PRICING STRATEGIES FOR NEUTRAL-TEMPERATURE DISTRICT HEATING AND COOLING NETWORKS BASED ON HEAT PUMPS

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Abstract: This work is related to the Flexynets project, pursuing the realization of a neutral-temperature (15-25 °C) district heating and cooling network based on heat pumps. In this concept, heat pumps substitute heat exchangers in residential substations. This approach would allow the integration of a large number of waste heat sources, at temperatures usually not accessible for traditional networks. The additional costs given by heat pumps would then be repaid by the availability of cheap heat, by reduced thermal losses, and by the consequent possibility to exploit long-term storages.

Clearly, the use of heat pumps implies the simultaneous presence of thermal and electrical energy consumptions. Furthermore, the heating/cooling duality of the network suggests the shift from the producer/consumer model to the prosumer concept, as in electrical smart grids. These aspects, while yielding more operational flexibility, increase the complexity of the corresponding market models, with different possible prices for buying/selling thermal/electrical energy.

Considering energy prices, reference technologies, and a reasonable performance range for heat pumps, we identify simple bounds for the admissible costs of a Flexynets network, under the constraint of having final user prices no higher than for current reference options. Though the obtained values are rather demanding bounds considering the present energy costs, they still offer margin for the feasibility of the proposed approach.

Key Words: district heating and cooling, heat pumps, economics

1   INTRODUCTION

The reduction of fossil fuel consumptions and thereby of CO_2 emissions is currently at the top of the European agenda for the energy sector. A crucial element to tackle this challenge has been identified in district heating and cooling (DHC) technology (Lund et al. 2010, Connolly et al. 2014). Furthermore, this technology has been identified by the European Commission as an important contributor to moderate the heating and cooling energy demand in order to reduce the EU's external energy dependence (European Commission 2014). Thanks to the use of

combined heat and power (CHP), waste to energy (WTE), and industrial waste heat recovery, a certain number of otherwise unexploited thermal sources can be integrated into district networks, significantly improving the overall efficiency of the energy system. Moreover, more innovative solutions based on solar heat and/or a sustainable use of biomass can correspondingly increase the renewable fraction of the supplied heat (Lund et al. 2010).

In a context of potential expansion of district heating (DH) – or more generally district heating and cooling – it is important to investigate all possible directions of improvement for this technology (DHC+ 2012). A key element was identified in the reduction of the network operating temperature, in order to decrease thermal losses, as proposed for the so-called 4-th generation district heating (Lund et al. 2014). The Flexynets project (EURAC 2015), funded within the Horizon 2020 programme, aims to push this concept to the limit, considering a low-temperature network (at around 20 °C) based on distributed heat pumps (HPs) and with the potential to simultaneously provide heating and cooling. Such a strong reduction in temperature, besides dramatically decreasing heat losses, opens up the possibility of exploiting more waste heat sources within urban areas, at temperatures usually not exploitable for traditional networks.

In general, the Flexynets project focuses on the following main topics. A strong reduction in network temperatures is considered in combination with the introduction of distributed heat pumps. High COP values can be obtained by properly tuning the operating temperatures. The installation of HPs at user substations can also be exploited for reversible operation, with simultaneous availability of heating and cooling and the advantage of offering two services with a single network. Moreover, these changes suggest the use of innovative piping solutions, possibly without insulation. On the other hand, a low supply-return temperature difference is expected for this network, requiring larger flow rates and hence larger diameters. Understanding advantages and disadvantages of this approach requires an investigation of several aspects, both on the technical and economic side.

The Flexynets concept exhibits common points with water loop solutions found in geothermal applications and commercial buildings. Examples including groups of buildings are already available, though not on the large scale proposed in Flexynets. Similar types of analysis are being developed also in other research projects (EU FP7 e-hub project 2010) and institutions (Foster S. et al. 2016).

