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Enhanced Performance Buildings Connected to District Heating Systems: Multi-Objective Optimisation Analysis

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Enhanced performance buildings connected to district heating systems: multi-objective optimization analysis

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ABSTRACT

This paper aims to define the energy and economic performance of a district heating (i.e., DH) considering the impact of cost-optimal refurbishment solutions of the connected buildings. The possibility to shift to a low-temperature DH is considered a feasible solution to reduce thermal losses and hence increasing the network efficiency that is connected with a systematic approach to the refurbishment of the connected buildings. For this purpose, an integrated model has been developed.

The energy performance of the coupled DH - buildings system has been assessed taking into account different measures for the improvement of the existing buildings considering different refurbishment levels of the building stock, i.e. 30 %, 60 % and 100 % of refurbished buildings. The considered improvements involve building envelope. A multi-objective optimization has been carried out to reduce the energy needs while minimizing the Net Present Value (NPV) for the final user. The minimum distribution temperatures that satisfy the requirements of the buildings are used to compute the network distribution temperature along the year. Finally, NPV, primary energy (EP), distribution efficiency and generation-distribution efficiency are evaluated for the whole DH system to investigate the energy and economic performance.

The results highlight how the cost-optimal building refurbishments, from a user perspective, influence NPV, EP, distribution efficiency and generation-distribution efficiency of the whole DH system.

1. INTRODUCTION

The European directive 2010/31/EU states that by the end of 2020, all new buildings should be nearly zero-energy buildings (NZEB), and in the meanwhile, new and renovated buildings performance should comply with new requisites established through a cost-optimal approach. The Commission Delegated Regulation EU 244/2012 (European Commisssion, 2012) establishes a methodology for calculating cost-optimal based energy performance requirements for new and existing buildings. The result should be a trade-off between the maximum energy saving and the minimum economic costs.

Moreover, Member States should ensure that, before construction of new buildings starts, the technical, environmental and economic feasibility of high-efficiency alternative systems are considered and taken into account, such as, among others, decentralized energy supply systems based on energy from renewable sources, cogeneration, district or block heating or cooling (European Commission, 2010). The requirements to keep on running the existing district heating (DH) while connecting new buildings and to refurbish the existing buildings, seem to lead to economic and energy conflict. The decreasing thermal needs of the buildings causes a reduced utilization of the DH capacity with a consequent reduction of both the system efficiency and the revenues.

The problem mentioned above could be tackled connecting new buildings to the DH network. The possibility of a network extension should be carefully evaluated comparing network extension and heat need of new users (Münster et al., 2012; Nielsen and Möller, 2013; Reidhav and Werner, 2008).

One aspect to consider is the typical oversizing of both heat exchangers and radiators which are designed for the most critical weather condition that the building is facing along the year. This means that for most of the year the heat load is smaller and a reduce network temperature could be considered improving the distribution efficiency. Furthermore, the use of control algorithms could be used to produce the lowest possible return temperature of the network (Lauenburg and Wollerstrand, 2014). Innovative control system based on mass flow control by means of pumps with inverter could also be adopted to improve the heat transfer, decrease the return temperature and reduce the pumping losses (Kuosa et al., 2013). The concept of low temperature district heating (LTDH), i.e. 55/25 °C (supply/return), is considered as a possible solution to face the challenge of supplying DH to the low heat density area and to adapt the DH to low energy buildings (Li and Svendsen, 2012). In high density areas, the reduced heat demand is not considered a barrier for the DH but it will lose competiveness in low heat density areas (Connolly et al., 2014; Persson and Werner, 2011).

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. It is also mainly focused on micro networks, with less than 20 buildings, since they could be particularly affected by refurbishment of the connected buildings due to the limited number of users. The heating need is calculated by means of TRNSYS 17, the domestic hot water need is quantified in accordance with UNI/TS 11300-1 (UNI, 2008a) and a model of the distribution network is developed for the purpose. Several measures are 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. Firstly, the retrofit measure that minimizes both the energy consumption and the NPV is defined for each considered building. The buildings are then ranked with increasing cost-optimal NPV and three different renovation percentiles (i.e. 30 %, 60 % and 100 % of the buildings) are assessed. The three resulting scenarios, with three different percentages of refurbished buildings in the network, are 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. Finally, primary energy (EP), NPV, distribution efficiency and the generation-distribution efficiency of the whole DH system are calculated.

