A multi-objective optimization analysis on high-performance buildings connected to district heating-CHP system

Dario Prando – Free University of Bolzano – dario.prando@unibz.it
Alessandro Prada – Free University of Bolzano – alessandro.prada@unibz.it
Fabian Ochs – University of Innsbruck – fabian.ochs@uibk.ac.at
Andrea Gasparella – Free University of Bolzano – andrea.gasparella@unibz.it
Marco Baratieri – Free University of Bolzano – marco.baratieri@unibz.it

Abstract

The European energy policy is strongly promoting the refurbishment of buildings and this affects the energy and economic performance of the district heating (DH) systems. The refurbishment of buildings connected to a DH system leads to the under-utilization of the DH capacity. This paper aims to define the energy and economic performance of a district heating (DH) considering the impact of cost-optimal refurbishment solutions of the connected buildings. For this purpose, an integrated model for both buildings and network has been developed. Several refurbishment measures for the existing buildings have been investigated and a multi-objective (energy and economic) optimization has been conducted, by means of a genetic algorithm. The possibility to shift to a low-temperature DH and the implementation of a CHP system have been investigated as feasible solutions to compensate for the loss of performance of the network.

The results highlight that the building refurbishment strongly influence both the energy and economic performance of the DH system. The DH performance is considerably low when a high number of refurbished buildings is considered in the district. The implementation of the minimum network temperature allows for a partial compensation for both the energy and the economic losses deriving from the refurbishment. However, this measure is not sufficient for a profitable DH. The installation of a CHP system in the network, thanks to the revenue from the electricity trade, allows for a profitable operation of DH network with a heat density of 0.15 MWh (m year)$^{-1}$. Although the installation of a CHP system is economically convenient, its primary energy saving (PES) index is negative for such a micro DH networks.

1. Introduction

The recast of Energy Performance of Buildings Directive (EPBD) (European Commission, 2010) states that by the end of 2020, all new buildings should be nearly zero-energy buildings, and in the meanwhile, the performance of the buildings that undergo major renovation should be upgraded in order to meet new minimum energy performance requirements, defined in accordance with the cost-optimal approach (European Commission 2012).

On one hand, the reduction of buildings' heating demand leads to the reduction of fuel consumption in the DH area (Nielsen and Möller, 2013). On the other hand, it causes a reduced utilization of the DH capacity with a consequent reduction of both the distribution efficiency (because constant network losses will be a higher fraction if the total heat is reduced) and the revenues.

The building refurbishment could reduce the difference of thermal power between the heating season and the period with only DHW demand (Lund et al., 2014). A more constant heat load during the year would enable a higher equivalent utilization time of a new CHP system installed with a proper size. However, also in the case of DH networks, the minimum heat demand could be very low and would not justify the installation of a CHP plant (Sartor et al., 2014).

The reduction of the grid temperatures (i.e., supply and return) is another measure, mentioned in the literature, to upgrade the DH systems. Both heat exchangers and radiators are usually oversized because they are usually designed for the most critical weather conditions. Actually, this condition

Part of
Baratieri, M., Corrado, V., Gasparella, A. & Patuzzi, F. (Eds.). 2015.
Building simulation applications BSA 2015. bu,press.
https://doi.org/10.13124/9788860460745

rarely occurs and, therefore, a reduced network temperature could be sufficient to satisfy the building heat need. A lower temperature means lower network losses and thus higher distribution efficiency of the DH network.

A pilot project carried out in Denmark, showed that the low temperature district heating (LTDH), i.e., 55/25 °C (supply/return), is a suitable solution for DH systems in low heat density area with low energy buildings (Li and Svendsen, 2012). In accordance with Dalla Rosa and Christensen (2011), LTDH systems in areas with linear heat density of 0.20 MWh m^{-1} $year^{-1}$ are supposed to be feasible from an energy and economic point of view. A study carried out on a DH plant based on a CHP system highlighted that a decrease of the DH network temperature of 10°C can improve the electric efficiency of the ORC generator of one percentage point (Prando et al., 2015).

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. Several measures have been considered for the refurbishment of buildings and a genetic algorithm is used to reduce the number of configurations to investigate among all the possible combinations to get the optimal ones. Different scenarios, with a different number of refurbished buildings in the network, have been analyzed comparing two strategies as for the supply temperature: the current fixed network temperature (i.e., 90 °C) and the lowest network temperature required by the most critical building. Moreover, the installation of a CHP system has been considered as a potential measure to improve the DH profitability.