This paper aims to provide some preliminary economic estimates from a general point of view, avoiding as much as possible technical details, which are still being developed within the project consortium. A top-down approach is adopted, where current energy prices are taken as an input and estimates for the admissible prices of a Flexynets network are calculated as an output, exploiting simple relations for HP performances. In this way, upper bounds for economic margins can be estimated. The dependence of these results on the considered assumptions is also discussed. Note that this avoids an explicit estimate of investment costs (which would be needed in a bottom-up approach). Of course, estimating the latter is needed to carry out a full feasibility study and will be one of the outputs of the Flexynets project.

The paper is organized as follows. In section 2, the Flexynets content is described in more details, explaining expected strengths and weaknesses of this approach and presenting possible configurations for substations. Section 3 focuses instead on the aforementioned bounds, including a simple sensitivity analysis as a function of electricity and reference prices. Finally, section 4 contains the conclusions.

2 THE FLEXYNETS CONCEPT

As anticipated in the introduction, the core idea of the Flexynets concept consists in operating the network at a neutral (i.e., close to surroundings) temperature and then raising/lowering the latter through heat pumps directly at user substations, according to corresponding needs. This difference has some important consequences, which is useful to highlight.

A network operation temperature close to the surrounding temperature strongly reduces the need for highly insulated pipes. Special pre-insulated pipes represent one important cost item in traditional thermal networks and avoiding them would introduce significant savings. On the other hand, installing heat pumps instead of simple heat exchangers would increase investment costs for residential substations. For a low temperature network (11-18 °C) installed in Duindorp (The Hague, Netherlands), it has been estimated an additional cost of about 5500 € per dwelling with respect to the installation of a conventional heating system (Foster S. et al. 2016). Similarly, while lowering the network temperature would allow the integration of a larger number of cheap waste heat sources, the operation of heat pumps would require a certain fraction of expensive electric energy. The balance between these four drivers – pipe costs vs substation costs, source heat costs vs operation electricity costs – is expected to be the main factor determining the success or the failure of the Flexynets concept.

2.1 Substations

Traditional substations are constituted by a heat exchanger surrounded by some auxiliary components. On the primary side (i.e., the network side) these can be differential pressure controllers, differential pressure restrictors, and flow regulating valves, while on the secondary side (i.e., the user side) they are typically pumps and recirculation valves (Frederiksen and Werner 2013). Depending on the actual implementation (direct or indirect – i.e., hydraulically separated – connection to the heating equipment), other details can be introduced. In particular, several types of domestic hot water (DHW) generation solutions can be implemented, either instantaneous or tank-assisted.

Similarly, also for the Flexynets concept a range of possibilities can be considered. The core difference with respect to the traditional case is anyway the substitution of the heat exchanger with a water-water heat pump. The operational limits of the latter can somehow influence the operating conditions of the connected circuits, though using for example recirculation solutions a significant flexibility can still be granted.

In Figure 1 it is reported a simplified scheme for a Flexynets substation, including a backup boiler besides the heat pump. Other combinations of equipment (e.g., including solar thermal panels) are being considered in the Flexynets project. A compromise between the additional flexibility provided by the installation of more components and the higher investment costs must of course be found.
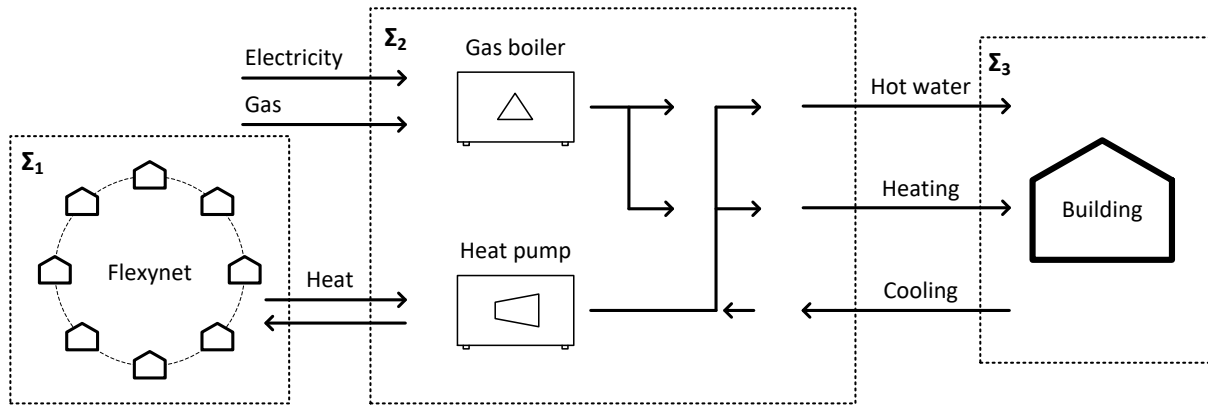
Figure 1: Schematic of Flexynets' substation (boundary Σ₂). The substation exploits low temperature heat from Flexynets (boundary Σ₁) for covering heating, cooling and hot water loads of residential buildings (boundary Σ₃).