2. DISTRICT HEATING SURVEY

The 13 micro networks involved in this study (Figure 1) are located in South Tyrol, a mountainous area in northern Italy. The considered micro networks are shorter than 3 km, as total length of the pipes. The networks with a predominantly linear trend correspond to networks with similar users in terms of energy demand. Some networks have high pipe length to reach one or few users. In this case, the user has high heat demand to justify the effort to cover such a distance. An average network, marked in dashed line (Gasser and Meran, 2014), has been elaborated as arithmetic mean in term of number of buildings and length of the pipes. Table 1 reports the distance of each building from the power plant in terms of piping length. Different types of users are observed in the surveyed networks and the typology strictly depends on the managing authority of the district heating system.

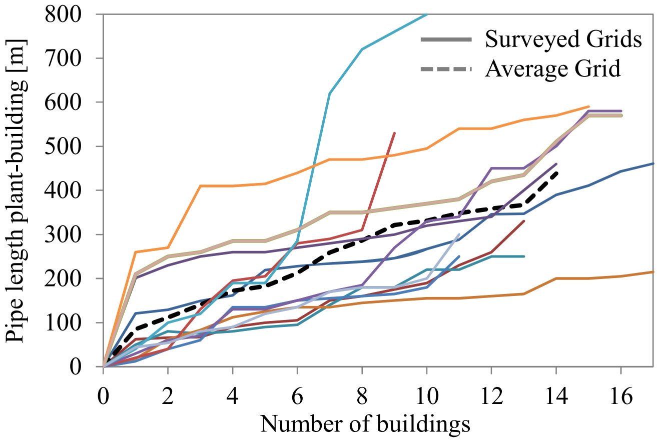

Figure 1: Pipe length from the power plant to the buildings for the surveyed networks and average network

It is not possible to define an average scenario but three main scenarios could be considered as representative of the surveyed district heating. The first scenario, mainly deals with public buildings (town hall, school, fireman house, community center, etc.), with the district heating realized by public authority on behalf of the community. In the second scenario, the users are mainly residential buildings; the district heating is realized by a cooperative who cooperate for their mutual benefit. In the third scenario, a hotel or a firm and eventually some residential buildings are connected; the district heating is realized by a private company such as the hotel owner or the entrepreneur that consumes a significant share of produced heat. In this paper, the first scenario has been considered and analyzed considering the possible refurbishment of the buildings connected to the common network.

Table 1: Pipe length from the power plant to each building for the elaborated average network

Building #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pipe length (m)	85	112	140	172	183	212	259	286	321	331	348	358	367	438
Floor area (m^2)	126	182	422	375	245	75	139	111	129	341	392	89	356	179

3. BUILDINGS RETROFITTING

3.1 Reference buildings

The floor area (see Table 1) is the only data available for the surveyed buildings hence the buildings' set has been configured based on the typical statistical data of the considered locations. Starting from a base module with a simplified square floor, area corresponding with the surveyed data, and considering 3 m internal height, the main characteristics have been deduced from the data collected by the National Statistical Institute (i.e. Istituto Nazionale di Statistica – ISTAT). In South Tyrol, 37 % of the residential buildings was built before 1960, 49 % between 1960 and 1991, and 14 % after 1991 (ISTAT, 2001). Accordingly, three types of reference buildings (Table 2) have been defined for the initial scenario that represents the investigated area. The proportion of the three reference buildings is fixed according with ISTAT survey and their distribution on the network is randomly defined. The thermal characteristics of the opaque envelope are chosen according to the abacus of the existing buildings published in the Italian technical specification UNI/TS 11300-1 (UNI, 2008a).

Table 2: Characteristic of the envelope and heating system of the reference cases