2. Materials and methods

2.1 Buildings retrofitting

2.1.1 Reference buildings

The retrofitting of buildings is investigated by means of several energy simulations in order to find the cost optimal solutions. The multi-objective optimization analysis focuses on different residential buildings representative of the South Tyrol context. The floor area has been sized on the weighted average surface for residential buildings computed from the data provided by the National Statistical Institute (i.e., Istituto Nazionale di Statistica – ISTAT). Each building has been simplified as a base module with a square floor and an internal height of 3.0 m.

Besides, 14 representative buildings have been defined in order to represent a typical set of building connected to the micro-grid in South Tyrol. Each building has been assigned to one of the three construction periods according to the statistics provided by National Statistical Institute (i.e., Istituto Nazionale di Statistica – ISTAT). In South Tyrol, 37% of the residential buildings were built before 1960, 49% between 1960 and 1991, and 14% after 1991 (ISTAT, 2001). The construction period is important since it is associated with a specific type of building envelope, as reported in the Italian technical report UNI/TR 11552 (UNI, 2014).

All the characteristics of the reference buildings and the networks are reported by Ref. (Prando et al., 2014b). The heating need of the buildings has been computed by means of a dynamic simulation model – developed in TRNSYS environment − with a time step of 1 hour. The analysis has been carried out using the weather conditions of Bolzano, HDD_{20} = 2791 K d, which is the most populated city of the province.

2.1.2 Refurbished buildings performance and economic analysis

The research aims to analyze the extent to which the refurbishment of a building connected to district heating can become an issue for the district heating utility. For this reason, the main standard energy saving measures that contribute to the reduction of the building's energy needs have been investigated:

- external insulation of the vertical walls with a possible thickness increment from 1 cm to 20 cm using a 1 cm step;
- external insulation of the roof with a possible thickness increment from 1 cm to 20 cm using a 1cm step;

- external insulation of the floor with a possible thickness increment from 1 cm to 20 cm using a 1cm step and screed replacement;
- replacement of existing glazing systems with higher thermal performance windows such as double or triple-pane with either high or low solar heat gain coefficients. Besides, also the frames are replaced with an improved aluminum frames with thermal break;
- installation of a mechanical ventilation system with heat recovery to control the air exchange;
- replacement of the high temperature hydronic system with a underfloor heating, that ensure a reduction of the supply water temperature of the house. Also this intervention requires the screed replacement.

The reference prices of the different refurbishment measures are obtained from a survey comparing the prices in different zones of the national territory (Penna et al., 2014). The adopted prices are reported by Ref. (Prando et al., 2014b).

The NPV for each retrofit solution is based on the methodology proposed by the regulation EU 244/2012 (European Commission, 2012) and computed according to the EN 15459:2009 (UNI, 2007) procedure.

The full parametric analysis of the energy conservation measures would take a considerable computational time. To overcome this problem, a Genetic Algorithm code has been implemented in Matlab environment (Holland, 1975; Haupt and Haupt, 2004). The details of the algorithm implementation are reported by Penna et al. (2014).

2.2 District heating system

2.2.1 Numerical model of the DH system

A numerical model has been developed to simulate the thermal behavior of a DH network and calculate its performance. The network has been configured based on the arithmetic mean − in terms of the number of buildings and length of each pipe segment – from a survey of 13 micro DH networks located in South Tyrol. The study focused on micro DH networks because they are particularly affected by refurbishment of the connected buildings due to the limited number of users. However, the results of this study can be extended to larger systems. The detailed characteristics of the modeled network are reported by Prando et al. (2014b).

The network has been sized based on the design heat load of the connected buildings, which has been calculated in accordance with the European normative EN 12831:2003 (CEN, 2003). This approach can be used to calculate the size of the network piping, the heat exchanger of each substation and the boiler. In accordance with the normative, the design heat load is calculated considering the transmission and ventilation heat losses without taking into account the solar and internal heat gains. For residential buildings, the minimum ventilation thermal loss is calculated with an air change rate per hour of 0.5 ACH. According to the national specification (UNI, 2006), the external design temperature for Bolzano, county town of South Tyrol, is -15°C.

The network temperature is defined per each hour in accordance with the temperature requirement of the most critical building in terms of temperature. The radiators of each building have been sized to provide the nominal power at the design heat load condition with an average temperature around 70°C, i.e. typical value if not regulated according to the outside air temperature. During the heating season, in particular for the refurbished buildings, the heating load of each building is lower than the design heat load. For this reason, the radiator temperature, and therefore the network temperature, can be lower. On this basis, the minimum temperature required on the network has been hourly calculated and it represents the minimum theoretical temperature for the network.

