FLEXYNETS Guide Book

Fifth generation, low temperature, high exergy district heating and cooling networks

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1 Introduction

This document presents guidelines for the application of the concept of neutral-temperature networks based on reversible heat pumps, which is the focus of the FLEXYNETS project. It condenses the main results found within the project, while detailed information is reported in specific reports downloadable from the website www.flexynets.eu.

Of course, heating and cooling can significantly vary from country to country. However, a common denominator between all European regions is the general trend towards increasing urbanization. For this reason, heating and cooling approaches based on a “district” perspective, rather than on individual solutions, are becoming more and more relevant.

Thinking in terms of energy districts offers the advantage of better balancing multiple users’ loads. Conventional 3rd generation district heating (DH) embodies this concept from the point of view of thermal energy and can be considered a consolidated praxis in many EU member states. However, it suffers from some drawbacks, mainly due to its relatively high operating temperature (supply temperature of the order of 90 °C). Indeed, this gives rise to non-negligible thermal losses, despite the high-quality pre-insulated pipes typically used. Moreover, such operating conditions are not suitable for the direct recovery of low-temperature excess (waste) heat, which is often available in the urban context.

To overcome these drawbacks, 4th generation DH (4DH) has been proposed. This solution, while demonstrated in several variants, has its key ingredient in lowering of the network temperature, to the minimum value admissible for direct space heating and domestic hot water preparation: around 50-55°C supply temperature.

The FLEXYNETS project made a further step forward, introducing a 5th generation of district heating. The proposed concept consists of a network at neutral temperature, corresponding to a supply temperature of 15-25 °C, connected to decentralised reversible heat pumps (HP), which allows to simultaneously provide heating and cooling along the same pipes.

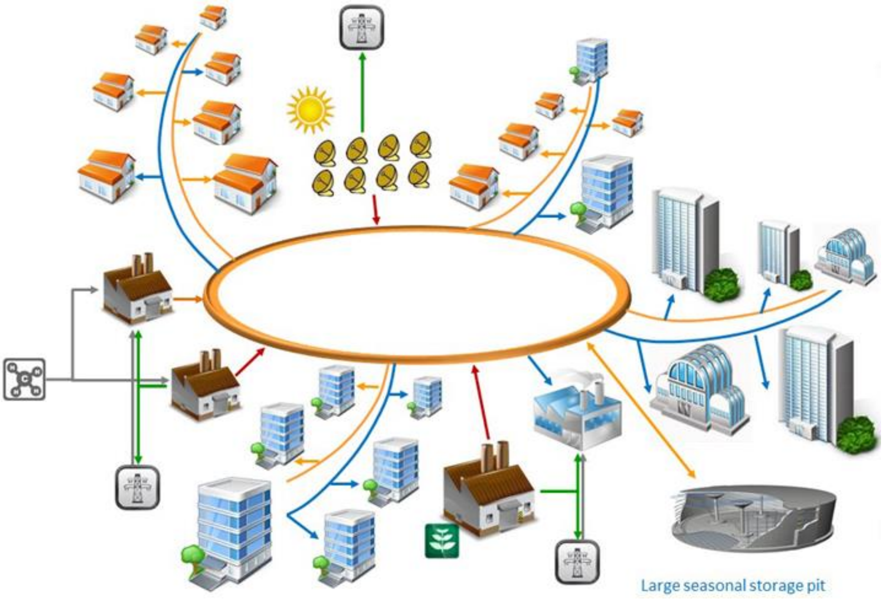

Figure 1. Schematic of a fifth generation DHC network

This concept has been exploited so far in relatively few cases and often called “cold district heating”, where only heating is distributed. Typical sources for these applications are ground source heat or water basins.

FLEXYNETS, however, explicitly considers the implementation of a district heating and cooling (DHC) network, with the advantage of recycling heat from cooling needs of residential tertiary and industrial applications. This allows to easily integrate multiple low-temperature waste heat sources, ranging from refrigeration applications in shopping malls to industrial waste heat.

The reversibility of HP-based substations transforms users into prosumers, similarly to distributed photovoltaics applications in the electric sector.

This solution is not an attempt to replace 4DH networks, but rather to enable enhanced and additional benefits of thermal networks compared to a more conventional DH supply.

The resulting system is evidently more complex than conventional ones. The presence of multiple energy sources and the higher complexity of heat pumps with respect to simple heat exchangers (used in conventional DH substations) requires proper control strategies to be implemented. Also, the role of energy storages becomes more important in this context, due to the non-dispatchable nature of waste heat.

While the system complexity management is a challenge, it also lends to favour the introduction of additional services. HP systems installed at prosumer side, inherently use storage tanks which thermal capacity can be effectively used. Moreover, the intelligent management of the storages’ thermal capacity opens to Demand Side Management practices: as electricity is used to run the HPs, a link is created between the thermal energy sector and the electricity distribution one, enabling the integration of the electric sector in the district heating segment.

The need of a more detailed metering and communication, for example, with the installation of the corresponding equipment, could provide utilities with the possibility to offer internet services to their customers, thereby enlarging their business portfolio.

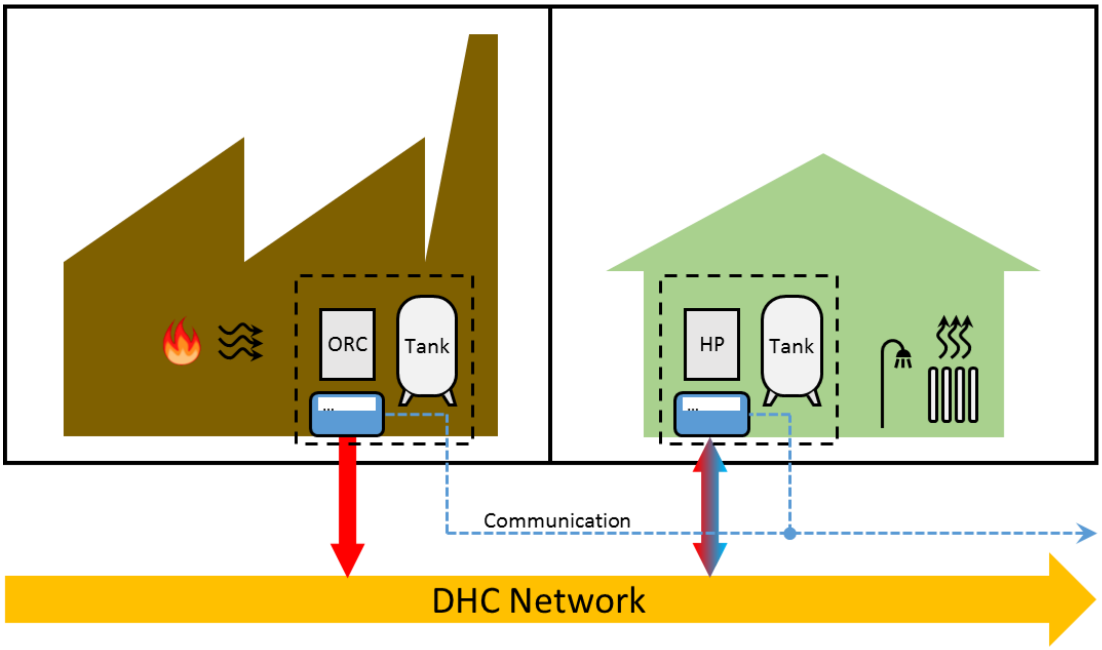

Figure 2. Examples of Substations exchanging heat with the DHC network

Besides these considerations, the potential to improve the energy efficiency of the overall system has a direct consequence in terms of emission reductions, for both CO_2 and local pollutants. Although HP based substations require a higher initial investment compared to conventional substations, under suitable conditions (i.e. proper heating and cooling demand, sufficient waste heat availability, competitive electricity prices), the overall system costs can be at least comparable to those of high-temperature district heating applications.

As the heat generation is diffused, this can be extended together with the heat demand, alongside the network growth: it is therefore not necessary to foresee the huge initial investment related to the installation of large generation plant, like a biomass or waste incinerator. This allows the investment to be split through the years and opens to the adoption of the technology by small utility companies and to private investments.

Moreover, the enhanced use of local resources (even in terms of job positions) can benefit the local economy beyond what emerges from the analysis of the internal costs of the system.

2 Network layouts in selected urban contexts

Within the FLEXYNETS project, the layout of a DHC network in a real built environment has been investigated: a range of settlements has been analysed together with different network options, in order to provide recommendations for their layout.

A FLEXYNETS network and a conventional DH network are different in several ways. Regarding the type of pipe, it should be kept in mind that the FLEXYNETS concept uses much lower temperatures (and temperature differences) than conventional DH. The lower temperatures may allow the use of pipes with little insulation or none.

Plastic pipes may even be an option which could introduce the following advantages: low weight, flexibility, resistance to corrosion, low friction and a lower price compared to conventional DH.

A drawback of the FLEXYNETS concept is, however, that the lower temperature difference entails a much higher flow rate to transfer the same thermal power, which results in larger pipes and higher pumping energy. It should be noted that, because in the FLEXYNETS concept the electricity consumed by the consumers' heat pumps contributes to the end user's heat demand, the amount of heat that the distribution network supplies to the end user's is lower than the corresponding amount in a conventional DH network. Assuming an end user's thermal power demand $\dot{Q}$, a COP (coefficient of performance) of the individual heat pumps of 4 and a temperature difference in case of FLEXYNETS 3 times smaller than in conventional DH (ΔT_{DH}), the flow required in a FLEXYNETS network $\dot{m}$ would be $\dot{m} \propto \frac{\dot{Q}\cdot(1-1/4)}{(\Delta T_{DH}/3)} = \frac{2.25\cdot\dot{Q}}{\Delta T_{DH}}$, i.e. 2.25 times larger than in the conventional DH network.