Reference building before 1960					
Opaque Envelope				Windows	Single-pane
	Clay	Insulation		U_{gl} (W m^{-2} K^{-1})	5.693
d (m)	0.2	0		SHGC	0.810
λ (W m^{-1} K^{-1})	0.25	0.04		Frame	Std Timber
ρ (kg m^{-3})	893	40		U_f (W m^{-2} K^{-1})	3.2
c (J kg^{-1} K^{-1})	840	1470		$A_f/A_{wind.}$ (%)	22.2
Reference building between 1960 and 1991					
Opaque Envelope				Windows	Single-pane
	Clay	Insulation		U_{gl} (W m^{-2} K^{-1})	5.693
d (m)	0.2	0.01*		SHGC	0.810
λ (W m^{-1} K^{-1})	0.25	0.04		Frame	Std Timber
ρ (kg m^{-3})	893	40		U_f (W m^{-2} K^{-1})	3.2
c (J kg^{-1} K^{-1})	840	1470		$A_f/A_{wind.}$ (%)	22.2
Reference building after 1991					
Opaque Envelope				Windows	Double-pane
	Clay	Insulation		U_{gl} (W m^{-2} K^{-1})	3.44
d (m)	0.2	0.05		SHGC	0.757
λ (W m^{-1} K^{-1})	0.25	0.04		Frame	Std Timber
ρ (kg m^{-3})	893	40		U_f (W m^{-2} K^{-1})	2.63
c (J kg^{-1} K^{-1})	840	1470		$A_f/A_{wind.}$ (%)	22.2

*equivalent to an air cavity (R = 0.25 m^2 K W^{-1})

The opaque envelope is a simplified two-layer structure with a massive clay block layer on the internal side and an insulating layer on the external side. The glazing system is a single-pane glass (buildings before 1991) and double-pane glass (buildings after 1991) with standard timber frame equally distributed on the four vertical walls for a total area of 15 % the floor area. The solar heat gain coefficient (SHGC) is with 0.810 high for both the single-pane and double-pane glass, see Table 2. Radiators, with an exponent of the characteristic curve equal to 1.3, are considered for all the buildings connected to the network.

The reference climate is that of Bolzano (HDD20 = 2791 K·d). The domestic hot water need (DHW) is determined in accordance with the Italian technical specification UNI/TS 11300-2 (UNI, 2008b). All the surveyed building have DHW tank because the systems, before the connection to the network, were based on biomass boiler. For this reason, the DHW need is distributed along the whole day from 8 am to 24 pm (i.e. charging period of the DHW tanks).

3.2 Refurbished buildings performance and economic analysis

Several building refurbishment measures are considered in the analysis, as reported in Table 3. The application of an insulation layer to the opaque components, i.e. vertical (VW) and horizontal (HW) walls, is considered in the range 1-20 cm with a step of 1 cm. The substitution of the existing windows with higher thermal performance windows is considered with four possible alternatives as for the glazing types (double or triple pane with either high or low SHGC) and improved frames. The last refurbishment measure is the mechanical ventilation system with heat recovery (MVHRS) to reduce the energy demand. The heat exchanger efficiency of the MVHRS is 0.82-0.92 depending on the external air temperature.

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 NPV for each retrofit solution is calculated in accordance with the methodology proposed by the EU 244/2012 (European Commisssion, 2012). According to EN 15459:2009 (UNI, 2007), the calculation is based on a period of 30 years and considers the initial Investment Cost (IC), the running costs (i.e. maintenance, operational and energy costs), the replacement cost, due to periodic substitution of building elements, and the residual value at the end of the calculation. The yearly heating need is calculated by means of a dynamic simulation model (i.e. TRNSYS) and then it is used as an input for the economic analysis to determine the cost-optimal refurbishment measures.

Table 3: Refurbishment measures, IC without VAT and parameters for the economic analysis

Opaque Envelope: Insulation Layer			
Thermal characteristic of Polystyrene EPS			IC (EUR m^{-2}) (1)
λ (W m^{-1} K^{-1})	0.04		t = thickness (cm)
c (J kg^{-1} K^{-1})	1470		IC_{VW} = 1.6 t + 38.53 IC_{HW} = 1.88 t + 8.19
ρ (kg m^{-3})	40		
Transparent Envelope			
Aluminium Frame with thermal break Uf = 1.2 (W m^{-2} K^{-1})			
Glazing	U_{gl} (W m^{-2} K^{-1})	SHGC	IC (EUR m^{-2}) (1)
DH – Double, high SHGC (4/9/4, krypton, low-e)	1.140	0.608	IC_{DH} = 404.33
DL – Double, low SHGC (6/16/6, krypton, low-e)	1.099	0.352	IC_{DL} = 439.06
TH – Triple, high SHGC(6/12/6/12/6 krypton,low-e)	0.613	0.575	IC_{TH} = 477.65
TL – Triple, low SHGC (6/14/4/14/6 argon, low-e)	0.602	0.343	IC_{TL} = 454.49
Mechanical ventilation heat recovery system (MVHRS)			
Ventilation Rate (m^3 h^{-1})	150		IC (EUR) (1)
Power (W)	59.7		IC_{MV} = 6000 EUR
Parameters for the economic analysis			
Heat price (2)	0.10 EUR kWh^{-1}	Electricity Cost (4)	0.25 EUR kWh_{el}^{-1}
Increase heat price (3)	2.8 %	Increase electricity price (3)	1.71 %
VAT	10 %		
		Real Interest Rate	3 %