The minimum limit temperature of the network has been fixed at 65°C in order to ensure the domestic hot water (DHW) production (Brand et al., 2013). Although a lower temperature in the supply line (i.e., 50-55°C) could be sufficient for DHW production, it strongly depends on the heat exchanger characteristics (Brand et al., 2010; Dalla Rosa and Christensen, 2011).

The size of the pellet boiler has been determined in accordance with the design load calculated through the EN 12831:2003 (CEN, 2003), as mentioned at the beginning the section. The generation efficiency has been considered to be 0.9 at nominal load and 0.88 at 30% of the nominal 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%).

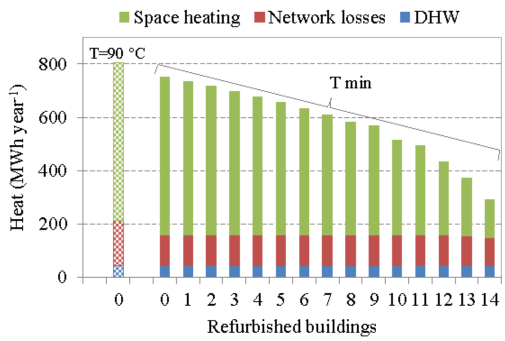

Fig. 1 – Heat shares delivered to the network for the scenario with constant network temperature (column with texture) and minimum network temperature (solid columns).

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.

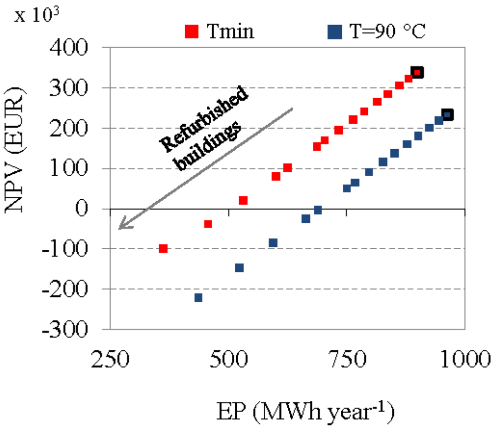

Fig. 2 – NPV and EP of the DH system for the two scenarios: T=90 °C, T_{min}.

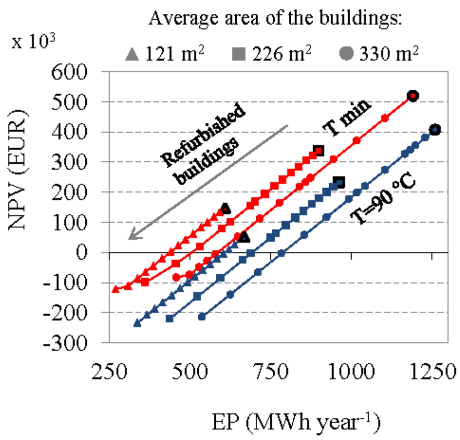

Fig. 3 – NPV and EP of the DH system for larger and smaller buildings.

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.

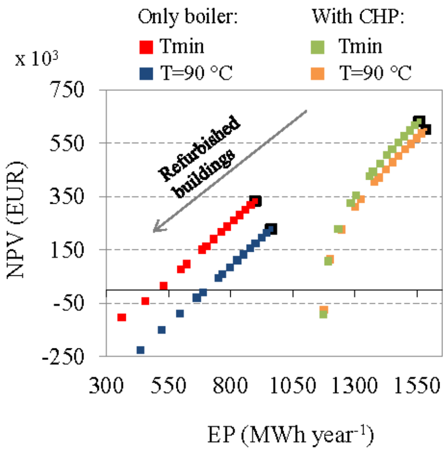

Fig. 4 – NPV and EP of the DH system for T=90 °C, T_{min} with (red and blue dots) and without CHP system (green and yellow dots).

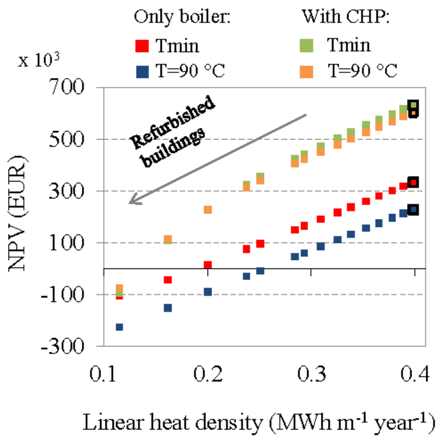

Fig. 5 – NPV and EP of the DH system for T=90 °C, T_{min} with (red and blue dots) and without CHP system (green and yellow dots).