From the point of view of thermal energy, the introduction of HPs makes it possible to consider network users not just as consumers or producers, but as prosumers, similarly to what happened in the electric grid context with the penetration of distributed photovoltaic (PV) generation. This reversible – or, more precisely, invertible – operation mode is expected to have some limitations, actually not very different from the electric case. First, it can be considered only in locations with a non-negligible need of cooling. Second, it is affected by a strong seasonality, where an energy flow towards the grid is typically expected only in summer, with intra-day oscillations given by the possible alternating need of cooling and DHW. This resembles effects present also in the electric sector, where PV generation depends on location and seasonality, so that excess electricity production with respect to self-consumption only takes place in summer.

2.2 Supply stations

Supply stations, in principle, do not need to be much different from those already used in traditional networks. However, the lower network temperature would significantly improve the profitability of cogeneration systems, like combined heat and power (CHP) stations. Moreover, it could open up the possibility of exploiting different sources or technologies.

Some notable examples are worth to be discussed. A first one concerns waste heat from chillers as found in shopping malls or food cycle facilities. While these systems cannot produce all the heat required by a district network, they represent a non-negligible amount of energy and have the considerable benefit of being often very close and well integrated in the urban environment. Consequently, their connection is expected to be less expensive than for industrial facilities typically located at a certain distance from residential areas.

A second example concerns solar thermal heat. Solar fields based on flat plate collectors are already being considered for traditional DH networks, within the so-called solar district heating concept (Nielsen 2012). However, a neutral network temperature would greatly improve the profitability of these systems, either in terms of performances or in terms of reduced investments costs (thanks to the use of cheaper low temperature collectors).

The last proposed example concerns ORC engines. These systems are suitable to produce electricity from low-medium temperature thermal sources, where common steam turbines are not applicable. However, unless the condenser side is at a reasonably low temperature, their efficiency is poor, making the system not economically attractive. A neutral temperature

network could therefore make these systems more viable, provided a large number of operation hours can be guaranteed.

In Figure 2 it is reported an example of a Flexynets heat supply station. It includes an ORC engine and a sorption chiller, supplied by a concentrating solar field (in order to produce the required operating temperatures for these machines) and by a backup boiler. As for substations, other (possibly) simpler combinations are possible.