(1) (Penna et al., 2014); (2) (Gasser and Meran, 2014); (3) (European Commission, 2009); (4) domestic customer (AEEG, 2013)

The dynamic simulation would take a considerable computational time to investigate all the possible combinations of refurbishment measures. To overcome this problem, a Genetic Algorithm implemented in Matlab environment has been used. The algorithm allows the evaluation of a large number of retrofit measures since it investigates the more relevant configurations according with the "survival of the fittest" mechanism (Haupt and Haupt, 2004; Holland, 1975; Penna et al., 2014). The refurbishment measures that allow the minimization of both the heat demand and NPV define the cost-optimal configurations. These configurations correspond with the so-called Pareto front. The optimization is carried out for all the buildings connected to the network.

4. DISTRICT HEATING SYSTEM

4.1 Network and boiler simulation

The network consists of pre-insulated steel pipe, whose main characteristics are reported in Table 4. The piping has been chosen on the basis of the commercial sizes regulated by the standard EN 253. The pipes are considered to be installed 80 cm underground in average.

The network has been designed in accordance with the design heat load of the connected buildings, which has been calculated in accordance with EN 12831:2003 (CEN, 2003). This approach can be used to size the network, the heat exchanger and the heat generator. 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 (h^{-1}). The external design temperature for Bolzano, county town of South Tyrol, is -15 °C.

After the calculation of the design load for each building, the mass flow rate on the heat exchanger is calculated considering 20 °C as temperature difference between the supply and return to the primary network. The piping from the generation system to each building is sized to keep the water velocity lower than 2 m/s in the main branches and 1.5 m/s in the secondary branches (Vallios et al., 2009). Furthermore, the specific total pressure drop is kept below 980 Pa/m in order to avoid high electricity consumption of the circulation pump.

The heat transfer coefficient between the water and the ground is calculated for each segment of the network depending on its diameter, insulation thickness and length. The heat loss of the entire network is hourly computed depending on the network temperatures and ground temperature. The ground temperature at a depth of 80 cm is computed with Trnsys 16.1 considering a mean surface temperature of 12.6 °C, amplitude of surface temperature of 10.1 °C, a soil thermal conductivity of 2 $W\ m^{-1}\ K^{-1}$, a soil density 2500 $kg\ m^{-3}$ and a soil specific heat 0.8 $kJ\ kg^{-1}\ K^{-1}$.

The network temperature is hourly defined in accordance with the temperature required by the connected buildings, fulfilling the most critical building in terms of temperature. The radiators of each building are sized to provide the nominal power at the design heat load condition with a network supply temperature of 90 °C, i.e. typical value if no control strategy is adopted. Along 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 network supply temperature can be usually lower than 90 °C. On this basis, the minimum temperature required on the network is hourly calculated and it represents the minimum theoretical temperature for the network. The decrement of temperature along the network has been neglected because the network has a low extension (i.e. 1600 m). The minimum limit temperature of the network is fixed at 65 °C in order to ensure the domestic hot water (DHW) production. In accordance with Dalla Rosa et al. (Brand et al., 2010; Dalla Rosa and Christensen, 2011), lower temperature in the supply line (i.e. 50-55 °C) could be sufficient for DHW production but, it depends on the heat exchanger characteristics.

The district heating system is based on a pellet boiler of 300 kW, to supply the thermal power to all the connected buildings in the most critical condition (i.e. external temperature -15 °C). A market survey has shown that, for pellet boiler of the considered size, the generation efficiency is around 90 %. At partial load down to 30 % the nominal load, the efficiency decreases around 2 %. These values are used for the calculation of the input energy of the boiler. The electricity consumption of the circulation pump is hourly calculated depending on the water mass flow and pressure drop in each segment of the network. The pump is coupled with a motor for fixed speed operation.

