera cogeneration power plant simplified layout

2. Reference Case and Methods

A numerical model of the new system has been developed to ensure that the proposed solution provides the same amount of heat and in the same condition to the final users. Having to deal with this specific situation, the new system has some unique features not present in the original scheme, the main differences are listed below:

- Due to the lack of a suitable cold-water source in the neighbourhoods of the plant, the heat is removed through a set of air-cooled condensers (the same currently employed in the existing network, for a maximum heat removal power of about 6 MWt)
- The district heating network is realized with a pipe doublet serving all utilities (one for the CO2 vapor phase; one for the liquid phase) with slightly different pressure so that there is no need of using a pump to prevent the liquid from vaporizing in the return pipe.
- The condenser of the ORC provides the heat to the system evaporating the CO_2: this allows to provide heat at low temperatures decreasing the condenser temperature and increasing the power production in the ORC cycle with respect to the current solution.

2.1. Brief description of the developed models and physical assumptions

The overall model is composed of three main parts:

1. Model of the new District Heating concept
2. Model of the new ORC Cycle
3. A heat request prediction model for the network

Models 1 and 2 were developed in EES software environment [9], while Model 3 is a simple stochastic fit of the recorded time history of the existing (hot water) network, realized in a Python environment. The input and output temperature of the existing H_2O network, the volumetric flow rate, the environmental conditions, and the structure of the actual path of the pipelines were available and have been used in the model. Synthetic data of the DH power on an hourly basis in the considered period (1/10/2018-31/03/2019) are shown in figure 3 together with the daily average line.

The CO2 network is composed of two pipes: the first one (red in figure 4) contains vapor CO2 and the second one (blue) liquid CO2. At each final point of delivery of the network, CO2 is collected in the vapor phase and circulated back to the liquid side after being condensed to provide heat. The original CO2 vapor stream is generated by a main heat exchanger/evaporator (MHEV) located close to the power station, extracting heat from the ORC Condenser using an intermediate H2O circuit.

 2385 (2022) 012125 doi:10.1088/1742-6596/2385/1/012125

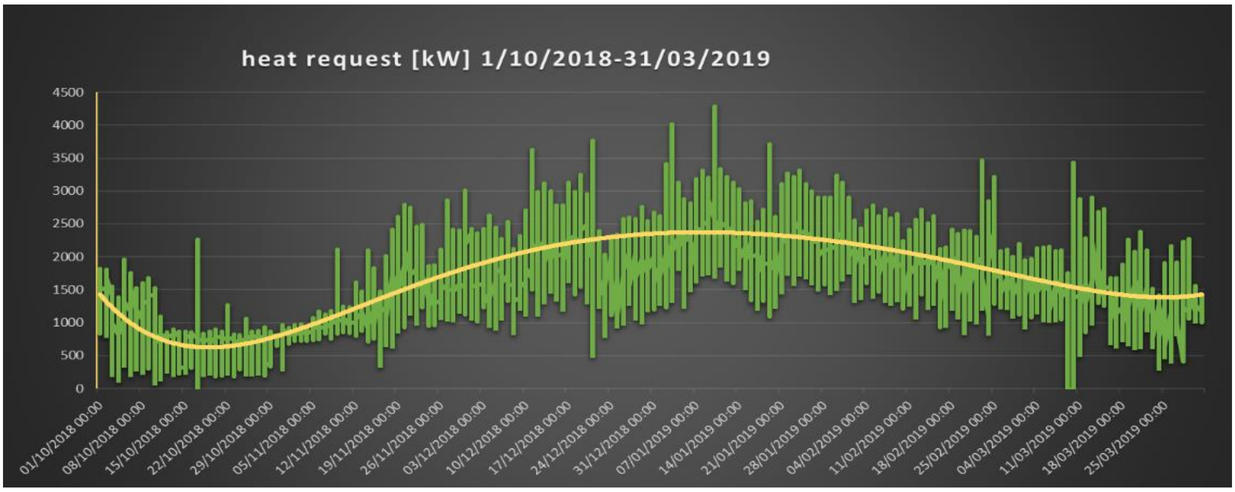

Figure 3. Heat [kW] required from the network during the period 1/10/2018-31/03/2019.