Other types of supply stations would benefit from the Flexynets concept. Important solutions to be analysed for Flexynets are stations for cold supply – in view of a fully reversible network – and appropriate storage solutions (possibly seasonal, for an optimal yearly energy balance). In particular, a crucial aspect is clearly given by network balance, i.e., matching supply and demand. While a certain amount of quick modulating equipment (e.g., gas boilers) should anyway be considered, proper storage solutions and an appropriate initial sizing of the network are expected to allow for the integration of a large number of non-balancing supply stations, whose operation can be optimized according to internal needs rather than to network requests.
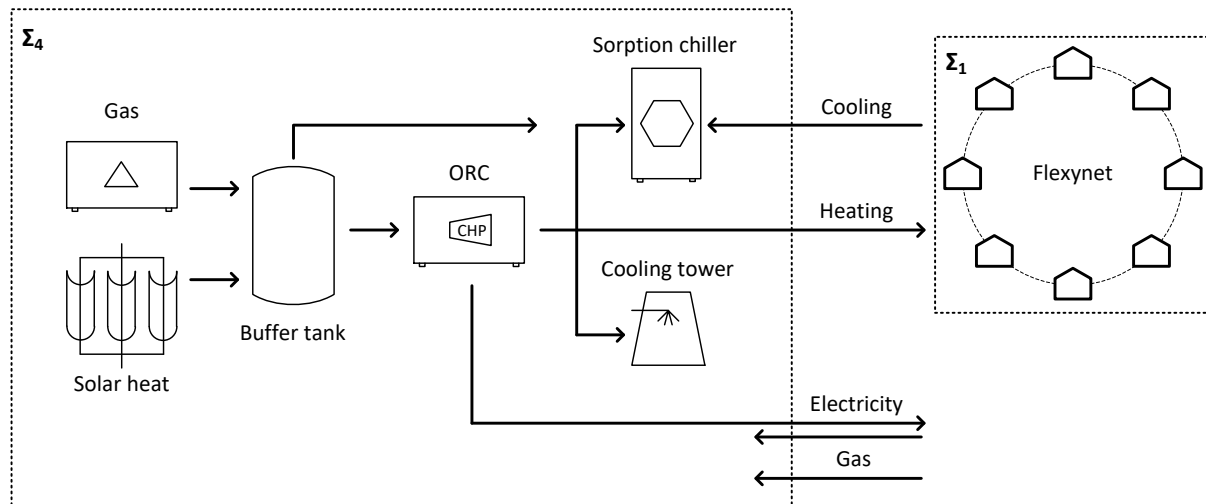

Figure 2: Schematic of Flexynets's powerstation (boundary Σ_4). This system aims to compensate Flexynets (boundary Σ_1) temperature fluctuations by delivering heating or cooling according to its needs.

3   ECONOMIC BOUNDS

In order obtain a detailed estimate of the techno-economic balance of the proposed thermal network, specific configurations will be designed and analysed within the Flexynets project, including information about costs and performances of all main components. Besides this bottom-up approach, where the overall system is explicitly built from its underlying components (generation stations, network, substations, each with its technical and economic parameters), it is however possible to consider also a top-down approach, where some useful bounds for the system elements can be obtained starting from general assumptions, derived by comparison with other reference cases. This is the methodology adopted in this paper to identify some requirements of a Flexynets network. In particular, inputs of this top-down approach are energy production prices, reference heating and cooling costs, and HP performances, while the output is the admissible energy price of a Flexynets network.

As far as reference solutions are concerned, good practical choices can be individual natural gas boilers and classic DH for heating and individual split units for cooling. These can be taken as systems to compare with. Reasonable estimates for the corresponding costs will be provided below, but general considerations can be made without using explicit values, but just referring to reference heating and cooling unitary prices (i.e., costs per energy unit) as $c_{H,ref}$ and $c_{C,ref}$.

It is assumed that the final price for residential users in a Flexynets network should be equal to or lower than these reference prices. This can be written as:

$$c_{H,FN} = c_{el} \frac{1}{\text{SCOP}_{FN}} + c_{th,H,FN} \left(1 - \frac{1}{\text{SCOP}_{FN}} \right) \leq c_{H,ref} \,, \tag{1}$$

$$c_{C,FN} = c_{el} \frac{1}{\text{SEER}_{FN}} + c_{th,C,FN} \left(1 + \frac{1}{\text{SEER}_{FN}} \right) \leq c_{C,ref} \tag{2}$$

where $c_{H,FN}$ and $c_{C,FN}$ are the heating and cooling overall costs for the user (including thermal energy and electricity costs), SCOP_{FN} and SEER_{FN} are the seasonal coefficient of performance (for heating) and the seasonal energy efficiency ratio (for cooling) of a heat pump in a Flexynets substation, c_{el} is the unitary electricity price, and $c_{th,H,FN}$ and $c_{th,C,FN}$ are the prices applied by the network manager to the user for supplying (in heating mode) or dissipating (in cooling mode) the thermal energy exchanged with the network. Note that the latter is smaller than the final energy consumed by the user in heating mode (where electricity gives an additional heating contribution), while it is higher than the energy rejected by the user in cooling mode (where electricity has also to be dissipated).