Table 4: Characteristics of the pre-insulated pipes for district heating network

DN (mm)	20	25	32	40	50	65	80	100	125	150
$t_{insulation}$ (mm)	29	25	31	28	29	29	32	39	39	36
$\lambda_{insulation}$ ($W\ m^{-1}\ K^{-1}$)	0.03									

4.2 Energy and economic analysis of the district heating

The refurbished buildings after the multi-objective optimization have ranked from the lowest to the highest NPV. The buildings on the top of the list are more likely to be refurbished because of the lower NPV provided by the optimal refurbishment solution. For this reason, three levels of refurbishment implementation scenarios are set: first 30 % of the buildings being renovated (very likely refurbishment), first 60 % of the buildings being renovated (likely refurbishment), 100 % of the buildings undergoing renovation (unlikely refurbishment). For each scenario, distribution efficiency, generation-distribution efficiency, EP and NPV of the district heating are calculated.
The distribution efficiency of the district heating system is monthly calculated with the following formula:

$$\eta_{\text{distribution}} = 1 - \frac{E_{\substack{\text{network}\\ \text{loss}}}}{E_{\text{boiler}}} \tag{1}$$

where $E_{\text{network, loss}}$ (kWh month^{-1}) is the network heat loss, E_{boiler} (kWh month^{-1}) is the heat generated by the boiler.
The generation-distribution efficiency of the district heating system is monthly calculated with the formula:

$$\eta_{\substack{\text{generation}\\ \text{distribution}}} = \frac{E_{\text{h}} + E_{\text{DHW}}}{m_{\text{pellet}} \cdot LHV_{\text{pellet}} + E_{\text{e}} \cdot f_{PE}} \tag{2}$$

Where E_{h} (kWh month^{-1}) is the space heating need, E_{DHW} (kWh month^{-1}) is the DHW need, m_{pellet} (kg month^{-1}) is the pellet consumption of the boiler, LHV_{pellet} (kWh kg^{-1}) is the lower heating value of pellet, E_{e} (kWh month^{-1}) is the electricity consumption of the auxiliaries and f_{PE} is the conversion coefficient from electrical to primary energy. In Italy, f_{PE} is currently fixed at 2.174 (AEEG, 2008) but it changes according with the average electrical efficiency of the national grid. The lower heating value of pellet is considered 4.7 kWh kg^{-1} (UNI, 2011).
The EP (kWh year^{-1}) of the DH system is calculated with the following formula:

$$EP = m_{\text{pellet}} \cdot LHV_{\text{pellet}} + E_{\text{e}} \cdot 2.174 \tag{3}$$

The NPV of the DH system is calculated as the sum of the discounted cash flows over a period of 30 years (Dalla Rosa and Christensen, 2011; Reidhav and Werner, 2008). The formula for NPV is the following:

$$NPV = \sum_{t=0}^{t=30} \frac{(E_{\text{h}} + E_{\text{DHW}}) \cdot p_{heat} - m_{\text{pellet}} \cdot p_{\text{pellet}} - E_{\text{e}} \cdot p_{\text{electricity}} - m_{ash} \cdot p_{\substack{\text{ash}\\ \text{disposal}}} - C_{\text{maint.}}}{(1+i)^t} \tag{4}$$

where p_{heat} is the price of the heat delivered to the users, p_{pellet} is the price of the input pellet and $p_{\text{electricity}}$ is the price of electricity used by the auxiliary equipment, m_{ash} is the ash production, $p_{\text{ash,disposal}}$ is the price for ash disposal, $C_{\text{maint.}}$ is the maintenance cost, t is the time of the cash flow and i is the discount rate (i.e. i = 3 %). The ash production is calculated as 1.5 % the pellet consumption (UNI, 2011). The prices for heat, pellet, electricity, ash disposal and maintenance (VAT and taxes excluded) are reported in Table 5.

Table 5: Prices for heat, pellet, electricity, ash disposal and maintenance

	Price	**Reference**
Heat (€/kWh)	0.10	Networks survey
Pellet (€/t)	263.5	(IRE, 2014)
Electricity* (€/kWh)	0.1358	(AEEG, 2013)
Ash (€/t)	150	Networks survey
Maintenance (€/year)	1500	(Viessmann, 2013)

*Industrial customer

5. RESULTS

The multi-objective optimization is carried out in accordance with the cost-optimal approach for each building connected to the network. Figure 2 shows the Pareto front for all the buildings involved in the optimization. The blue dots in the graph are the ones that optimize both the NPV and heat demand (i.e. cost-optimal refurbishment measures of minimum heat demand). The red dots correspond to the reference case.

