load, considering a linear trend in between (KWB 2014). These values have been used for the calculation consumption of the pellet boiler. The circulation pump operates at fixed speed. Its electricity consumption has been hourly calculated depending on the water mass flow rate and pressure drop in each segment of the network.

2.2.2 Energy and economic analysis of the DH plant

Among the cost-optimal configurations, obtained through the multi-objective optimization, those with the lower NPV are more likely to be implemented. The DH scenario changes every time that an additional building connected to the network is refurbished. For each scenario (15 in total considering the reference case with no refurbished buildings), the Energy Performance index (EP) and the net present values (NPV) of the district heating have been calculated.

The EP (kWh year^{-1}) of the DH system is:

$$EP = m_{\text{pellet}} \cdot LHV_{\text{pellet}} + E_{\text{el}} \cdot f_{PE}$$

where m_{pellet} (kg) is the pellet consumption of the boiler, LHV_{pellet} (kWh kg^{-1}) is the lower heating value of pellet, E_{el} (kWh) is the electricity self-consumption of the auxiliaries and f_{PE} is the conversion coefficient from electrical to primary energy. In Italy, f_{PE} is currently 2.174 (AEEGSI, 2008) but it is periodically updated according to the average electrical efficiency of the national grid. The lower heating value of pellet has been considered 4.7 kWh kg^{-1} (UNI, 2011).

The NPV of the DH system has been calculated as the sum of the discounted cash flow over a period of 30 years (Dalla Rosa and Christensen, 2011, Reidhav and Werner 2008). The present work investigates the refurbishment of the existing DH systems and, therefore, does not consider the investment costs of both plant and network. However, the biomass boiler is considered to have a lifespan of 15 years and therefore one substitution has been considered in the economic analysis (Viessmann, 2014). The formula for NPV is the following:

$$NPV = \sum_{n=0}^{n=30} \frac{(E_{\text{h}} + E_{\text{DHW}}) \cdot p_{heat} - m_{\text{pellet}} \cdot p_{\text{pellet}} - E_{\text{el}} \cdot p_{\text{electricity}} - m_{ash} \cdot p_{\substack{\text{ash}\\ \text{disposal}}} - C_{\text{maint.}}}{(1+i)^{n}}$$

where E_h (kWh) is the space heating need, E_{DHW} (kWh) is the DHW need, p_{heat} is the price of the heat delivered to the users, p_{pellet} is the price of the input pellet and $p_{electricity}$ is the price of electricity used by the auxiliary equipment, m_{ash} is the ash production, $p_{ash,disposal}$ is the price for ash disposal, $C_{maint.}$ is the maintenance cost, n is the time of the cash flow and i is the real discount rate (i.e., i = 3%). The inflation rates of electricity and heat have been considered to be 1.71% and 2.8%, respectively (see Table 1). The inflation of pellet price, as well as the remaining prices, has been considered the same of heat (i.e., 2.8%). The ash production has been calculated as 1.5% the pellet consumption (UNI 2011). Table 1 shows the investment costs (IC), the operational costs, the feed-in tariff and the revenues (VAT and other taxes excluded) required for economic analysis.

Table 1 - Prices for the economic analysis.

Item	Price
Heat⁽¹⁾	0.1 EUR kWh^{-1}
Pellet⁽²⁾	263.5 EUR t^{-1}
Electricity⁽³,⁴⁾	0.1358 EUR kWh^{-1}
Ash⁽¹⁾	150 EUR t^{-1}
Maintenance⁽⁵⁾	3.2 EUR kW^{-1}
Boiler substitution⁽⁵⁾	70 EUR kW^{-1}

(1)Network survey; (2)(IRE 2014); (3)(AEEGSI 2013); (4)Industrial customer; (5)(Viessmann 2014).

Moreover, both EP and NPV have been calculated considering two additional scenarios with different floor areas in order to assess the influence of the size of the buildings on both energy and economic analysis. The building stock has been divided in two categories; the buildings that are smaller than the median and the ones that are larger. A scenario with smaller buildings has been defined considering twice the buildings below the median and a scenario with larger buildings has been defined considering twice the buildings above the median.