A few remarks are in order. First, it is useful to stress that the final user cost is given by the sum of electricity and thermal energy costs. From a market point of view, one can figure out business models where the district manager also delivers electricity and possibly provides a unified DHC bill to the user, but in general two different companies can be expected to provide electricity and thermal energy supply/dissipation. Second, different thermal energy costs could be applied depending on the operation mode – either heating or cooling. In particular, while in heating mode thermal energy is supplied to the user, in cooling mode thermal energy is absorbed from the user. This resembles a sell/buy situation as found in the electricity market, with different prices in the two cases. Here, a more radical difference is present: as cooling is considered a "useful" effect, the user is assumed to pay also for dissipation (with a cost no higher than for the reference case). While different market approaches can in principle be devised, this seems to be the most natural one for the Flexynets system.

Taking a step further, it is interesting to consider the limiting case where the overall Flexynets costs for the user are assumed to be exactly equal to the reference cases, i.e., $c_{H,FN} = c_{H,ref}$ and $c_{C,FN} = c_{C,ref}$. In this way, it is possible to estimate an upper bound for the Flexynets thermal energy prices. It is indeed evident from the above relations that, as part of the user costs will be taken by the electricity quote, the maximum admissible thermal energy prices will have to be lower than in reference cases. Solving Eqs. (1) and (2) for $c_{th,H,FN}$ and $c_{th,C,FN}$ one finds

$$c_{th,H,FN} = c_{H,ref} \left(1 - \frac{c_{el}/c_{H,ref} - 1}{\text{SCOP}_{FN} - 1} \right) \tag{3}$$

$$c_{th,C,FN} = c_{C,ref} \left(1 - \frac{c_{el}/c_{C,ref} + 1}{\text{SEER}_{FN} + 1} \right) = c_{C,ref} \left(1 - \frac{\text{SEER}_{ref} + 1}{\text{SEER}_{FN} + 1} \right) \tag{4}$$

where SEER_{ref} is the reference seasonal EER value of the reference split unit.

In order to provide some order of magnitudes for these values, we consider an example based on typical current energy costs in the North of Italy. For the heating reference price, there is not a significant difference between individual gas boilers and district heating, yielding an indicative value of $c_{H,ref}$ = 0.10 €/kWh. For cooling, a typical SEER value for the considered region is SEER_{ref} = 3 (EU FP7 iNSPiRe project 2016), while a typical electricity cost is c_{el} = 0.18 €/kWh, yielding a cooling reference cost of $c_{C,ref} = c_{el}/\mathrm{SEER}_{ref}$ = 0.06 €/kWh. Finally, with network temperatures of 15-20 °C and supply temperatures typical of modern residential heating and cooling plants, existing heat pump models can deliver performance values of the order of SCOP_{FN} = 5 and SEER_{FN} = 6 (EU FP7 iNSPiRe project 2016). With these assumptions one gets $c_{th,H,FN}$ = 8.0 c€/kWh and $c_{th,C,FN}$ = 2.6 c€/kWh, which are the maximum prices applicable by the district manager in order to compete with the considered reference costs.

3.1 Sensitivity analysis

As it can be seen from Eqs. (3) and (4), the admissible costs charged by the district manager depend only on three parameters, namely the reference price, the electricity price, and the average heat pump performance in the Flexynets network. Apart from the indicative values provided above, it is interesting to investigate the variability of these parameters and to perform a simple sensitivity analysis for the resulting admissible costs as a function of these variables.

3.1.1 Heat pump performances

The HP performance depends on the chosen operating conditions (network temperature and secondary circuit temperature), as well as on the specific heat pump model. For models currently available on the market, one finds performances as those reported in Table 1. Here, in heating mode the COP is reported as a function of the inlet network temperature $T_{netw,in}$, for a given outlet temperature $T_{load,out}$ = 35 °C on the secondary circuit (supply temperature to the user). This outlet temperature is representative of a modern residential heating plant, e.g., exploiting radiant panels as heating terminals. In cooling mode, the EER is again reported as a function of the inlet network temperature for a given outlet temperature $T_{load,out}$ = 15 °C on the secondary circuit. This temperature is compatible with typical residential cooling terminals.