Table 6: (a) Ranking (i.e. from the lowest to the highest cost-optimal NPV) of the refurbished buildings, (b) reference case and three scenarios with different refurbishment degree (R = refurbished building)

(a)	**Reference case**		**Cost-optimal**	
Building #	**NPV (EUR)**	**$E_h + E_{DHW}$ (kWh m^{-2} year^{-1})**	**NPV (EUR)**	**$E_h + E_{DHW}$ (kWh m^{-2} year^{-1})**
6	52.2	239.2	28.9	54.7
12	61.1	235.6	34.3	55.3
8	75.1	232.3	42.6	59.8
1	81.6	202.9	47.6	60.3
9	85.8	228.4	49.4	59.9
7	88.8	200.5	52.1	62.3
14	111.8	197.4	66.6	62.1
2	113.3	196.8	67.6	63.4
5	99.2	101.0	82.8	38.5
13	140.5	99.4	112.1	38.5
10	201.4	189.4	114.7	42.9
4	220.1	188.6	124.2	43.1
11	229.1	187.9	129.0	42.4
3	255.0	207.6	139.2	43.9

(b)	**Refurbishment degree**		
Reference Case	**30 %**	**60 %**	**100 %**
-	R	R	R
-	R	R	R
-	R	R	R
-	R	R	R
-	-	R	R
-	-	R	R
-	-	R	R
-	-	R	R
-	-	-	R
-	-	-	R
-	-	-	R
-	-	-	R
-	-	-	R
-	-	-	R

Among the different cost-optimal configurations of each building, the one with the lowest NPV is selected as the refurbishment measure that would be adopted by the building owner. For refurbishment intervention, the economic index is preferable to the simple energy index. This procedure is conducted for all the buildings defining the characteristics of the refurbished building. The buildings are ranked from the lowest to the highest NPV (Table 6a) since a smaller NPV correspond with refurbished buildings more likely to be realized among the whole building stock. Table 6a reports both the NPV and the heat demand (i.e. space heating and DHW needs) of each reference case and refurbished building. Table 6b reports the reference case (i.e. 0 % refurbished buildings) and three scenarios with three different level of refurbishment of the buildings (i.e. 30 %, 60 % and 100 % refurbished buildings). The refurbished buildings of the three scenarios are selected in accordance with the NPV ranking.

The three scenarios reported in Table 6b have been investigated from a DH system perspective. NPV and EP of the DH system are calculated and displayed in Figure 3 (a). From the DH manager point of view, a positive NPV is expected from the operation of the DH system. The blue dots (i.e. T min) in the graph correspond to the performance in case of reduction of the network temperature (i.e. supply temperature) to the minimum temperature required by the most critical building. The red dots correspond to the case a constant network temperature of 90 °C is kept. The two dots with black fill correspond with the reference cases (i.e. 0 % refurbished buildings). Each point refer to an additional refurbished building and therefore to a new DH scenario. The three scenarios previously mentioned are highlighted in the graph (i.e. 30 %, 60 % and 100 % refurbished buildings). For both the control strategy of the network temperature (i.e. 90 °C or T min), 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 (blue dots) allows a constant benefit in terms of NPV and EP and partially compensate for the loss economic profitability deriving from the refurbishment: the case of 60 % refurbished buildings with reduced network temperature has a similar NPV as the starting configuration with constant temperature network. However, a reduction of EP leads to a reduction of the pollutant emissions. Figure 3 (b) shows the heat shares delivered to the network for the case in which the minimum network temperature required by the buildings (i.e. T min) is adopted. The graph reports the reference case (i.e. 0 % refurbished buildings) and the three scenarios with different degree of building refurbishment (i.e. 30 %, 60 %, 100 % refurbished buildings). Heat for DHW is constant for all the scenarios and it is 45 MWh year^{-1}. Network heat loss is constant for the first three scenarios (i.e. 110 MWh year^{-1}) while it is slightly lower for the last one (i.e. 105 MWh year^{-1}). The reduction of network loss is strictly related to the buildings to be refurbished because only one building can prevent the reduction of the network temperature. In case the network temperature is constant at 90 °C all along the year, the network loss is 167 MWh year^{-1}. The only implementation of the minimum network temperature required by the buildings (i.e. 0 % refurbished buildings), enables a considerable reduction of the network loss (i.e. -34 %). Only the refurbishment of all the buildings (i.e. 100 % refurbished buildings) enable a further small reduction of the network loss (i.e. -3 %).