Finally, the installation of a CHP system has been considered as a potential measure to improve the DH profitability. A gasification system has been considered as a possible solution to produce electricity – to be delivered to the national grid – and heat that can be delivered to the buildings through the DH network – the excess heat is considered to be discharged to the atmosphere. The smallest CHP system available in the market has been considered to be operated continuously for entire year. In this case, the biomass boiler is used as a back-up boiler and to supply heat when the DH demand is higher than the CHP heat production. The economic analysis for the DH system with a CHP generator has been conducted considering the costs in Table 1 and in Table 2, namely the investment costs (IC), the operational costs, the feed-in tariff and the revenues (VAT and other taxes excluded) related to the CHP system. The details of the energy and economic performance of the gasification system are reported in Prando et al. (2014a).

Table 2 – Costs for the economic analysis (Prando et al., 2014a).

Item	Price
IC, gasifier	4000 EUR kW_{el}^{-1}
IC, engine	500 EUR kW_{el}^{-1}
Maintenance cost	0.050 EUR kWh_{el}^{-1}
Biomass cost	165 EUR t^{-1}
Feed-in-tariff	0.220 EUR kWh_{el}^{-1}
Cogeneration bonus	0.040 EUR kWh_{el}^{-1}
Char disposal	150 EUR t^{-1}

3. Results

3.1 Building retrofitting

The multi-objective optimization has been carried out in accordance with the cost-optimal approach for each building connected to the network. The figure in Annex I shows the Pareto front for all the buildings connected to the DH network. The blue dots in the graph are the optimal ones. The red dots correspond to the reference case. Among the different cost-optimal configurations (Pareto front) of each building, the one with the lowest NPV is selected as the refurbishment measure that would be adopted by the building owner.

Once the cost-optimal configurations have been defined, the buildings have been ranked from the lowest to the highest NPV, since a smaller NPV values correspond to buildings that are more likely to be refurbished among the whole building stock, assuming a rational approach of the decision makers.

3.2 DH system

Fig. 1 shows the heat share delivered to the network for the scenario with high supply temperature “T=90°C” (column with texture in Fig. 1) and the scenario with low supply temperature “T min”. For the latter, the graph reports a column for each additional refurbished building. Heat for DHW is constant for both refurbished and not refurbished buildings and it is 45 MWh $year^{-1}$. Network heat loss is constant for almost all the degrees of refurbishment (i.e., 114 MWh $year^{-1}$) while it is slightly lower when all the buildings are refurbished (i.e., 106 MWh $year^{-1}$).

The reduction of the network losses is strictly related to the buildings to be refurbished because one single building can prevent the reduction of the network temperature. In the event the network temperature is constant at 90°C during the year, the network loss is 168 MWh $year^{-1}$. The simple implementation of the minimum network temperature required by the buildings (not yet refurbished), enables a considerable reduction of the network loss (i.e., 32%). Only the refurbishment of all the buildings enables a further small reduction of the network loss (i.e., 5%).

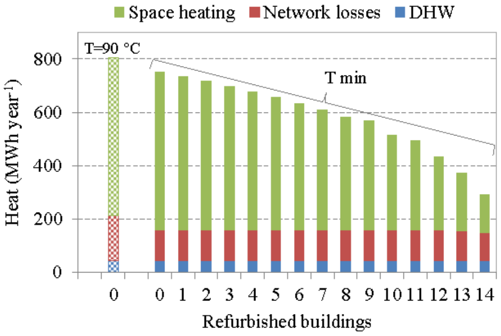

Fig. 1 – Heat shares delivered to the network for the scenario with constant network temperature (column with texture) and minimum network temperature (solid columns).

NPV and EP of the DH system have been calculated (Fig. 2). From the DH utility’s point of view, a positive NPV is expected from the operation of the DH system. The blue dots (i.e., T=90°C) correspond to the case in which a constant network temperature of 90°C is kept along the network. The red dots (i.e., T min) correspond to the cases in which the minimum network temperature, the one required by the most critical building, is adopted. The dots with a black border correspond to the reference cases (i.e., no refurbished building). Each point refers to an additional refurbished building and therefore to a new DH state. For all the DH scenarios, a complete refurbishment of the buildings would lead to a negative NPV that means the DH system would be no longer profitable. The operation of the DH system with the minimum network temperature (red dots) allows a constant benefit in terms of NPV and EP, and partially compensate for the loss economic profitability deriving from the refurbishment.