Five different base temperatures of the DH were investigated, T[0]: 10, 15, 20, 25, and 30 °C. The pressure in the district heating piping is determined in consequence, so that condensation in the red pipe (vapor) and boiling in the blue one (liquid) are avoided. Once temperature T[0] is set, the ORC condenser temperature is evaluated solving the energy balance among the Condenser, MHEV, and AUX COOL; this last is activated when the heat demand on the DH is less than the condenser heat duty (for the auxiliary dry cooling tower system a ΔTpinch=5°C between air and H2O was assumed). The power output of the ORC cycle is then recalculated considering the new condenser temperature. As for the present configuration, an auxiliary gas boiler is present on stand-by for extreme cases of exceptional heat demand from the DH network or of a power station outage.

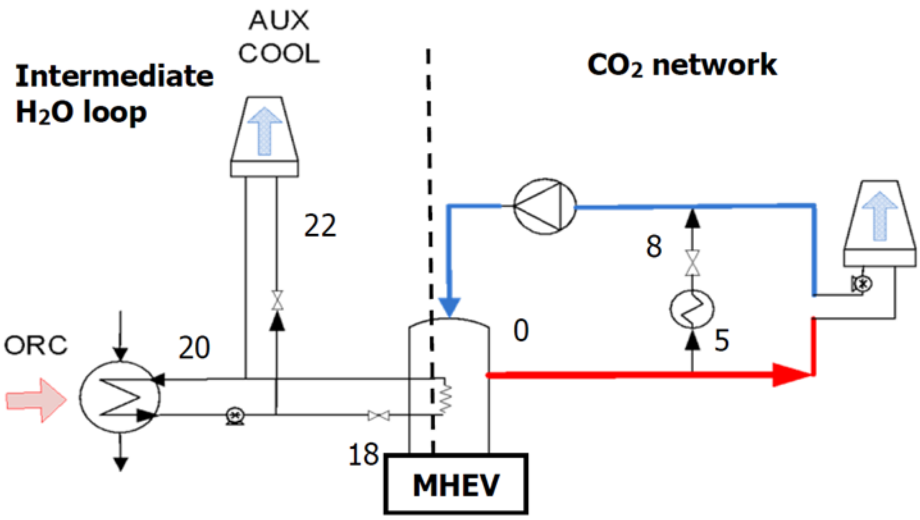

Figure 4. CO_2-based district heating, fundamental scheme

For what concerns the DH network, at each point of delivery vapor is collected and sent to the heat pump heat exchanger (Figure 5), where it is condensed and returned to the liquid return pipe adjusting the pressure through a valve. R134A was chosen as the heat pump working fluid, while the temperature of the hot water from the HP condenser to the final user was fixed at 65°C.

The electrical power required by the heat pumps increases as the temperature of the CO2 T[0] decreases; on the other hand, a lower value of T[0] determines a lower temperature and pressure in the ORC condenser, and therefore a greater power output from the ORC. The net electrical power is given by:

$$\dot{W}_{net} = \dot{W}_{ORC} - \sum \dot{W}_{HP} \tag{1}$$

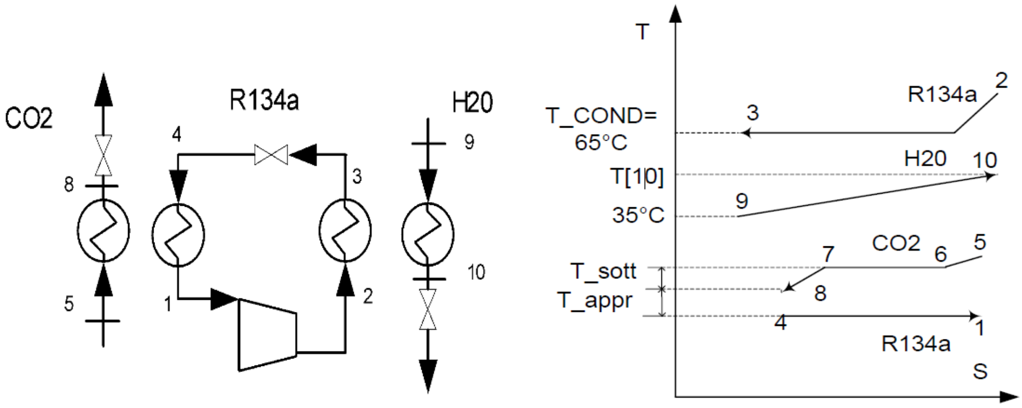

Figure 5. Final user's heat pump

The decrease in the ORC's condenser pressure suggests the utilization of a different working fluid for the ORC cycle: maintaining the same ORC fluid would require a complete substitution of the existing turbine that otherwise would work in a severe off-design condition. For this reason, MM (Hexamethyldisiloxane) was chosen as a substitute for MDM (octamethyltrisiloxane). Anyway, it should be underlined that the volumetric flow rate across the turbine is increased, so that a larger unit would be needed to maintain high isentropic efficiency.

3. Results and Discussion

The performances of the system were calculated for each working hour in the period 1/10/2018-31/03/2019 and are compared to the measured performance of the water-based DH+ORC plant in the same period.

Figure 6 displays the net electrical power produced as a function of different CO2 baseline temperatures. This is indeed the difference between the gross power produced by the ORC, and the cumulative power required by the operation of the heat pumps for the local heat upgrading, which is also displayed in the same figure.

Figure 7 shows that increasing the CO2 delivery temperature determines a reduction in the power consumption of the heat pump, but at the same time, the gross power output of the ORC is reduced. In this specific case, there is a trend to adopt relatively high CO2 delivery temperature (close to 30°C); however, it should be reminded that this entails higher pressurization of the distribution line, with pressures close to the critical value (31,1°C at 73,8 bar), so that values in the range of 25-30°C are recommended; this determines a net power output close to 1200 kW, which is significantly higher than the value corresponding to the original H2O cooling configuration (850 kWe).