If the fluid velocity is assumed to be the same in the two systems, then the pipe (inner) diameters of the FLEXYNETS network will approximately be 1.5 times larger than those used for conventional DH.

Regarding the network structure, a FLEXYNETS network recovering heat from several decentralized heat sources may benefit from having a different topology than the "branch" one, typical of conventional DH systems. In case of several sources of excess heat in the peripheral areas of a town, the network should reach out towards these areas. A ring structure network could do so by having a main ring running close to the several excess heat sources. If a branch-structured network has to reach the same excess heat sources, it should be equipped with one or more transmission pipes from the peripheral area to the network centre or extended network capacity (pipe dimensions) to each of these sources.

The two above-mentioned network structures (branch and ring structure) were investigated through a GIS-based tool. A model for a conventional DH system and for a FLEXYNETS network was developed based on the corresponding temperature levels and pipe insulation classes (Series 3 for conventional DH, Series 1 for FLEXYNETS). In both cases, the goal of the model was to identify the shortest grid length which allowed supplying all the consumers while evaluating the network dimensions needed. For each pipe of the network, the tool calculates the pipe diameter necessary to carry the thermal peak demand which the pipe is expected to deliver. Once the network is sized in terms of lengths and diameters, its investment cost, heat losses and pumping power can be evaluated.

The two network structures were applied both to the FLEXYNETS concept and to conventional DH in different town areas, representing different settlement typologies. The different network structures and types were evaluated in the same town areas, meaning that each area was evaluated with a minimum of four different applications of networks; FLEXYNETS ring and FLEXYNETS branch as well as conventional DH ring and conventional DH branch. Some areas were also evaluated with the presence of a small ring in the network and compared to a network including a larger ring.

The results showed that local conditions had a significant influence on the optimal solution, so that it cannot be concluded that one network structure is in general more suitable than the other. However, the analysis of the different network layouts in different contexts showed that a ring structure could be a suitable solution in the presence of:

- dense urban areas,
- excess heat available in significant quantities,
- excess heat that is scattered across the peripheral area around the centre of the town/city,
- excess heat that is limited in each supply point.

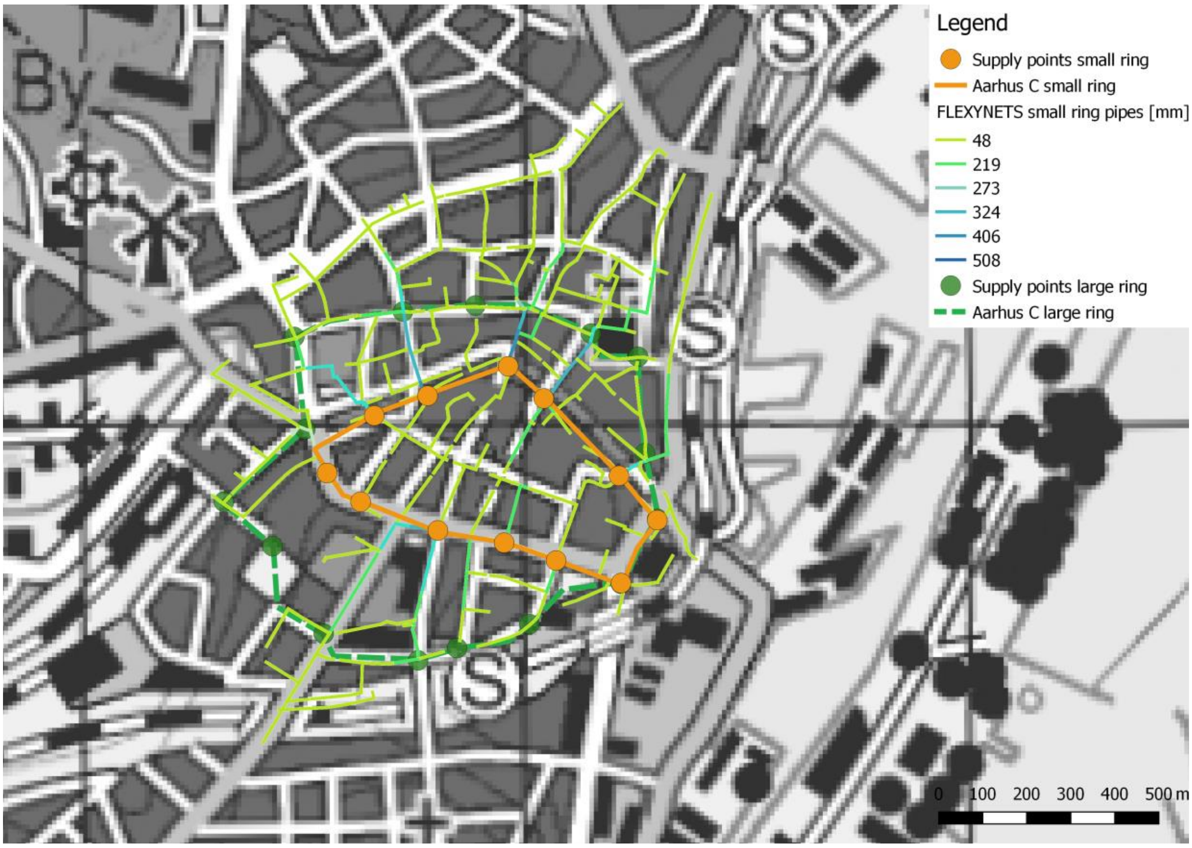

Figure 3. Network layout example by using the GIS based tool for the case of Aarhus for the FLEXYNETS concept, small ring structure scenario (the large ring structure is also shown). (Background map from Geodatastyrelsen Denmark.)

The ring does not need to be located in the peripheral area of the city, where the main excess heat sources are typically located. An alternative solution can be to have a smaller (and hence cheaper) ring running closer to the city centre, with branches spreading both outward and inward toward the heat consumers, as shown in Figure 3.

However, in some cases the ring structure may result in a longer network length compared to a branch structure, with consequently higher investment costs and pumping costs. Yet, if the alternative heat supply is expensive (economically and/or environmentally) compared to the available excess heat, the higher investment cost of the ring structure may be balanced by the lower heat production cost. Therefore, care should be taken to identify (and quantify) the benefits and drawbacks of different network structures in the specific case under investigation before deciding the final network layout. For example, if few and large-size excess heat sources area available, a branch structure – potentially with transmission pipes – may be more economically feasible than forcing a ring structure.

Additionally, when connecting several smaller grids, the distance between two rings will in general be shorter than that between two main branch centre points. Hence, the ring structure could offer an advantage in terms of scalability and of connection to neighbouring networks if this is foreseen e.g. in a stepwise development of new urban areas.

When comparing a FLEXYNETS system and a conventional DH system using the same network structure, the following trends could be identified:

- The heat losses in FLEXYNETS were about 75 % lower than in conventional DH.
- The investment cost of a FLEXYNETS network was on average slightly higher than a conventional DH network if traditional DH pipes are used, due to the larger pipe diameters, only partially compensated by the lower insulation thickness (Series 1 against Series 3 in the network model). The costs of the pipes for FLEXYNETS temperatures may be further lowered by using non-insulated pipes or pipes with very limited insulation. This was for example assumed in the developed pre-design Excel tool, where the pipe insulation class "Series X" was introduced, having an insulation thickness equal to 1/3 of that of a Series 3 pipe with the same metal pipe diameter.
- The pumping power and pumping energy in FLEXYNETS were significantly higher than in conventional DH (it should, however, be considered that the pumping energy is converted into thermal energy of the heat carrier fluid, so it is recovered by the system, at least in heating mode).

<table>
<tr><th colspan="2">FLEXYNETS KEY RECOMMENDATIONS ON NETWORK DESIGN</th></tr>
<tr><th>BENEFITS</th><th>DRAWBACKS</th></tr>
<tr><td>• Significantly lower network losses
• Potential to use less insulation and/or cheaper pipes – potentially even in other materials than typically used (e.g. plastic).
• It can be considered if a ring structure would be suitable especially if the case involves a dense urban area with excess heat available in significant quantities scattered across the peripheral area around centre.
• In peak periods the network temperature can potentially temporarily be increased. Hence, “safety margin over-dimensioning” may be reduced (i.e. several network operator optimisation options are available).</td><td>• Low network ΔT means higher flow rate for a certain energy supply (compared to conventional DH) which means that higher pumping power (pump capacity), higher pumping energy and bigger (inner) pipe diameters are required (though limited by lower heat demand for the network thanks to HP electricity contribution). *BUT*:
○ lower insulation thickness can compensate for the bigger inner diameter thus resulting in similar outer diameters;
○ the pumping energy is converted in thermal energy in the heat carrier fluid, so it is recovered by the system;
○ when comparing with other total costs pumping electricity is a minor part.
• High investment costs in substations compared to conventional DH.
• High electricity costs (incl. for HPs) compared to conventional DH. *BUT*:
○ less heat transported in the network since some is provided by the electricity of the HPs.</td></tr>
</table>

3 Large storage systems

The FLEXYNETS project also investigated how large-scale thermal energy storage (TES) — which are already used in DH networks — could be adopted in the context of low-temperature networks, such as FLEXYNETS. The analysis included both spatial requirements, energy performance (temperature dependency) and economics of such storages. Four types of TES were considered:

- Tanks (TTES)
- Pits (PTES)
- Aquifers (ATES)
- Boreholes (BTES)

The main characteristics of the above-mentioned storage technologies are listed in the table below. All four types of TES are considered relevant for low-temperature networks.

Table 1. Thermal storage classification and description.