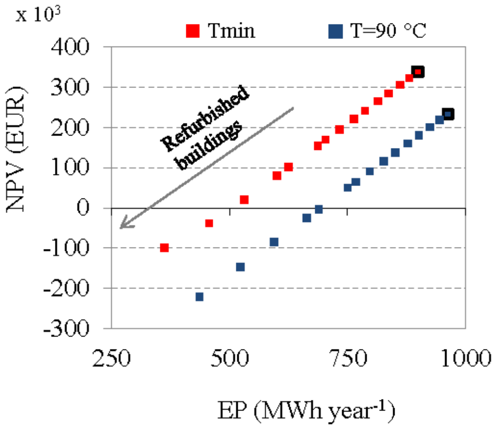

Fig. 2 – NPV and EP of the DH system for the two scenarios: T=90 °C, T_{min}.

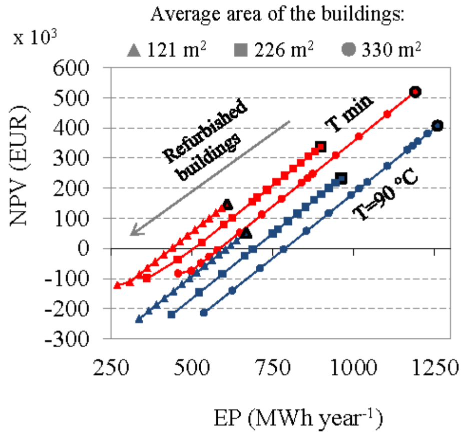

Fig. 3 – NPV and EP of the DH system for larger and smaller buildings.

Fig. 3 shows EP and NPV considering different size of the connected buildings. According to the survey, the reference buildings have a floor area that corresponds to an average area of the buildings stock of 225 m². A scenario with smaller buildings involves buildings with a floor area between 75 m² and 178 m² (average area of 121 m²) while a scenario with larger buildings corresponds to a floor area between 182 m² and 421 m² (average area of 330 m²). The EP, and therefore NPV, is much higher for larger buildings. Nevertheless, for a high number of refurbished buildings, the NPV for smaller and larger buildings is not considerably different because the income from heat sale is a minor share of the cash flow, which is dominated by the costs to manage the network. This result is similar for both the scenarios with "T=90°C" and "T min".

Finally, the installation of a CHP system (30 kW_{el} and 80 kW_{th}) has been investigated. The minimum size currently available in the market has been selected in order to limit the heat discharge. The plant has been considered to be constantly operated for the whole year, which is the most profitable strategy with the Italian incentive on the electricity production (Prando et al., 2014a). Fig. 4 shows EP and NPV considering the scenario with and without CHP system. The dots with a black border correspond to the reference cases (i.e., no refurbished building). The scenarios with the CHP system enable a higher NPV due to the revenues from the electricity sale. However, also EP is higher due to the CHP input energy to produce electricity. The benefit coming from the implementation of the minimum temperature is weakened – the two curves are closer – because the dominant revenue is due to the electricity sale (in particular when the buildings are refurbished). The slope of the curves (orange and green) is higher - increasing the refurbished building - because the EP of the CHP system is constant even if the heat required by the DH is lower.

The NPV of the abovementioned scenarios is reported depending on the linear heat density (MWh m^{-1} $year^{-1}$) in Fig. 5. The linear heat density is defined as the ratio between the heating annually sold to the customers and the trench length of the DH network. Studies in the literature state that areas with a linear heat density of 0.2-0.3 MWh (m year)$^{-1}$ can be supplied by DH in a cost-efficient way (Dalla Rosa and Christensen, 2011; Zinko et al., 2008), which is confirmed by the present study. Moreover, the graph in Fig. 5 highlights that the implementation of a CHP system could shift this threshold to 0.15 MWh (m year)$^{-1}$.