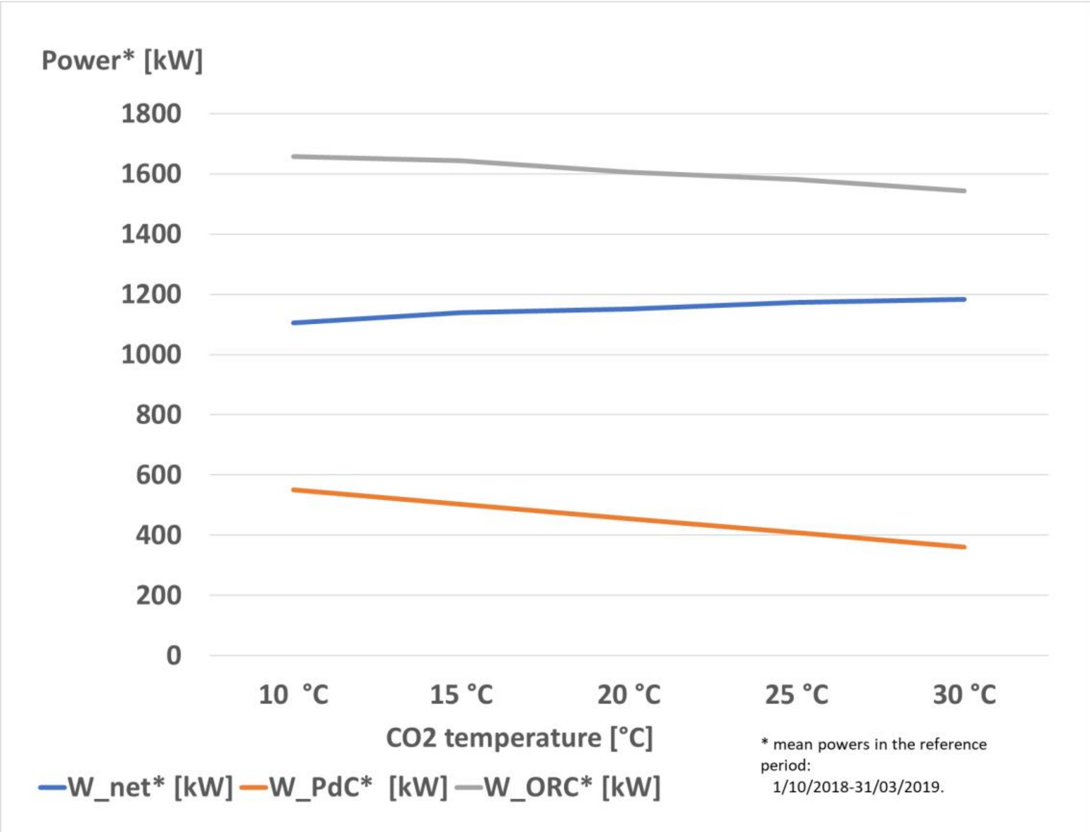

Figure 6. Net power of the system, gross power output, and overall power for heat pump operation as a function of the CO2 temperature T[0]

Figure 7 shows in terms of cloud data the analysis of the year-round system performance with a limit CO2 supply temperature set at 30°C, with variable ambient temperature. As the ambient temperature increases, the power required by the heat pump (orange dots) is reduced. The power output of the ORC (grey dots) remains roughly unchanged: the slight decrease at high ambient temperatures is due to the increasing temperature of the condenser (determined by the operation of the air cooler in a hot climate)—in any case, the gross power output of the ORC lies between 1400 and 1600 kW during the year, so that problems connected to the off-design operation of the turbine should be limited (the present unit has proven to be able to operate efficiently with a power rating between 800 and 900 kWe).

Each point shown in figure 7 represents a predicted operating condition in a specific moment of the year - the considerable dispersion of the data is due to the time-dependent heat request from the users. In periods of high ambient temperature, the CO2 network requires little heat decreasing the dispersion of the W_ORC data (figure 7) as the condenser is substantially cooled by the AUX COOL whose operation is independent of the heat demand. As a result of the combination of the grey and orange curves, the net power output (blue dots) tends to increase with increasing ambient temperature, with an average value of about 1200 kW.

Figure 8 shows the behavior of the net power output as a function of the DH network power demand. As previously anticipated, the reduction of the condenser temperature allows for a relevant increase in the net electric power output (from 850 to over 1500 kW, average values). The increased efficiency of the ORC cycle also means that less heat is released into the environment.