Type	TTES	PTES	BTES	ATES
Storage medium	Water	Water (gravel-water)	Soil surrounding the boreholes	Groundwater in aquifers
Specific capacity [kWh/m^3]	60-80	60-80 30-50 for gravel-water	15-30	30-40
Water equivalents	1 m^3 TES = 1 m^3 water	1 m^3 TES = 1 m^3 water	3-5 m^3 TES = 1 m^3 water	2-5 m^3 TES = 1 m^3 water
Geological requirements	• stable ground conditions • preferably no groundwater • 5-15 m deep	• stable ground conditions • preferably no groundwater • 5-15 m deep	• drillable ground • high heat capacity • high thermal conductivity • low hydraulic conductivity • groundwater flow <1 m/a • 30-100 m deep	• high yield aquifer
Application	Short-term/ diurnal TES, buffer TES	• Long-term/seasonal TES for production higher than 20,000 MWh/year • Short term TES for large CHP	Long-term/seasonal TES for DH plants with production of more than 20,000 MWh/year	Long-term /seasonal heat and cold TES
Storage temperatures [°C]	5-95	5-95	5-90	7-18
Specific investment cost [€/m^3 water equivalent]	110-200 €/m^3 (if >2,000 m^3)	20-40 €/m^3 (if >50,000 m^3)	20-40 €/m^3 (if >50,000 m^3 water equivalent incl. buffer tank)	50-60 €/m^3 Cost depends on charge capacity, rather than storage capacity
Advantages	High charge/discharge capacity	• High charge/discharge capacity • Low investment cost	Most underground properties are suitable	• Provides heat and cold TES • Many geologically suitable sites
Disadvantages	High specific investment cost	Large area requirements	Low charge/discharge capacity (potentially need of a buffer tank)	• Low temperatures and temperature difference

For very large TES, PTES currently offer the lowest specific investment costs (see Figure 4). Additionally, PTES – as well as the other water-based TES (TTES and ATES) – are characterized by high efficiencies and high charge/discharge capacities. Of the water-based TES, ATES have a lower specific storage capacity due to the low temperatures and consequently low temperature differences. BTES can be implemented almost independently of the geological properties, but they have a low charge/discharge capacity.

The specific investment cost (C) of a TES can be calculated through (Eq.1), as a function of the storage capacity of the TES (Q), temperature difference of the TES (ΔT), density (ρ) and specific heat (c_p) of the storage medium, and coefficients (a, b) which represent the effect of the economies of scale on the investment cost.

$$C = a \cdot \left(\frac{Q}{\rho \cdot c_p \cdot \Delta T} \right)^{b+1} \qquad \text{(Eq.1)}$$

The coefficients a ($a > 0$) and b ($-1 < b < 0$) are specific of the TES technology and determine the shape of the fitting curves of the specific investment cost based on a collection of existing examples (see Figure 4).

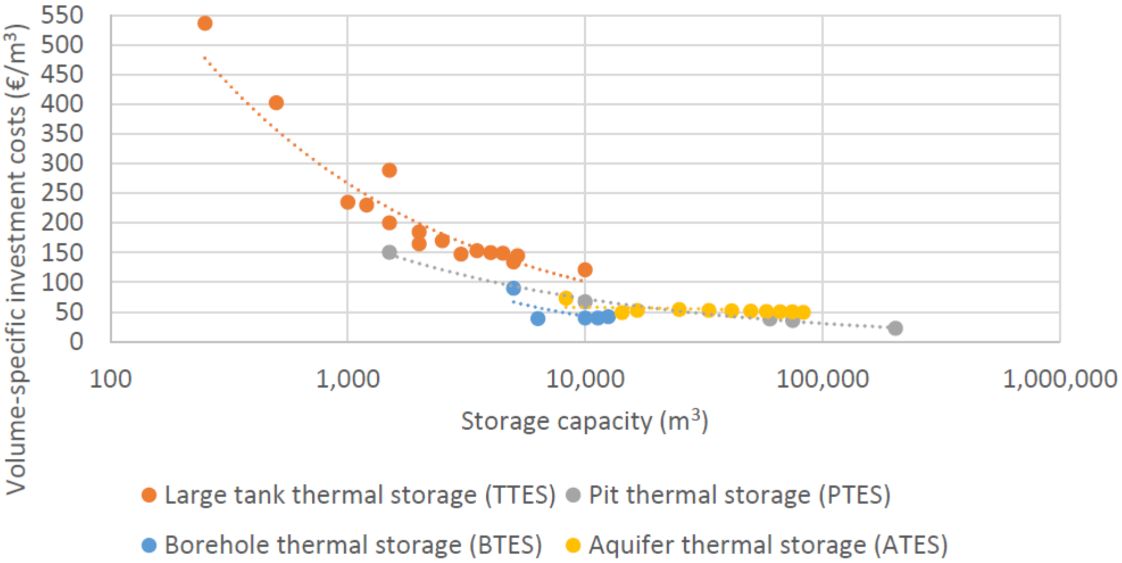

Figure 4. Investment cost per m³ of water equivalent for TTES, BTES, PTES and ATES.

(Eq.1) entails that the investment cost is higher, the lower the temperature difference across the TES. As the FLEXYNETS concept works with low temperature differences between forward and return temperatures (approx. 5-15 K), this would require any TES to be larger (i.e. more expensive) than in a conventional DH application.

However, if surplus heat is available at temperatures higher than the FLEXYNETS temperatures, this heat can be stored in a TES at the heat source temperature, so taking advantage of the larger temperature difference between the heat source temperature and the FLEXYNETS cold pipe temperature, which lowers the required storage volume and investment cost.

The economic feasibility of recovering surplus heat depends on the distance between the surplus heat source and the FLEXYNETS network, i.e. on the length of the transmission pipes which are required to connect the two. Even in the case of free surplus heat, the value of this heat must outweigh the cost of the transmission pipes for the recovery of the surplus heat to be economically viable. This puts a limit on how far away from the FLEXYNETS network the surplus heat can be feasibly recovered.

Assuming an existing network supplying annually the amount of heat Q_{tot} at a heat price p_{netw} (without recovery of surplus heat), and that surplus heat is possibly available at the heat price p_{exc} at a distance x from the network. If the annualized investment cost per unit length of the transmission pipe between the surplus heat source and the network is c_{annual}, a function of the amount of heat carried annually by the transmission pipes, the new heat price for the network p_{total} can be expressed as function of the distance x:

$$p_{total}(x) = p_{netw} \cdot (1 - s) + p_{exc} \cdot s + c_{annual}(s \cdot Q_{tot}) \cdot x \qquad \text{(Eq. 2)}$$

where s is the fraction of the network heat demand which is potentially covered by surplus heat.

The installation of a x-long transmission line is profitable only if the resulting heat price p_{total} is lower than the original heat price p_{netw}.

Based on the above-mentioned considerations, TRNSYS simulations were performed to evaluate whether and in what contexts different types of large-scale TES (possibly equipped with long transmission lines) could be beneficially used to store surplus heat in the context of the FLEXYNETS concept.

The results of the simulations showed that especially ATES (but also PTES and BTES) is a promising TES technology for the FLEXYNETS concept. Investing in a TES significantly lowered the system's annual CO_2 emissions (by up to 95 % under the assumed boundary conditions), regardless of the TES technology. Additionally, if the surplus heat was assumed to be available free of charge, also the heat supply cost could benefit from the installation of a TES.

The suitability of the ATES technology is explained by the fact that ATES have separated warm and cold wells and operate at temperatures very close to the FLEXYNETS temperatures (10 °C - 25 °C), which can save the system considerable amounts of auxiliary energy, especially for cooling.

It should be noted that ATES require very specific geological conditions. If these are not present in the specific site under investigation, PTES and BTES could be valid alternatives. TTES is typically relevant only as short-term (buffer) storage.

The benefits offered by long-term TES can play an important role during the decision-making phase of a specific FLEXYNETS project.

It should be mentioned that, although simulations were performed for different geographical locations (Rome, Stuttgart and London) with different load profiles as a consequence of this, the implementation of TES proved to have a similar effect (in terms of trends) on the heat price and CO_2 emissions, irrespective of the geographical location.

FLEXYNETS KEY RECOMMENDATIONS ON LARGE STORAGES	
BENEFITS	DRAWBACKS
• Seasonal TES make use of high shares of (potentially low temperature) excess heat possible. It may be feasible to include a transmission line (even several km) to access high/medium temperature excess heat. • Some TES types can be used also as cold storage. • Depending on heat supply in the reference case, CO_2 emissions from a central heat supply could potentially be almost eliminated and total system costs could be reduced significantly. • As with conventional DH, thermal storages can contribute in times of peak demand thus avoiding overinvestments in auxiliary supply capacity.	• Low ΔT means low energy density if supply is provided through the FLEXYNETS network. • High-temperature excess heat storage requires direct connection (i.e. transmission line length depending on location).

4 Network operation scenarios and system planning

The performance of a DHC network with decentralized heat pumps is affected by several factors. This section reviews the main aspects influencing the system design and performance, both technical and economic, highlighting the ideal conditions for the implementation of a FLEXYNETS network.

A high demand density is always a positive condition for the feasibility of a district/network application with respect to individual solutions. However, thanks to the reversibility of the network, in the case of FLEXYNETS both the heating and the cooling demand can be tackled. This is an advantage with respect to conventional DH applications. This effect is shown in Figure 5, which reports the annualised cost of the system for a few scenarios, as obtained with the pre-design Excel tool developed in FLEXYNETS and available on the project website.

All scenarios refer to the climate of Rome and assume a high-density building stock made of small multifamily houses with a space heating demand of roughly 45 kWh/(m^2 year)., i.e. corresponding to average newly built or retrofitted homes. The scenarios marked with “FL” assume a FLEXYNETS system, while in the scenarios marked with “DH” considered a conventional DH system plus individual space cooling solutions. Moreover, space cooling demand is considered to be covered in 25 %, 50 %, and 100 % of the buildings: codes 10, 11, and 12. The waste heat recovered from space cooling is used as a heat source for the network.