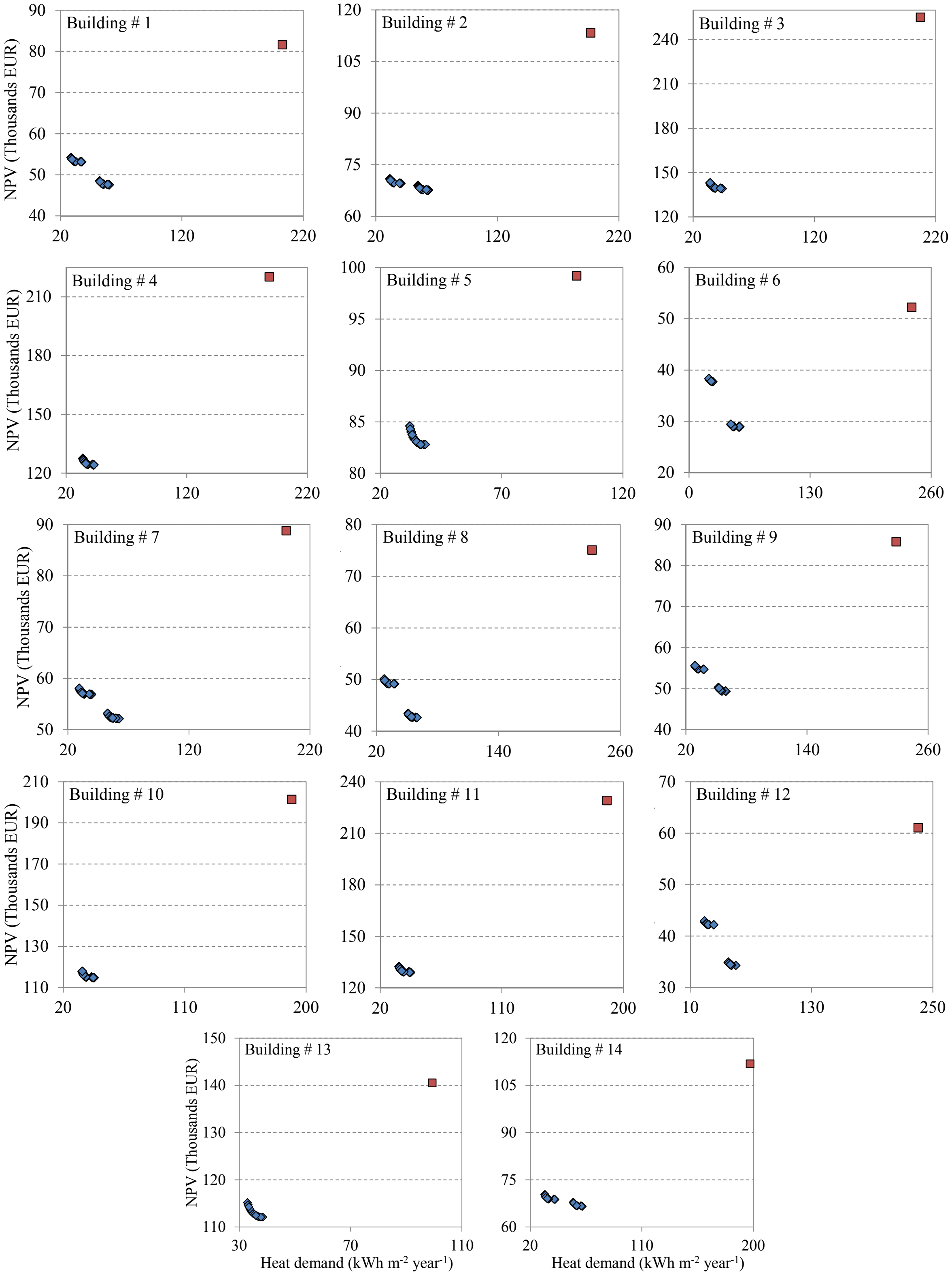

Figure 2: NPV and heat demand for the reference case (red dots) and the cost-optimal configurations (blue dots) for all the buildings