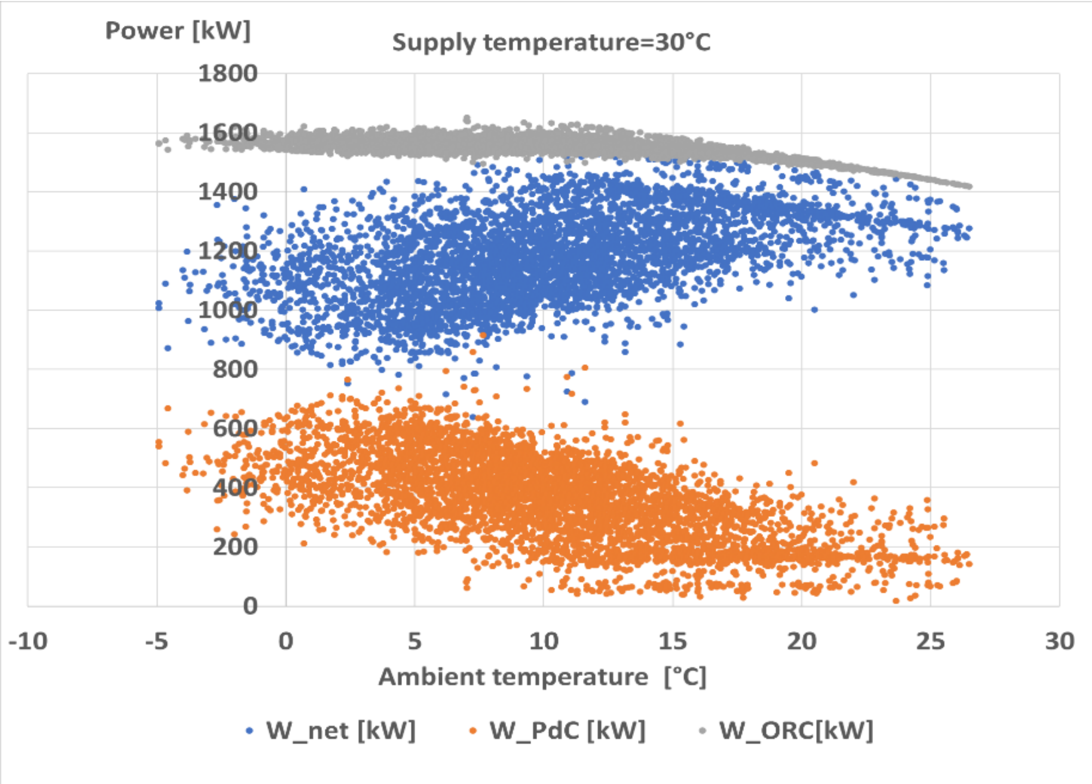

Figure 7. Net power of the system as a function of the ambient temperature

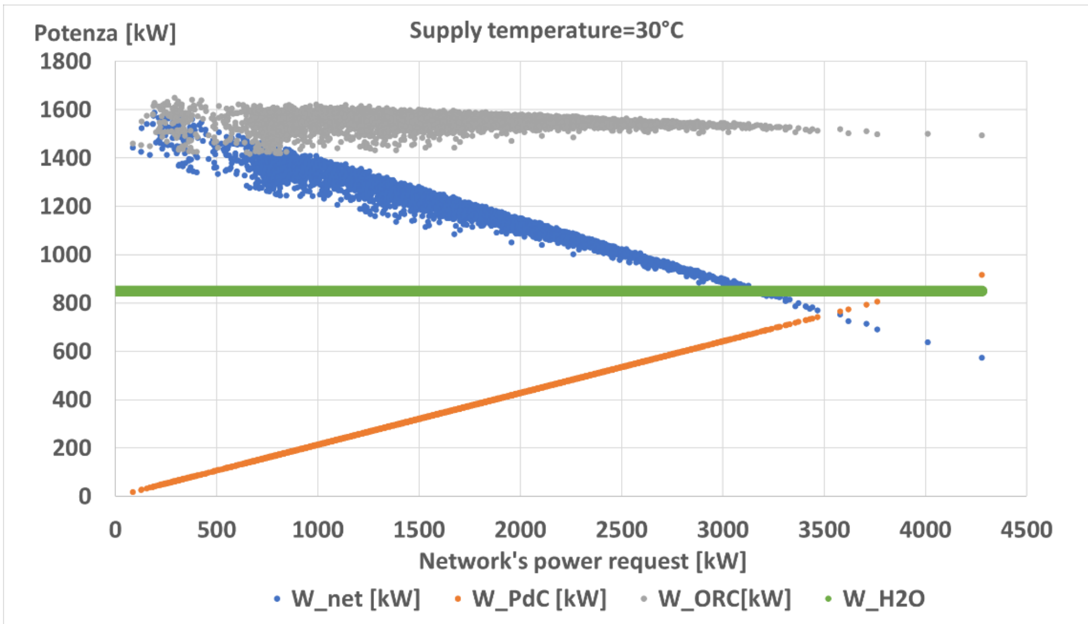

Figure 8. Net power of the system as a function of the heat request and comparison with current configuration

The price to pay to realize a CHP system based on the proposed CO2 distribution is the power absorbed locally by the compression heat pumps. The net balance is largely positive in most operating conditions. Only for a District Heating (DH) heat duty exceeding 3 MW the CO2 solution would be worse than the current one. Most frequently, the requested power from the DH is lower than the 3 MW limit, as is shown in figure 9. Specifically, the blue dots in figure 9 represent the October-November period; the red squares the December-January period; and the black triangles the February-March period. Only a few points in the December-January period lay on the right side of the current configuration boundary line (green band, 830-1080 kW power output). This means that most of the time, the CO2 configuration – while satisfying the same heat demand – would allow a considerably larger power production compared to the current one.

Further, as can be noticed from figure 8, the actual data dispersion is relevant at low-medium network heat demand. This is due to the ORC power output, which depends mainly on the ambient temperature. Referring to figure 3, at high heat demand, the H2O flow rate at point 18 (figure 3) increases, and the flow rate at point 22 decreases, so the ORC power output begins to depend more on the DH network heat request. The power demand of the heat pump is on the other hand mainly affected by the heat request by the final users.