For the sake of a fair comparison, initially a centralized gas boiler (“heaters”) was assumed as the main heat generation system in all cases.

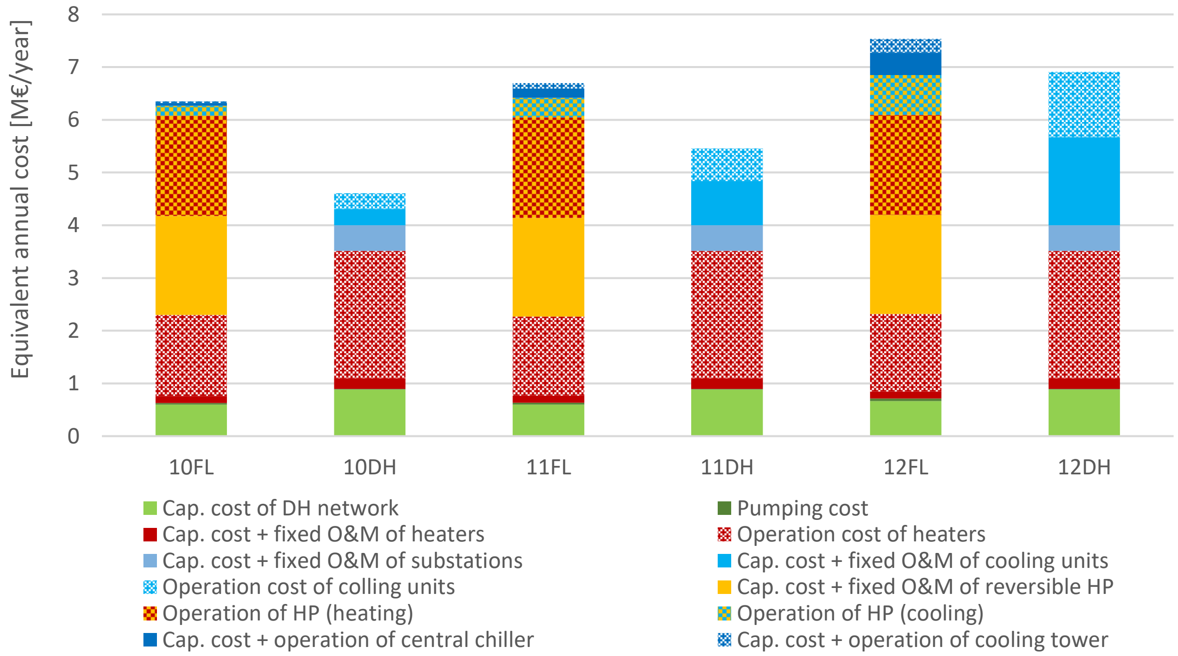

Figure 5. Equivalent annual cost items for the FLEXYNETS systems in the scenarios 10FL-12FL and for conventional DH + individual cooling in the scenarios 10DH-12DH. FL supply temperature 25 °C, DH supply temperature 80 °C. Average seasonal HP COP (heating) / EER (cooling) = 5.5 / 4.5. Natural gas price = 30 €/MWh. Waste heat provided for free to the network.

The figure shows a split of the costs related to the different elements of the system. While many items were considered in the analysis, one can see that only a few of them contribute most:

- For FLEXYNETS systems, network setup, HP substation investment costs, gas consumption and electricity consumption for HPs.
- For conventional systems, investment costs for network setup, substations, individual cooling units, gas consumption for the centralized boiler and electricity consumption to run the cooling units.

The analyses show that the reduced thermal network losses are typically not significant enough to compensate for the increased costs of the FLEXYNETS system. Hence, other benefits must come into play for the FLEXYNETS concept to be competitive. Despite not being as significant as substations and electricity costs, the network costs are an important parameter. Here the analyses indicate that cheaper pipes with less (or no) insulation would be economical, but that the overall network costs are expected to remain roughly the same compared to conventional DH.

It has to be pointed out that residential electricity prices (200 €/MWh) are used for individual cooling units, while industrial electricity prices (100 €/MWh) are used for FLEXYNETS substations, as it is assumed here that these are run by the network manager.

In general, under the abovementioned conditions and if only heating uses are accounted for, the FLEXYNETS approach is about 50 % more expensive than conventional DH networks. While lower operation costs of central heaters are clearly encountered, these are more than topped by electricity costs at customers' substations. Moreover, distribution pipeline costs are slightly lower due to cheaper materials, but the investment needed to install the same substations is much larger than in case of conventional solutions. Hence, savings in the supply chain (e.g. by enabling the use of low-temperature excess heat) is key to make the FLEXYNETS concept competitive compared to conventional DH.

One can see from the figure that increasing cooling penetration reduces the cost gap between FLEXYNETS and conventional systems. In particular, while at 25 % cooling penetration FLEXYNETS results significantly more expensive than conventional solutions (about 25 % higher), at 100 % cooling penetration the difference is quite small (about 7 % higher).

These values apply to the considered scenarios. Qualitatively however, the larger cooling loads make FLEXYNETS more economically convenient.

This shows how building and managing 5th generation networks as "low-temperature conventional networks" driven by central high temperature heat sources is not a suitable solution.

This is not only valid from an economic point of view, but also from the environmental one: the overall CO_2 emissions calculated are basically the same for all the above cases. This is due to the fact that, while FLEXYNETS exhibits efficiency improvements – in particular lower thermal losses and higher EER when space cooling is considered – the emissions[1] related to the higher electricity to run HPs compensate the reduction of emissions from gas utilisation.

From a practical perspective, reducing the temperature of a high-grade heat source (i.e. the hot water produced by the central gas boiler), to then increase the temperature level again after distribution through electricity, is not convenient both from the exergetic and from the economic perspectives.

Reducing operation costs and CO_2 emissions through cost-effective waste heat and renewable energy sources is key. More heat sources come into play due to lower temperature requirements.

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[1] Electricity CO_2 emission factor = 377 kg/MWh. Natural gas CO_2 emission factor = 250 kg/MWh.

Table 2. Carbon emission equivalents for different scenarios.

Scenario	10FL	11FL	12FL	15FL	18FL	10DH	11DH	12DH
Total CO_2eq [kton/year]	20.9	21.6	23.6	19.8	16.5	20.6	21.2	22.4

Having observed that a scenario with high space cooling demand is more convenient for the FLEXYNETS concept, it is interesting to discuss the introduction of waste heat starting from this point. Therefore, scenarios 12FL and 12DH are now compared with two additional FLEXYNETS scenarios, 15FL and 18FL: waste heat contributes 30 % and 60 % respectively to the overall heat supplied to the network. The waste heat price (paid by the network manager to the waste heat provider) here is assumed equal to 10 €/MWh.

The comparison among the scenarios is shown in Figure 6. It can be seen that with a 60 % share of waste heat, the FLEXYNETS costs are equal to the ones of the conventional system based on a centralized gas boiler and individual space cooling units. Beyond this point, FLEXYNETS becomes more economically convenient than conventional solutions.

Besides this, once waste heat is introduced, the FLEXYNETS approach gives rise to emission savings up to 30 % (see Table 2).

Several comments should be added to this. Concerning waste heat, the comparison is done for a situation where there is availability of low-temperature waste heat (in variable amount), but not of high-temperature waste heat. Consequently, this could not be directly exploited in a conventional DH network. This is a frequent case, as high-temperature waste heat is not as common as low-temperature.

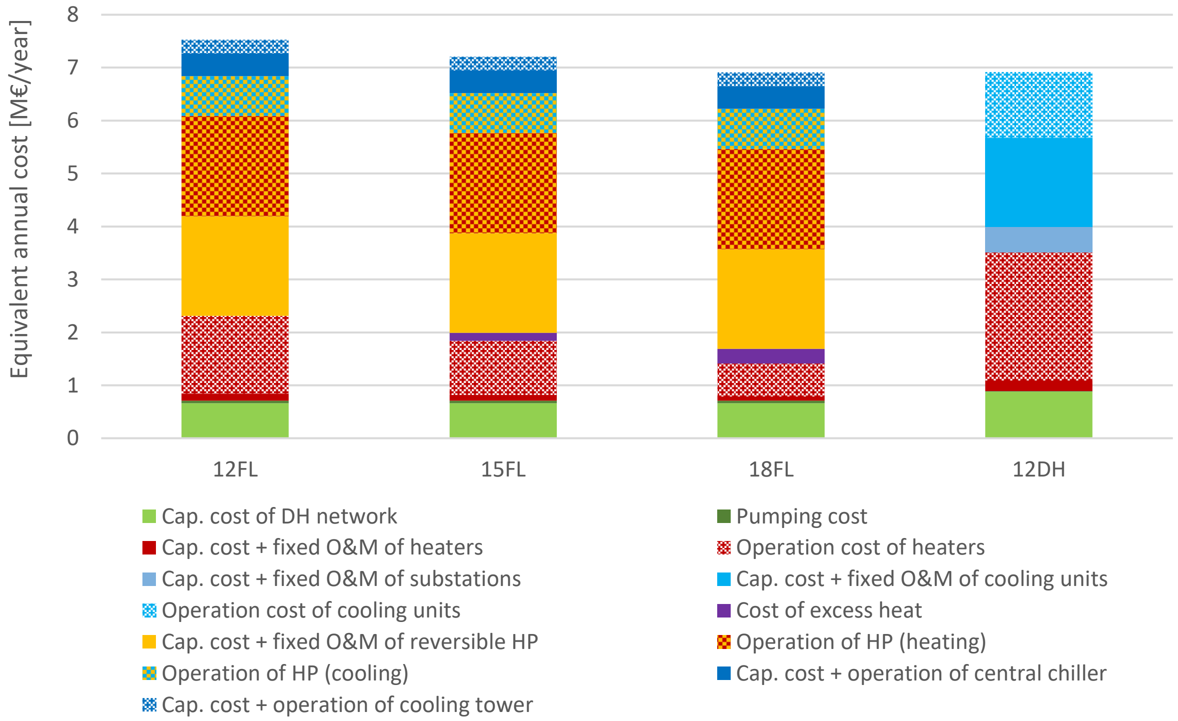

Figure 6. Equivalent annual costs share for the FLEXYNETS systems in the scenarios 12FL, 15FL, 18FL as compared to a conventional DH + individual cooling in the scenario 12DH.