Table 1: Typical ranges of HP performances depending on operating temperatures.

Heating mode			Cooling mode		
$T_{netw,in}$ [°C]	$T_{load,out}$ [°C]	COP_{FN}	$T_{netw,in}$ [°C]	$T_{load,out}$ [°C]	EER_{FN}
10	35	4.8	25	15	6.5
15	35	5.3	30	15	5.8
20	35	5.8	35	15	5.1

It can hence be seen that, with network temperatures in the range 20-25 °C, seasonal averages SCOP_{FN} = 5 and SEER_{FN} = 6 in heating and cooling mode respectively are feasible, while the expected performance variation for network temperature fluctuations of ±5 K is of the order of 10 %.

3.1.2 Dependence on electricity and reference prices

This subsection discusses the sensitivity as a function of electricity and reference costs. To this purpose, HP performances are fixed to $\text{SCOP}_{FN} = 5$ and $\text{SEER}_{FN} = 6$ in heating and cooling mode, respectively,

Electricity and reference prices can significantly vary from country to country, as well as in time. From Eqs. (3) and (4) it can be seen that the admissible Flexynets prices have a linear dependence on both the electricity and reference prices. In terms of derivatives

$$\frac{\partial c_{th,H,FN}}{\partial c_{el}} = -\frac{1}{\text{SCOP}_{FN} - 1} \;,\; \frac{\partial c_{th,H,FN}}{\partial c_{ref,H}} = 1 + \frac{1}{\text{SCOP}_{FN} - 1} \tag{5}$$

$$\frac{\partial c_{th,C,FN}}{\partial c_{el}} = -\frac{1}{\text{SEER}_{FN} + 1} \;,\; \frac{\partial c_{th,C,FN}}{\partial c_{ref,C}} = 1 - \frac{1}{\text{SEER}_{FN} + 1} \tag{6}$$

This shows that both admissible prices (in heating and cooling mode) must decrease when electricity prices increase, while they can increase when reference prices increase, as expected. In the following figures, these behaviours are explicitly visualized for a certain range of values.

In particular, Figure 3 shows the dependence of the admissible price applied by the district manager to the user in heating ($c_{th,H,FN}$) and cooling ($c_{th,C,FN}$) mode. Different curves of constant admissible price are visualized in the figure, like in a contour plot (these are just straight lines, as derived from the above linear equations).
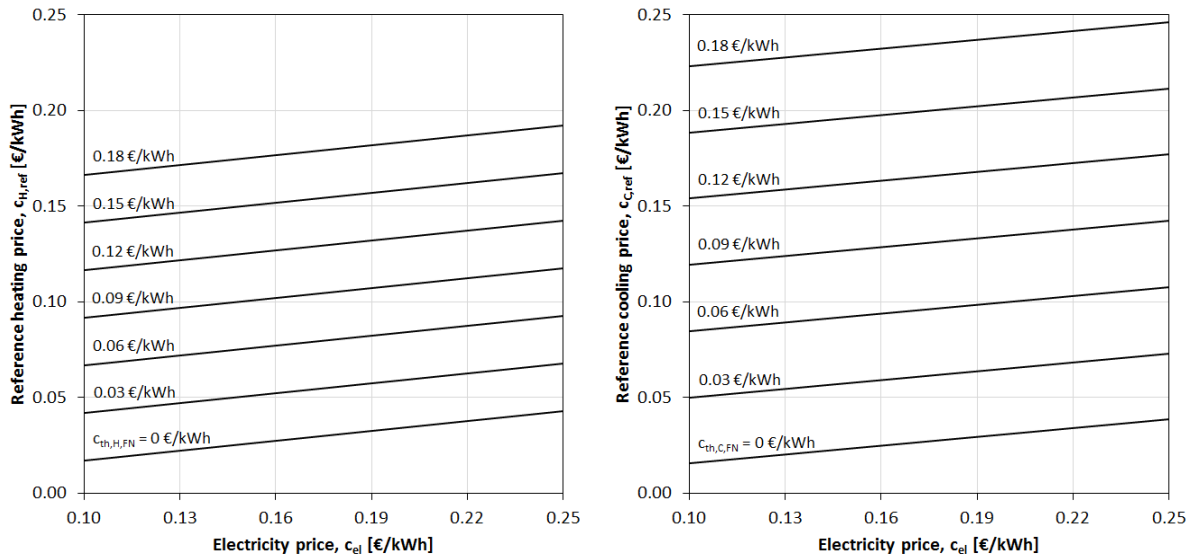