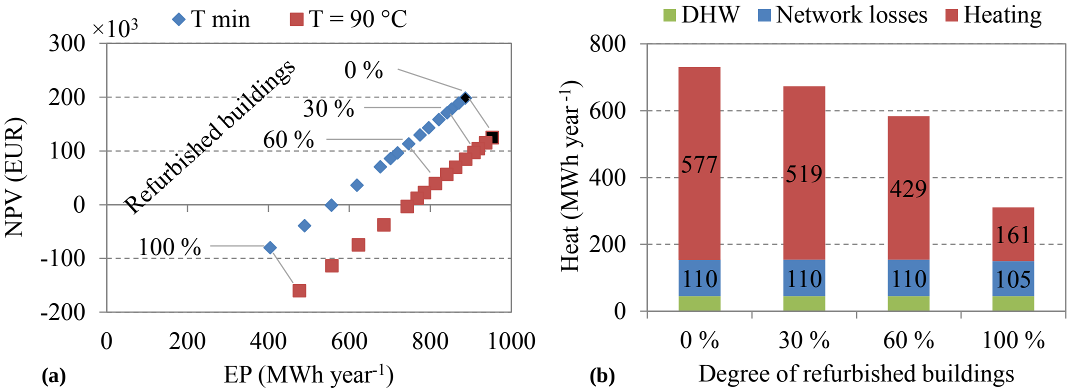

Figure 3: (a) NPV and EP of the DH system, (b) Heat shares delivered to the network (network temperature: T min)

Figure 4 reports the distribution efficiency (Fig. 4a) and generation-distribution efficiency (Fig. 4b) of the DH system for the case in which the minimum network temperature required by the buildings (i.e. T min) is adopted. The black columns represent the reference case (i.e. 0 % refurbished buildings). The red, blue and green columns represent the 30 %, 60 % and 100 % of refurbished buildings respectively. The efficiency is particularly low for the months in which only heat for DHW is delivered by means of the network. A sensible reduction of the efficiencies is displayed for each degree of refurbishment of the building stock. The reduction is significant in case all the buildings are refurbished (i.e. 100 % refurbished buildings).

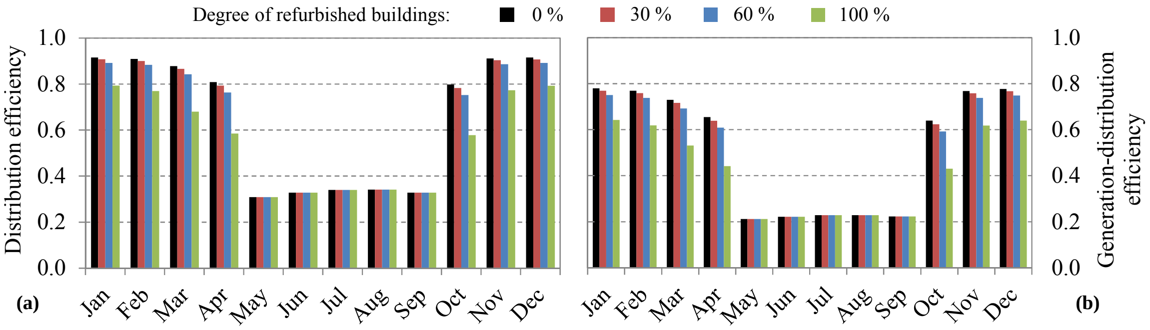

Figure 4: Distribution (a) and Generation-distribution (b) efficiency of the DH system for each month

6. CONCLUSIONS

In the near future, a massive building refurbishment is expected and the current DH systems need to be upgraded in order to be a valuable option to integrate renewable energy in the building sector. The heat demand reduction of the buildings leads to an efficiency reduction of the DH system. Furthermore, the DH with high degree of refurbishment of the connected buildings could be no longer used due to negative cash flows. From both the economic and energy point of view, the reduction of the network temperature is essential for a successful operation of DH systems. The DH managers cannot force the users to adopt measures that aim to decrease the temperature level of their heating systems but they could promote it by means of heat trade depending on the temperature level. Future development of this work foresees the assessment of different incentive regimes to promote refurbishment measures of the buildings that enable the upgrade towards low-temperature DH system.

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