Another important comment is related to supply and load profiles. The used profiles are shown in Figure 7. It can be seen that waste heat is assumed to have a rather constant profile throughout the year. This is indeed typical for low-temperature waste profiles used, e.g., in refrigeration (the relatively minor increase occurring in summer is here neglected).

On the other hand, heating and cooling obviously exhibit a strong seasonality, basically in counter-phase. This implies that not all the available waste heat can be recovered: during summer, a large amount of excess heat has to be discarded. Within the considered scenarios, it was assumed that the amount of heat rejected from space cooling that is in excess with respect to heating needs (e.g., for domestic hot water) is dissipated through a centralised cooling station, with additional costs for the network both in terms of installation and electricity use. The non-exploited waste heat was instead assumed to be dissipated by alternative systems at the producer site, without any additional cost for the network (since this waste heat is bought by the network, a "buy-when-needed" contract is assumed here). In conclusion, a full "recycling" of heat is prevented by the mismatch between heat production and consumption profiles.

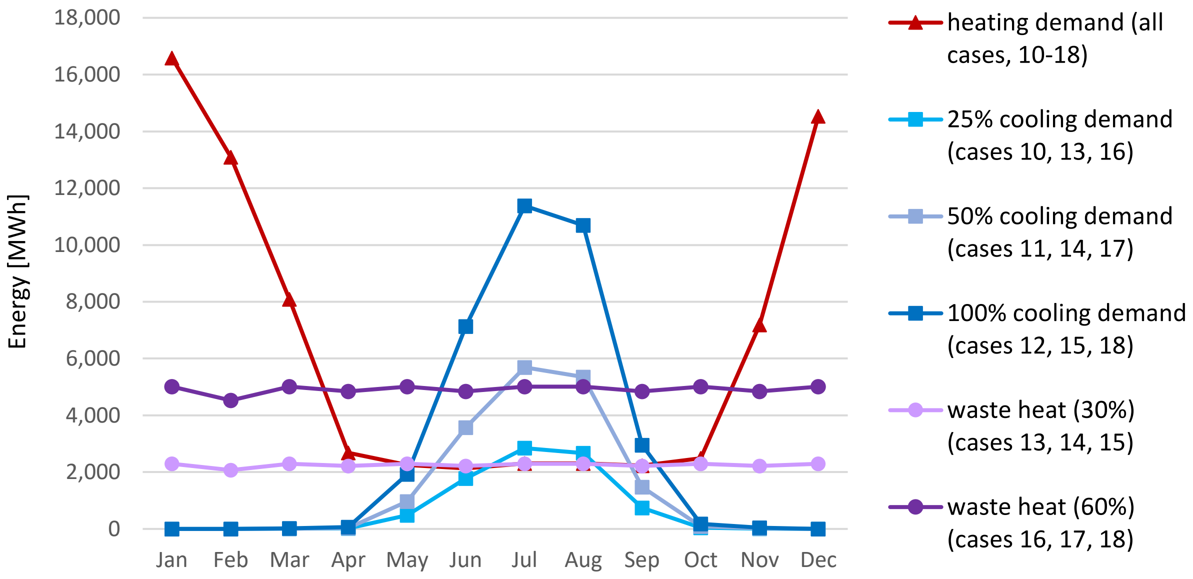

Figure 7. Profiles of space heating and cooling demands as well as waste heat availability in the considered scenarios (scenarios 10, 11, 12, 15, 18).

This consideration leads to two important factors affecting the overall system performance:

- Cost-effective heat sinks should be adopted to reject eventual excess heat during hot season.
- If the previous condition cannot be met, seasonal storage assumes high relevance in case of large amounts of waste heat introduced in the network.

With respect to the first factor, water wells and superficial water sources like rivers, lakes and sea water are suitable heat sinks that can be exploited easily from a technical point of view and with limited initial investments. The same can be used as heat sources to the network, thus rendering these solutions ideal candidates as the main supply to the network, balancing both excess heat during summer and missing energy during cold season.

When technically feasible, seasonal storages produce relevant advantages to the energy performance of the DHC network, clearly paid with relevant additional investments .

The scenario analysis carried out within the project focused on the PTES case, which features are implemented in the aforementioned pre-design Excel tool. The analysis shows that investment costs increase by 5 to 20 %, assuming waste heat stored at temperatures between 45 °C and 25 °C respectively (temperature differences of 30-10 K compared to network supply).

As a practical example, the needed storage capacity to fully recover the excess heat in summer in the FL18 scenario would be of about 37 GWh, which, for a temperature difference of 15 K, would correspond to about 2.1 million cubic meters. At a cost of about 20 €/m^3 (see previous section) and with a lifetime of 25 years for the PTES, the yearly cost would be about 2.4 M€/y. The stored energy would avoid summer cooling and winter gas consumption for about 1.5 M€/y which correspond to an increase of the investment cost of about 12.5 %.

It is to be pointed out that the considered storage volume means that the required land area is typically not available in a densely populated urban context, thus making this solution more suitably located in less dense areas e.g. small towns and villages. ATES are on the contrary more suited in highly populated cities.

Apart from economic aspects, the key advantage of seasonal storages is related to extremely high abatement of carbon emissions introduced. With current emission factors (2018) and assuming COP = 5, emissions savings of the order of 70 % would be achieved in a purely electrical system. Higher renewable shares in the future electric system would further improve this result.

All this stated, the scenarios study shows that, despite the improvement in terms of reducing investment costs thanks to waste heat recovery and cost-effective renewable energy harvest, and the major reductions of CO_2 emissions that seasonal storage allow to reach with respect to conventional DH networks, most of the overall costs are associated to the high investment needed to install substations at prosumer side and the related electricity uses.

With respect to installation costs, it is to be pointed out that here they are calculated as if the heating and cooling system would be built at prosumer side by an installer by assembling components (i.e. HP, storage tank, pumps, valves, pipes, etc.) in the conventional way. This is clearly time-inefficient and involves large work costs.

The remarkable reduction of the HP cost foreseen in the next years, economies of scale and prefabrication would reduce the investment costs e.g. by a factor 1.5 to 2. This analysis thus shows clear development drivers for the manufacturing industry.

With respect to the high electricity consumption costs, three development paths are needed:

- local renewable electricity for example produced by PV fields installed at prosumer side helps reducing running costs. The impressive cost reduction foreseen for this technology in the next few years will make electricity available to final consumers at prices far lower than grid electricity's. **Applying local PV electricity to the the prosumers substations seems to be a consistent planning strategy**.
- waste heat should be used wisely to increase the temperature of the network (thus heat pumps' COP) when high space heating demand is needed, and conversely, network temperatures should be lowered when cooling demand is present. Moreover, demand side management practices should be implemented with respect to domestic hot water production in order to profit of available thermal storage capacity.

- the “merit order effect” due to the incremental introduction in the energy market of RES electricity that have lower production overheads, is lowering the power prices. This is producing already today negative electricity prices in some countries (e.g. where high shares of wind energy are installed) during specific periods of the year. Although electricity is in general more valuable than heat, especially in future energy systems with large shares of fluctuating electricity production, an efficient use of electricity for production and storage of heat will be key. This requires that the electricity use is controlled in a smart way facilitating the balance of demand and supply: although this is not easily managed today due both to technical (i.e. high digitalisation level needed) and legislative (i.e. related to aggregating and managing the demand of a range of consumer) constrains.

The last three points are in line with new trends in the energy sector and make the FLEXYNETS concepts and other similar projects relevant as an indication of pathways for energy utility companies and policy makers.

FLEXYNETS KEY RECOMMENDATIONS FROM A SYSTEM PERSPECTIVE	
BENEFITS	DRAWBACKS
• Potential to supply district heating and district cooling with the same network. Cooling demand and/or excess heat supply is key to make the concept feasible compared to alternatives. • By applying flexible operation schemes the system can make use of (mainly) surplus electricity which is especially important in future energy systems with increasing amounts of fluctuating renewables (mainly wind and solar). • Potential for the utilisation of renewable energy and excess heat from various processes which is not (directly) useable with conventional DH, thereby minimising primary energy use and CO_2 emissions. • Resilient system by having several supply units/options thereby not relying on one sole fuel (and the associated cost dependence).	• High investment costs in substations compared to conventional DH. • High electricity costs compared to conventional DH. • Still work needed in terms of substations industrialisation and controls development, in order to reduce upfront and running costs.

5 Network control

The end of the previous section shows how important control strategies are in this kind of DHC networks' management.

Historically, Demand Response programs in the electric sector have existed to ensure grids reliability, frequency balancing and to prevent blackouts and brownouts. In recent years, Demand Response has become a more dynamic resource that can also provide price mitigation and participate in providing ancillary services to utilities and grid operators. Until now, Europe has mainly seen commercial and industrial Demand Response projects. Little has yet been done in the residential sectors.

FLEXYNETS concepts offer a massive opportunity for Demand Response services as buildings thermal loads are covered through heat pumps – therefore thermal and electric sectors are coupled – and several thermal energy prosumers can be aggregated through the network manager. Moreover, the FLEXYNETS concept is largely based on the availability and management of distributed thermal energy storages, which can be effectively used to shift thermal – therefore electric – loads through the day.