Figure 3: Flexynets' heat prices (€/kWh) for heating (left, $c_{th,H,FN}$) and cooling (right, $c_{th,C,FN}$) as a function of the electricity price and reference heating/cooling prices. Curve of constant value are shown, like in a contour plot.

As discussed, for the heating case one has $c_{th,H,FN} \leq c_{th,ref}$. If the reference price is considered to be that of a traditional DH system, this relation shows how in a Flexynets network heat must be sold at a lower price to be competitive. It is hence interesting to analyse how this affects the district manager margin with respect to the heat production cost. To this purpose, explicit cases are considered. In particular, two different types of sources are assumed for both heating and cooling, a high-cost (e.g., a centralized natural gas boiler for heating and a centralized compression chiller for cooling) and a low-cost source.(e.g., waste heat for heating and free cooling for cooling). The corresponding assumed costs are reported in Table 2.

Table 2: Assumed production costs [€/kWh] for heating and cooling.

	High cost	Low cost
Heating	0.037	0.010
Cooling	0.027	0.001

In a real DHC network, these sources can then be combined with different weights. For the present analysis, the weights for heating are assumed to be $w_{hc,H}$ = 50 % (high-cost) and $w_{lc,H}$ = 50 % (low-cost), while for cooling $w_{hc,C}$ = 30 % (high-cost) and $w_{lc,C}$ = 70 % (low-cost). Other possible combinations could be realistic, with a significant dependence on the location. One then gets for the production costs $c_{prod,H}$ = 0.023 €/kWh (heating) and $c_{prod,C}$ = 0.0087 €/kWh (cooling). Finally, the margin is calculated as $c_{m,H,FN} = c_{th,H,FN} - c_{prod,H}$ and $c_{m,C,FN} = c_{th,C,FN} - c_{prod,C}$, for heating and cooling respectively.

The results are shown in Figure 4, where the curves of constant margin are plotted as a function of the electricity price and of the reference price.
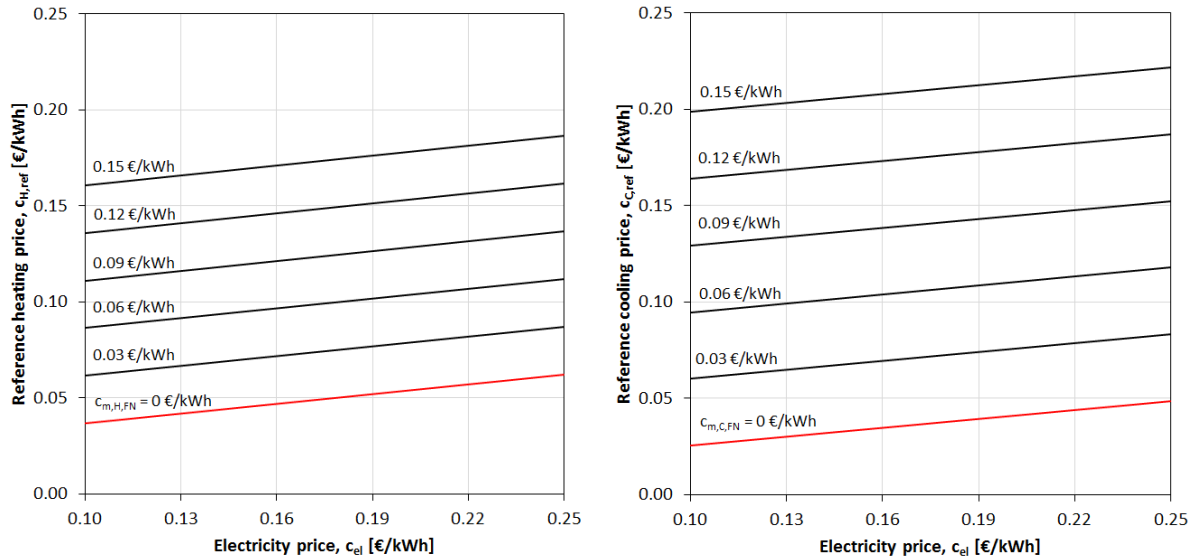