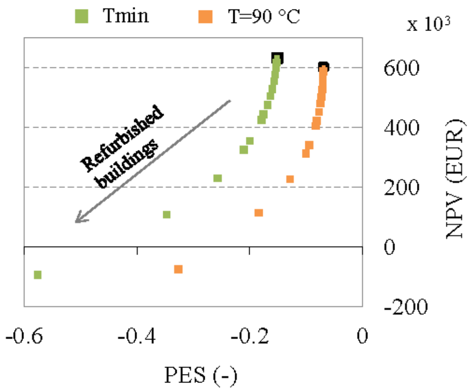

Fig. 6 – NPV and PES of the DH system for T=90 °C, T_{min}.

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.

References

AEEGSI (Italian Regulatory Authority for Electricity, Gas and Water). 2008. Approval EEN 3/08 Update of the conversion coefficient from kWh to tons of oil equivalent related to the mechanism of the energy efficiency.

AEEGSI (Italian Regulatory Authority for Electricity, Gas and Water). 2013. Annual report on the state of services and regulatory activities. Milan (Italy).

Autonomous Province of Bolzano. 2014. Energy service of the Autonomous Province of Bolzano (In italian: Ufficio Risparmio Energetico Provincia di Bolzano).

Brand, M., A. Dalla Rosa, P.S. Svendsen. 2010. *Performance of Low-Temperature District Heating Systems for Low-Energy Houses*. In: The Future for Sustainable Built Environments with High-Performance Energy Systems Conference. Munich - Germany.

Brand, M., S., Svendsen. 2013. Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment. *Energy* 62:311–319.

CEN 2003. EN 12831: Heating system in buildings - Method for calculation of the design heat load.

Dalla Rosa, A., J.E. Christensen. 2011. Low-energy district heating in energy-efficient building areas. *Energy* 36:6890–6899.

European Commission. 2009. EU energy trends to 2030.

European Commission. 2010. Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings (recast).

European Commission. 2012. Commission delegated regulation (EU) No 244/2012 of 16 January 2012.

Haupt, R.L., S.E. Haupt. 2004. *Pratical Genetic Algorithm*, II. ed. John Wiley & Sons, Hoboken - New Jersey.

Holland, J.H. 1975. *Adaptation in natural and artificial systems*. University of Michigan Press, Ann Arbor.

IRE (Institute for the Economic Research). 2014. Price list of the Chamber of Commerce of Bolzano Available at: www.camcom.bz.it/19338.pdf [Accessed: 04 May 2014].

ISTAT (The National Institute of Statistics). 2001. 14° Building and population census. Available at: http://dawinci.istat.it/MD/ [Accessed: 04 May 2014].

KWB (Kraft und Wärme aus Biomasse). 2014. Available at: www.kwb-heating.co.uk/fileadmin/media/%C3%96sterreich/Downloads/Technik_Planung/TP_Powerfire_2014_EN_Low.pdf [Accessed: 02 December 2014].

Li, H., S. Svendsen. 2012. "Energy and exergy analysis of low temperature district heating network". *Energy* 45: 237–246.

Nielsen, S., B. Möller. 2013. GIS based analysis of future district heating potential in Denmark. *Energy* 57:458–468.

Penna P., A. Prada, F. Cappelletti, A. Gasparella. 2014. Multi-Objectives optimization of Energy Saving Measures in existing buildings. *Energy and Buildings*, Article in press DOI: 10.1016/j.enbuild.2014.11.003.

Prando, D., F. Patuzzi, G. Pernigotto, A. Gasparella, M. Baratieri. 2014a. "Biomass gasification systems for residential application: An integrated simulation approach". *Applied Thermal Engineering* 71(1): 152–160.

Prando, D., A. Prada, F. Ochs, A. Gasparella, M. Baratieri. 2014b. "Enhanced performance buildings connected to district heating systems: multi-objective optimization analysis". In *3rd International High Performance Buildings Conference*. Purdue (US), pp. 3525(1–10).

Prando, D., M. Renzi, A. Gasparella, M. Baratieri. 2015. "Monitoring of the energy performance of a district heating CHP plant based on biomass boiler and ORC generator". *Applied Thermal Engineering* 79: 98–107.

Reidhav, C., S. Werner. 2008. "Profitability of sparse district heating". *Applied Energy* 85: 867–877.

Viessmann. 2014. *Boiler fed by lignocellulosic biomass*. Bressanone: Viessmann Engineering.

Zinko H., B. Bøhm, H. Kristjansson, U. Ottosson, M. Rama, K. Sipila. *District heating distribution in areas with low heat demand density*. International Energy Agency 2008.

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.