FLEXYNETS has analysed strategies for the energy efficient integration of a DHC network with the electric grid. On the one hand, **the implementation of the control strategies shall be based on**:

- **smart meters installed at each connection to the network**. They are used to meter the energy supplied and used, and to communicate in real-time energy needs and thermal storage tanks' availabilities to the central management system.
- datamining software capable of gathering large amounts of monitoring data and converting it into pre-elaborated information for the control.

On the other hand, by acting in advance with respect to the foreseen thermal energy demand in each single building, an optimised balancing can be continuously guaranteed, together with low energy production and transportation costs. To this purpose, the elaboration of **management strategies based on Model Predictive Control** and adapting to the ever-changing operation conditions (through the day, seasons and year) have shown certain potential.

Although computationally very efficient and technically effective from the load shifting perspective, the implementation of advanced predictive controls is quite complex due to the monitoring and communication infrastructure that must be set into place for their utilisation (which is far ahead the actual praxis in the DH sector). Thus, a thorough demonstration phase carried out in real networks is yet needed to move to the full-operation.

From a practical perspective, FLEXYNETS has split control strategies into two main categories:

- **Centralised control** systems managed by the heat provider
- **Local control** systems managed by customer substations.

Some analysis and hierarchical classification of control elements relevant for FLEXYNETS is reported in Table 3. The level-3 control concerns the overall, centralised management of the system and is expected to be implemented on a machine owned by the operator. Level 2 distinguishes between four fields of control: 1) the network control of the physical measurable variables head and temperature, 2) the energy flow control to solve the unit commitment problem and to manage the storage capacity in the system, 3) the user control, 4) the network interaction control.

Table 3. Hierarchical classification of control levels.

Level-3 control	Level-2 control	Level-1 control	Level-0 control
Centralised control Highest level. It can be compared with the definition and choice of operation modes in classical district heating networks.	**Network control** Ensures energy transfer within the network (distribution control)	Head/pressure control	Critical pressure driven, main pressure driven, outdoor T driven
		Temperature control	Outdoor T driven, set point tracking
		Distribution optimization	-
	Energy flow control Ensures optimized generation and delivery to the network	Utility operation (incl. unit commitment)	On/off, continuous
		Storage	Charging/ discharging
	User control Ensures energy transfer to/from customer and optimizes generation by directly manipulating consumption	Flow/temperature control substation	-
		Sensor manipulation	Shift measured value
		Set-point manipulation	Shift T set point
		Local storage (fast = tanks, slow = buildings)	Charging/ discharging
		Response to tariff variation	-
		Consumer cooperation	Shift supply set point
	Network interaction control Takes other networks (electric, gas) into account	Gas network	-
		Electricity network	-

Network control

Differential pressure control. As the hot water in DH networks is usually pumped by variable speed pumps, an open loop control for the head elevation in the supply plant is applied in many installations. However, closed loop algorithms use the measured values for the pressure difference at the critical consumer (the most distant) to adapt the head elevation. This control was implemented in FLEXYNETS simulations with good results.

Temperature control. For most heat sources, the supply temperature control in FLEXYNETS can be very similar to that of high temperature DH networks.

A peculiar case can be mentioned separately. It is indeed possible to use the return pipe of a high-temperature network as the source for a low-temperature network. This can be useful to implement a network extension for a system where the original pipes have already reached their flow rate limit. In this case, it is not possible to cover an additional demand without refurbishing the entire network unless the supply-return temperature difference is increased. The connection with a low-temperature network offers this opportunity.

Two typical connection possibilities can be considered: direct connection with mixing or indirect connection through a heat exchanger. If the temperature difference between the FLEXYNETS network and the source (the higher temperature network) is small (< 15 °C), the return line of the FLEXYNETS grid can be used to lower the temperature of the supply. When the temperature difference is higher than 15 °C, the use of a heat exchanger is instead expected to be more convenient.

Energy flow control

In simple words, the energy flow control refers to the control of the heat generating stations. For example, in the case of multiple generation units, one has to deal with the problem of which unit shall be used to cover the load at a given instant and certain extent. In other words, one has to solve the unit commitment and load dispatch problem. This is a case, where a deterministic approach should be adopted to define the priority of operation for each unit to cover the load. For example, define the renewable energy and/or waste heat sources to cover the base load and then compensate for the rest by eventually putting backup boilers into operation. Using more advanced optimization algorithms could also be involved to cut down the cost of operation.

The general structure of the energy flow control in FLEXYNETS is shown in Figure 8. The controller has basically, 3 layers (high, supervisory and low level). With input data being introduced to the controller based on the forecast and the technical parameters of the system, the controller shall be able to generate operation profiles (schedules) for different schedulable units based on an optimization algorithm and eventually try to minimize a target function. This finds place at a physical level along with other non-reschedulable substations. Depending on the weighting/cost factors within the target function, the optimization tries to e.g. minimize the operational costs or reduce CO_2 emissions.

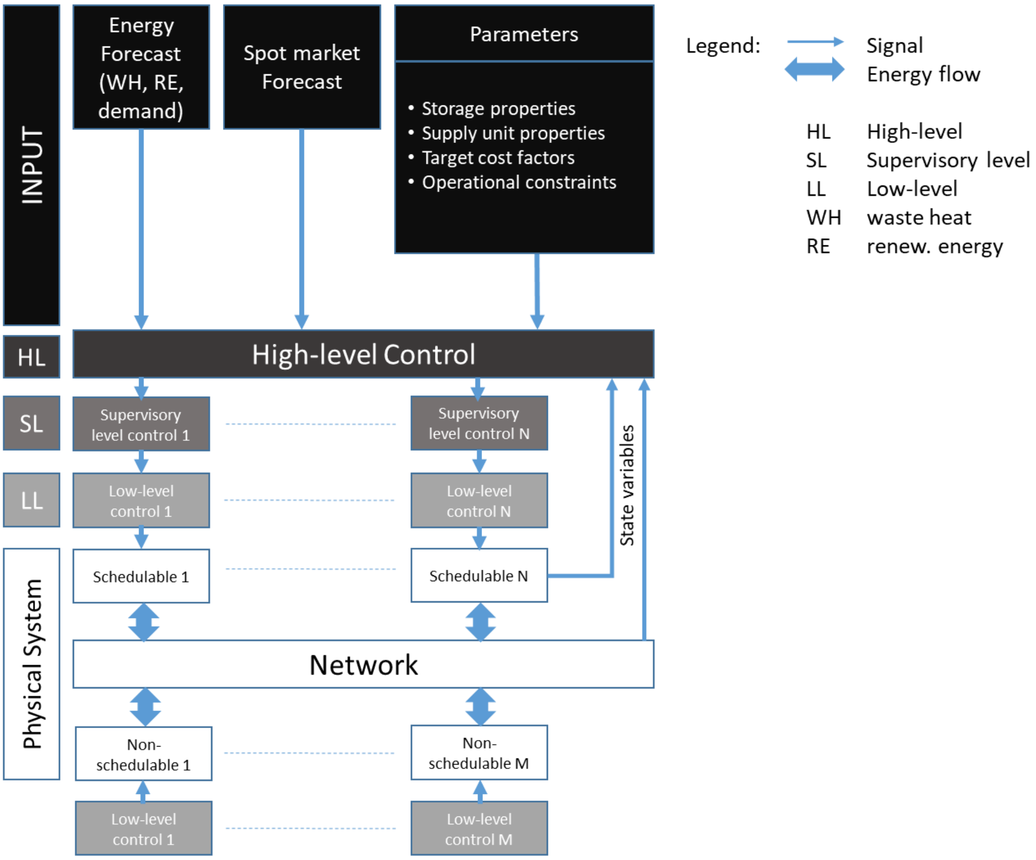

Figure 8. The general energy flow structure of the heat generating systems.

The input data provided to the optimizer are of two main types: forecast and system parameters. The heat load data of a residential building (based on e.g. weather forecast) or the waste heat available from an industrial building are calculated and provided for the upcoming time horizon. Fuel and electricity prices in this case could also be provided. Basically, load forecast models can be classified into black box and physical models. Black box models are built out of empirical data sets, where measurements can for example be used as fitting parameters in a so-called training phase. **Artificial Neural Networks (ANN) are an advanced representative of this model family.**

The high-level control uses a look-ahead planning structure. It consists of an optimization that uses the mentioned input data to schedule the operation of the (reschedulable) generation units for a time horizon of several hours, currently set to 10-12 hours in the models used for FLEXYNETS. From this schedule, the values of the first hour are used as targets within the two levels below. One hour later, the optimization restarts following a rolling horizon scheme. The supervisory-level control translates the scheduled energy flows into physical quantities (e.g. flow) whereas actuators (like pumps and valves) are regulated one level below. The supervisory-level controller checks whether the heat amounts of one hour are transferred as planned or not. The most intuitive implementation of this structure is presented in Figure 9 as a cascade control for storage charging. This controller is meant to react to deviations from the situation assumed in the planning phase, which typically arise in the real system due to the simplifications done in the optimization and, in the real world, due to the uncertainty of predictions as well as physical disturbances.

The ideal open loop control computed with the help of the high-level optimizer is expected not to be robust enough in real installations because of the mentioned model simplifications and load prediction errors. To circumvent this problem, a closed loop control is defined by feeding the so-called state variables back to the top level. For each hour, the resulting network temperature as well as the storages´ state of charge are provided. The optimization model is then ‘updated’ and relaunched for the next time interval of 12 hours.