Figure 4: Flexynets' margins (€/kWh) for heating (left, $c_{m,H,FN}$) and cooling (right, $c_{m,C,FN}$) as a function of the electricity price and reference heating/cooling prices. The red line at the bottom highlights the limit of zero margin.

4   CONCLUSIONS

This paper, after providing a description of the Flexynets concept, presents a simple analysis of the price requirements of such a thermal network. This system is indeed based on distributed heat pumps, which involve electricity costs and consequently modify the user cost distribution. Considering HP performances and electricity price, an upper bound for the network heat/cold price (i.e., a maximum admissible price) can be derived. Using realistic values for electricity and reference heating and cooling prices, the above analysis yields maximum admissible prices of 0.08 €/kWh for heating and of 0.026 €/kWh for cooling. The paper discusses the dependence of this value on the parameters at play, through both equations and plots. A sensitivity analysis in terms of electricity and reference prices is explicitly carried out. Finally,

the paper discusses the consequences of the calculated prices on the network manager margin. This is calculated under certain assumptions for heat/cold production costs.

The research line related to these topics is currently raising a significant interest, as witnessed by the recent EU calls appeared on this field. This paper mentions only a limited part of the aspects involved in this type of analysis. In order to fully investigate the viability of the Flexynets concept, a more extensive analysis will be carried out during the project. A key point will be to assess the real potential of low temperature waste heat to be possibly integrated in the network. Indeed, this could significantly lower energy production prices, strongly affecting the margin for the district manager. Other activities being performed include technical investigations (e.g., about the optimal network and load temperatures for the system) and a full bottom-up analysis taking into account all investment costs for the system (heat/cold generation systems, piping, substations). Furthermore, provided the general feasibility of the system will be confirmed, the analysis of possible business models in this electric-thermal hybrid context will require special attention.

REFERENCES

Connolly D., H. Lund, B. V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P. A. Østergaard, and S. Nielsen, 2014. "Heat roadmap europe: Combining district heating with heat savings to decarbonise the EU energy system," *Energy Policy*, vol. 65, pp. 475–489.

DHC+ Technology Platform, 2012. "District heating & cooling: a vision towards 2020-2030-2050", Brussels.

EU FP7 e-hub project about District Heating, Cooling & Power with on-site renewable energy, started in 2010. Available at http://www.e-hub.org (accessed 04 November 2016).

EU FP7 iNSPiRe project, 2016. Deliverable 6.3.c and 6.3.d. Performance of the Studied Systemic Renovation Packages – Multifamily Houses (available online: http://inspirefp7.eu/).

EURAC, 2015. "Flexynets project", available at: http://www.flexynets.eu/en/Project (accessed 04 November 2016).

European Commission, 2014. "Communication from the Commission to the European Parliament and the Council: European Energy Security Strategy". Brussels.

Foster S., Love J., Walker I., Crane M., 2016. "Heat pumps in District Heating – Case studies", Department of Energy & Climate Change, United Kingdom Government available at: https://www.gov.uk/government/publications/heat-pumps-in-district-heating (accessed 04 November 2016).

Frederiksen S., S. Werner, 2013. District Heating and Cooling, Studentlitteratur AB, Lund.

Lund H., B. Möller, B. V. Mathiesen, and A. Dyrelund, 2010. "The role of district heating in future renewable energy systems," *Energy*, vol. 35, no. 3, pp. 1381–1390.

Lund H., S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, B. Vad Mathiesen, 2014. "4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems", Energy, vol. 68, pp. 1–11.

Nielsen J. E., 2012. "IEA-SHC Task 45: Large solar heating/cooling systems, seasonal storage, heat pumps", Energy Procedia, vol. 30, pp. 849–855.