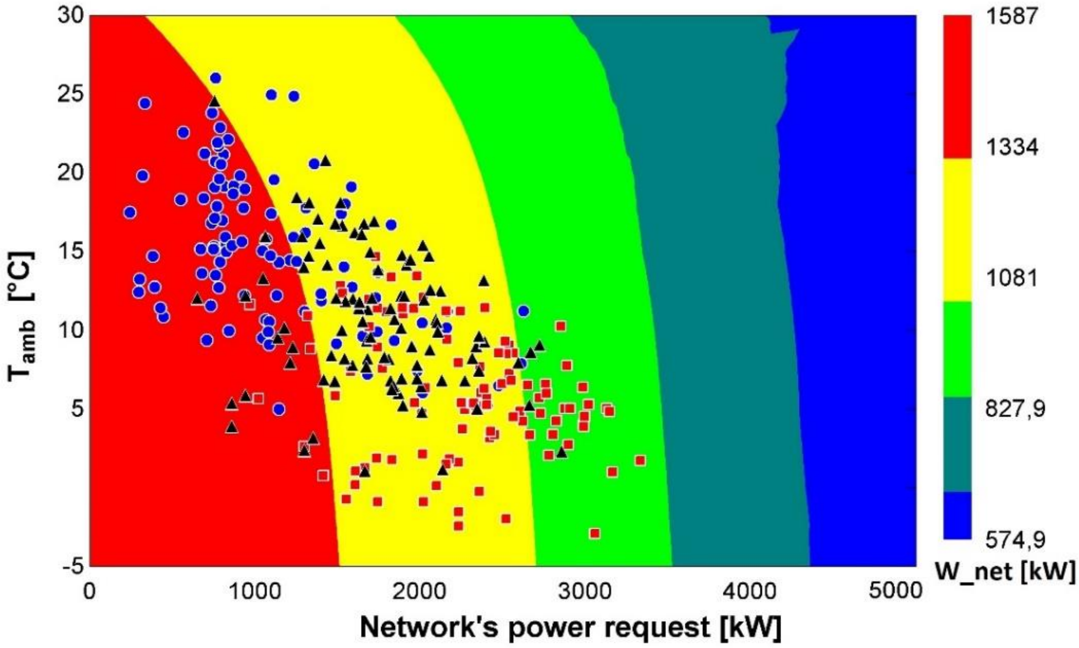

Figure 9. New proposed system electric power production map versus ambient temperature and DH heat duty; the DH heat demand cloud points recorded in different periods are superimposed.

Finally, simulating the behavior of the new configuration during the 6 months of analysis, an increment of 39% in electrical power generation was found (both networks provide the required 7300 MWh of user heating). The production of electricity is shown in Table 2.

Table 2. Comparison of electricity production during the period 1/10/2018 - 31/03/2019.

Current Network	CO_2 Network	Diffrence
3703 MWh	5150 MWh	1447 MWh

4. Conclusions

In this study, the effect of replacing water with low-temperature CO2 as a carrier fluid in a DH network was assessed. The pivotal point of this research was the evaluation of the possible performance improvements due to the change in the DH configuration. The main conclusions are summarized in the following:

- Real data of the DH demand were used to perform the analysis.

- The results confirm the possibility of a relevant increase in the overall seasonal net electricity production (39%), thus determining a substantial appeal of the proposed solution.

- Using CO2 as a heat carrier fluid allows a favorable arrangement of the DH network thanks to the low operating temperature (near to the environmental values) and to the possibility of upgrading on demand the heat delivered to each final user using a local heat pump cycle.

- The results are in line with the trend of the ecological transition, which is determining a shift to electric-only solutions starting from the lower temperature range of the use of heat. Indeed, the examined system is operated on biomass – in any case, the benefits of increasing the production of electricity and producing flexibly heat on demand of the users represent a considerable advantage with respect to the present traditional CHP+DH solution, which requires heat dissipation when the heat demand on the DH network is low.

Acknowledgments
The Authors are grateful to EstraEnergia for providing the detailed time history of the Biogenera district heating network, and to TURBODEN for providing the input data necessary to build the ORC power plant model.

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