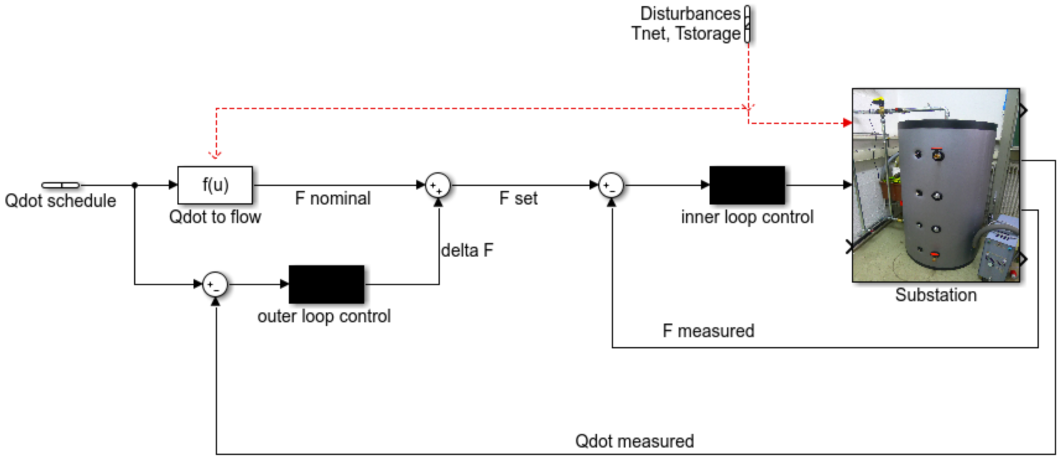

Figure 9. Cascade control for strorage discharging. The variable Qdot represents the heat flow, while F is the flow rate.

High-level-optimizer. Two different approaches have been tested to solve the optimization problem in the high-level control layer. In the first approach, scheduling is formulated as a **Mixed Integer Linear Programming (MILP) problem**, dealing with the minimization of a cost function. This objective function includes operation costs.

In the second approach, scheduling is divided into two separate tasks which are carried out in parallel: the unit commitment problem and the load dispatch. The load dispatch problem then sets the share of the produced energy among the running units. For each hour, the algorithm first solves the unit commitment problem by finding all possible combinations of committed units. Second, the share of heat supply between these units is calculated before switching to the next hour. The supply units are committed in order to cover the energy demand within a defined time horizon. Like in the first approach, the demand of the whole analysis period is considered to be known at the optimization starting time.

In the classic unit commitment problem formulation, the state vector is defined as a unique combination of committed and non-committed supply stations. In FLEXYNETS, the state vector is extended by the decision taken for each storage (either charge, discharge or keep). For each hour, the algorithm finds the potentially feasible states, takes all feasible states from the previous hour and checks if the transition to the current state (in the current hour) is possible. If the transition is possible, then the transition costs are calculated.

Production costs c_{prod} for the current hour are calculated based on demand taking into account production at previous hour (ramp-up and down constraints) as well as the level of charge in the connected storages. Dynamic programming is used to solve the unit commitment problem. It minimizes the accumulated state transition cost f at each time step taking the state transition cost $c_{trans}(s_n, s_{n-1})$ into account.

Within FLEXYNETS, the two approaches (MILP and dynamic programming) were tested for similar problems. With the used implementations, the more advanced MILP formulation showed shorter optimization times and the ability to cope with more extended systems (more than 100 prosumers). On the other hand, it always requires a linear formulation of the system dynamics. Consequently, it cannot be stated that dynamic programming (which has indeed been intensively applied to solve the unit commitment problem also in the power sector) is always the worst choice.

With the implementation of predictive strategies, a reduction in operational costs of about 10 % was observed in simulations when applying the MILP optimization to energy flow control (with respect to basic control based on simple priority rules).

Besides using an objective function based on an economic target (cost minimization), it is also possible to use an objective function based on environmental targets. To this purpose, within FLEXYNETS an objective function built with carbon emissions was also used. Optimization could be performed in the same way described above, showing the flexibility of this general control structure. It is also worth mentioning that an additional approach could consist in adding penalty costs for CO_2 emissions to the economic objective function, provided a reference value can be identified (e.g., from local regulations or from literature estimates about social costs of carbon).

User control and network interaction control

The presence of heat pumps, with their significant share of electricity consumptions, offers the possibility to implement demand side management (DSM) strategies within FLEXYNETS networks. The aim is to modify/shape the electricity demand, with benefit for electricity generation and distribution.

Demand response (DR) introduces incentive-based or price-based programs to push customers to adapt their consumption patterns to the grid convenience. A reasonable application for this strategy is peak shaving and load shifting, where the objective is to reduce the peak loads and hence the installed plant capacities and to avoid curtailments.

With the focus on the case of price-based DR, assuming Time-Of-Use (TOU) pricing (i.e. pricing based on a limited number of tariffs applied during different time periods of the day, as opposed to real-time pricing, where the electricity price can continuously change as in a stock exchange context), it is assumed that the DHC network operator sends this price signal to each user substation and that the user control reacts on the basis of this signal.

Operating the heat pump during off-peak hours, gives the obvious advantage of exploiting lower electricity prices. On the other hand, anticipating DHW production typically requires increasing the tank temperature on average (through the day). One then has the drawback of operating the HP at higher temperatures at the condenser, reducing its coefficient of performance (COP). These two competing effects must both be taken into account when evaluating the overall balance.

Neglecting additional thermal losses and effects on the network side, the consumed electricity is $E_{el} = E_{th}/COP$, where E_{th} is the thermal energy needed for DHW. One can then write the following simple inequality

$$\frac{c_{el,off-peak}}{\mathrm{COP}} < \frac{c_{el,peak}}{\mathrm{COP}_{max}},$$

where c_{el} is the unit electricity price, the subscripts “peak” and “off-peak” have obvious meaning, and COP_{max} is the maximum COP (obtained when the storage temperature is lowest). The above inequality must be satisfied in order to make the system economically convenient.

As mentioned above, the crucial point for the application of a DSM strategy is the presence of a thermal energy storage (TES) for domestic hot water preparation, which is always needed when using HPs.

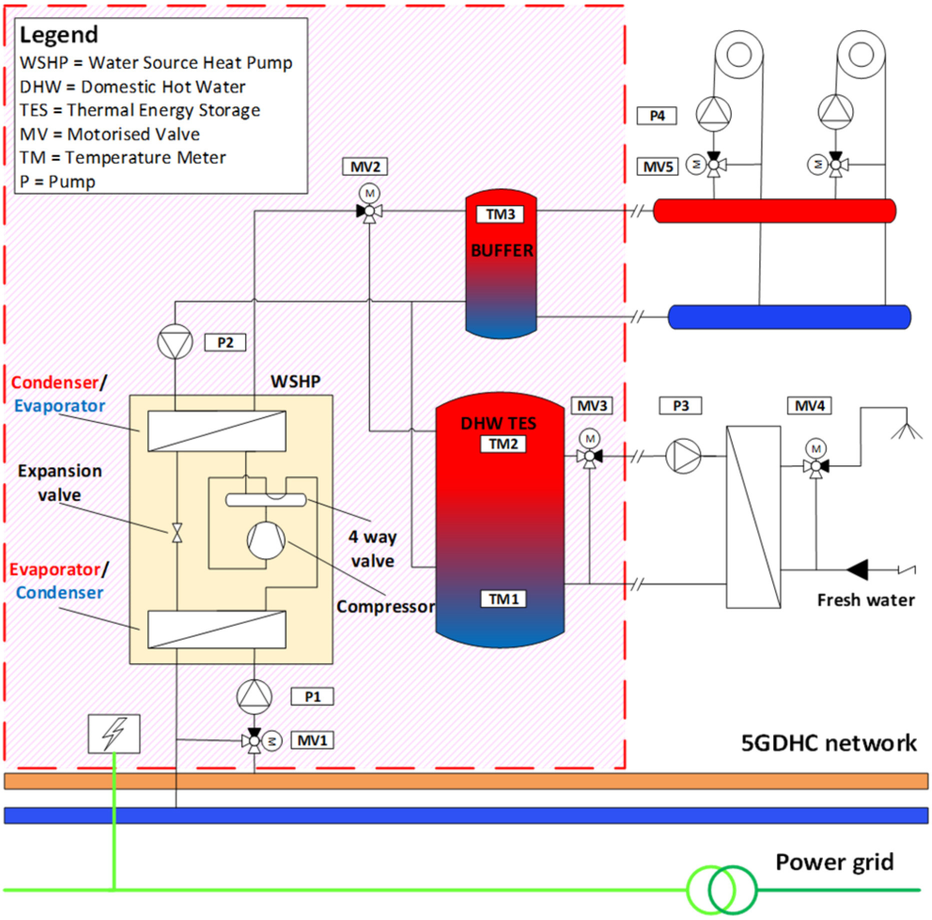

Figure 10. Plant scheme of the residential substation used for simulations on DSM strategies.

As an example, a time-of-use tariff was used, distinguishing peak hours (08:00-19:00, working days) from off-peak hours (remaining hours and weekends). The demand response signal is activated during off-peak hours, specifically during the last two hours before the start of the off-peak to pre-charge the DHW tank. Two cases are compared:

- TES set points without DR. The maximum temperature is set to 50 °C, with a bandwidth of 5 °C for the hysteresis cycle.
- TES set points with DR. The maximum temperature is set to 60 °C, with a bandwidth of 15 °C for the hysteresis cycle.

For electricity prices, an off-peak price of 0.15 EUR/kWh is assumed; two cases are considered for the peak electricity price, namely 0.17 EUR/kWh and 0.20 EUR/kWh. Similarly, two cases for the network heat price are analysed: 0.05 EUR/kWh and 0.10 EUR/kWh.

Under the above conditions, the strategy implemented does not allow to obtain significant economic savings for the user. Moreover, the additional flexibility came at the cost of a slight increase of electricity consumption. On the other hand, the electric energy shift from peak hours to off-peak hours was of the order of 20 % (with respect to the reference peak hour consumption for domestic hot water preparation), which is a sizable effect for the utility company managing the grid.