NPV and PES of the DH system can be seen in Fig. 6. Each point refers to an additional refurbished building and the dots with black border correspond to the reference cases (i.e., no refurbished building). PES is lower when the minimum network temperature is implemented because the heat demand is reduced and therefore a larger amount of heat has to be discharged – since the CHP system is not operated at partial load. Although the Italian incentive regime enables the profitability for all the scenarios considered in this work, none of them have positive primary energy saving (PES) index, as reported in Fig. 6.

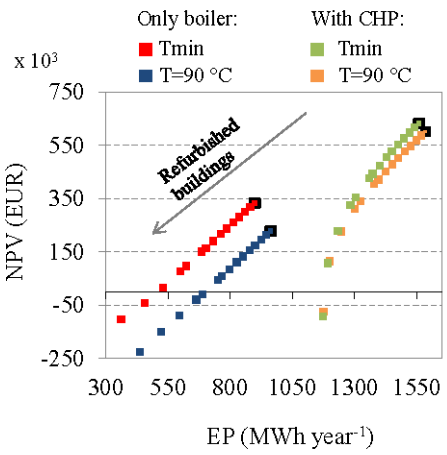

Fig. 4 – NPV and EP of the DH system for T=90 °C, T_{min} with (red and blue dots) and without CHP system (green and yellow dots).

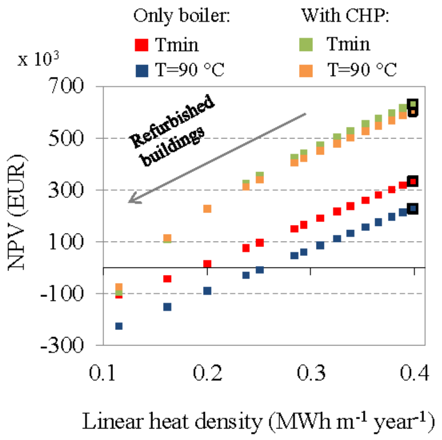

Fig. 5 – NPV and EP of the DH system for T=90 °C, T_{min} with (red and blue dots) and without CHP system (green and yellow dots).

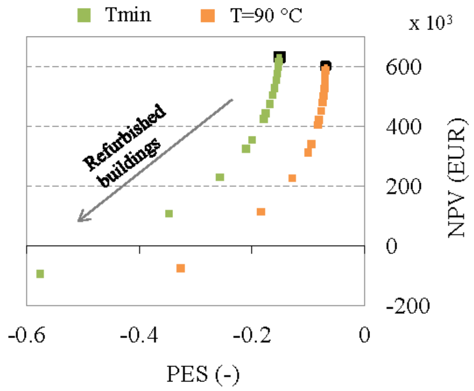

Fig. 6 – NPV and PES of the DH system for T=90 °C, T_{min}.

4. Conclusion

This work aims to define the energy and economic performance of the DH system considering cost-optimal solutions for the refurbishment of buildings connected to the DH system.

The implementation of the minimum network temperature required by the buildings (no refurbished building), enables a reduction of 32% of the network loss. This is possible because both heat exchangers and radiators are usually oversized, since they are usually designed for the most critical weather conditions. The complete refurbishment of the buildings leads to a negative NPV that means the DH system would be no longer profitable. The operation of the DH system with the minimum network temperature leads to a constant benefit in terms of NPV and EP, and partially compensate for the loss economic profitability deriving from the refurbishment.

Furthermore, it has been shown that EP - and therefore NPV - are much higher for larger buildings. Nevertheless, for a high number of refurbished buildings in the district, the NPV for smaller and larger buildings is not considerably different because the revenues from heat sale are a minor share of the cash flow, which is dominated by costs of the network management.

The implementation of a CHP system allows for higher NPV mainly due to the revenue from the electricity trade. Areas with a linear heat density of 0.15 MWh (m year)$^{-1}$ can be supplied by DH-CHP in a cost-efficient way.

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Annex I – NPV and EP for the reference case (red dots) and the cost-optimal configurations (blue dots) of the buildings for the scenario with constant heat price.