This shows that this solution offers a promising impact, but that in order to make it appealing also for users, larger and more dynamic price differences would be needed throughout the day.

FLEXYNETS KEY RECOMMENDATIONS ON CONTROL	
BENEFITS	DRAWBACKS
• Adaptation of deterministic approaches, offering more reliability for network operation and economic advantages (10 % reduction in operational costs was observed when applying MILP). • Implementation of high-level optimizers to satisfy a cost target function. • Flexibility of assigning the priority of the optimized operation. • Enhanced possibility for the implementation of DSM strategies (due to the presence of HPs), e.g. with the introduction of price-based DR. Electric energy shift from peak hours to off-peak hours in the order of 20 % with easy control strategies. • Operating the HPs during off-peak hours gives the obvious advantage of exploiting lower electricity prices.	• Predictive strategies might lack robustness in real-life installations, due to model simplifications and load prediction errors (this requires some initial tuning). • The time required to reach convergence for the optimization process can be too long when trying to include *all* possible combinations. The right degree of complexity is to be selected. • Anticipating HP operation in DSM strategies typically requires increasing the thermal energy storage temperature, during the storage change. This leads to operating the HP at higher temperatures at the condenser, reducing its COP.

6 Business models

The distributed energy generation approach elaborated within FLEXYNETS produces heat marketability and management issues: a change of paradigm is needed to move from the actual “monopolistic” generation, distribution and trading structure implemented in today’s DHC networks, to a structure where multiple actors can play the role of energy providers and where consumers can eventually profit economically from their waste heat provided to the network.

Trading strategies must stimulate on the one hand heat production from local renewable energy sources and waste heat. On the other hand, as already mentioned, they must boost energy storage practices and off-peak drawing of heat from the network. With respect to the first element, a number of sources can be considered as suitable for integration, from solar thermal fields to urban-available, low-grade waste heat provided by supermarkets, data centres and air-conditioning systems. With regard to the second element, once more, if the source of thermal energy cannot be switched on and off on demand, thermal power has to be wisely set up and managed at centralised and diffused level.

Installing thermal storage tanks at customer site (both final user and prosumer) produces contractual issues due to the additional volume needed in the technical room (compared to conventional solutions) and to the eventual demand side management. Conversely, integrating diffused thermal energy producers in the network involves a certain risk to the energy utility company as the energy delivery through the years is not fully assured: what happens if the provider moves or goes bankrupt? Contracts assuring penalties against missing energy delivered, would reduce the risk for the utility company but probably also dishearten entrepreneurs from considering the eventual integration. As the supply sources can be numerous, the risk of simultaneous disconnection is minimised and a combination of financial incentives for prosumers and utility backup capacity may be suitable.

FLEXYNETS has analysed a number of operation scenarios accounting for the integration of large and small size producers and prosumers, demonstrating the economic viability potential of the FLEXYNETS solutions from both the energy providers’ and consumers’ perspectives:

- What energy sources are worth to be integrated from the economic perspective?
- What price shall be granted to each energy source?
- What business models are reasonable from the energy utility and the customer perspectives (based on the entity bearing the investment cost)?

Figure 11 reports on the variants of business models accounted for: two main segments have been considered. The first segment accounts for *energy producers* providing thermal energy to the network either from waste heat or renewable sources, the second segment mainly looks at residential and office *prosumers* gathering thermal energy from the network for space heating and DHW preparation and providing thermal energy to the network during space cooling operation.

Concerning the first segment, the investment cost for the integration of the energy source into the network can be on the producer itself or on a third part company. In the first case, the producer has strong interest in the implementation of the measure since it experiences direct benefits, e.g. electricity savings for a data centre or super market refrigeration system. In the second case, the third party can be the energy utility managing the network, an ESCO or an aggregator acting as intermediary between the energy source and the network manager. For both combinations it is possible in principle that the thermal energy harvested is remunerated or not, and that the electricity needed to drive the production substation is paid by the producer or by the third part company.

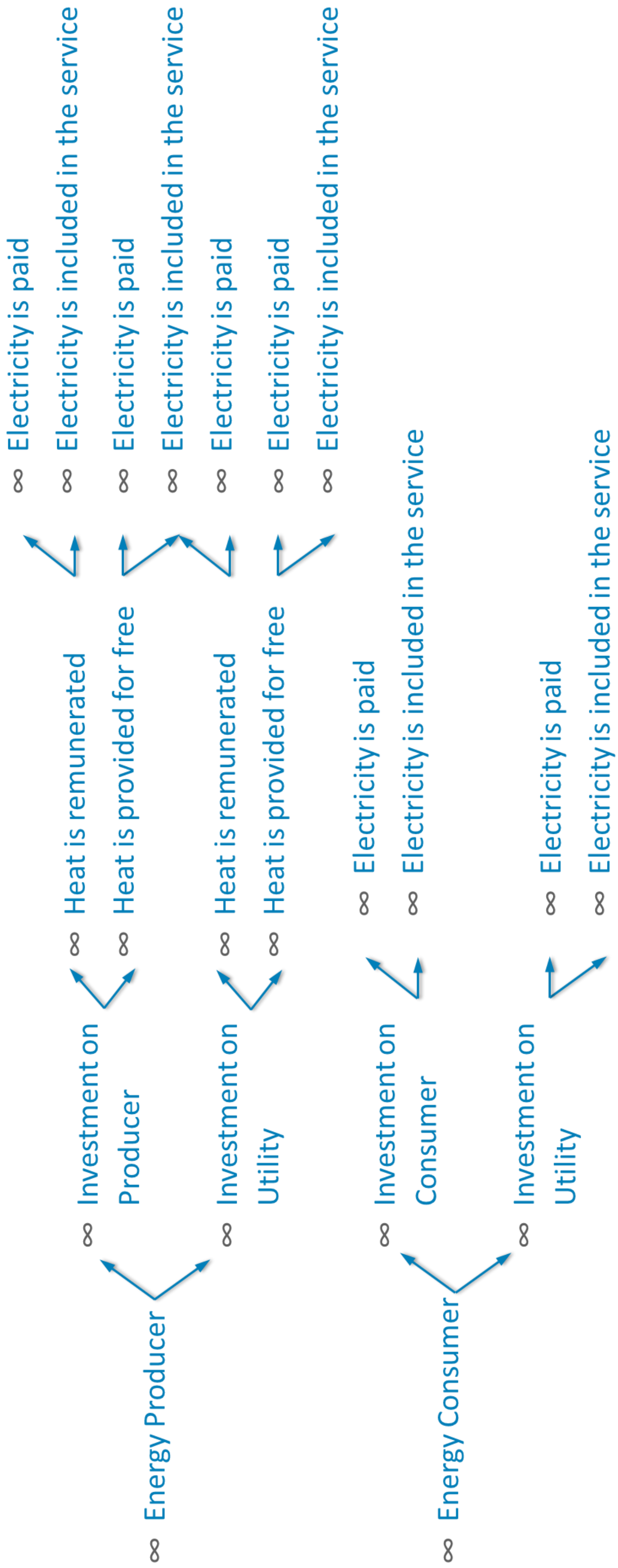

Figure 11 – Variants of business models dedicated to thermal energy Producers and Consumers

A meaningful case is represented for example by the abovementioned super market, which integration to the network is implemented by the utility company that also pays for the electricity running the substation. In this case, the data centre owner encounters a reduced energy consumption without any initial investment and minimal disruption during construction. Therefore, it might well be that the owner is inclined to render its thermal energy freely available.

As an exemplary business case, one can consider the refrigeration plant of a supermarket that is normally driven by a set of CO_2 chillers rejecting heat by means of a dry-cooler. Moreover, as the reliability of food quality and healthiness must be highest, refrigerators operate 24/7 at almost-constant conditions, which makes them seamless waste heat sources to FLEXYNETS networks. Retail managers are extremely sensitive to reducing refrigeration costs and several technologies are approaching the market in this sector. Typical thermal capacities of the refrigeration plant of an average size supermarket is in the range of 150 kW.

In this case, we consider that the design rejection temperature to the network (e.g. 25 °C) is not sufficient to be directly recovered, thus a substation including a heat pump is used to connect the supermarket to the network and to rise waste heat temperature from 25 °C to 40 °C. Due to the very limited temperature lift, the latter condition corresponds to SCOPs easily exceeding 6.

In case the investment is borne by a public utility company the return of the investment can be considered in the range of 20 years and the cost of the investment can be quite low. Table 4 reports on top the initial investment and maintenance costs of the substation installed. With an interest rate of 4% on the debt paying the investment (public investments are considered here), the annualised investment amounts to around 150,000 €, corresponding to an annuity of 8.4 % over the 20 years horizon.

Table 4 – LCoE (Levelised Cost of thermal Energy) of the waste heat recovered into the network

Investment per kW	600	€/kW
Capacity	150	kW
Maintenance	1%	-/year
Investment Cost	€ 90,000.00	€
Maintenance Cost	€ 900.00	€/year
interest rate	4%	-
Investment Horizon	20	years
Annualised Investment	€ 150,447.15	€
Annuity	8.4%	-
Operation hours 1	3000	hours/year
Operation hours 2	6000	hours/year
SCOP	6	-
Cost of electricity	100	€/MWh
Cost of heat 1 (Investment)	€ 16.72	€/MWh
Cost of heat 2 (Investment)	€ 8.36	€/MWh
Cost of heat 1 (electricity)	€ 16.67	€/MWh
Cost of heat 1 (prosumer)	€ -	€/MWh
Cost of heat 2 (prosumer)	€ -	€/MWh
Cost of heat 1 (total)	€ 33.38	€/MWh
Cost of heat 2 (total)	€ 25.02	€/MWh

The annualised cost of the waste heat recovered is proportional to the SCOP of the substation, the electricity price and the operation hours of the substation. In this simulation:

- SCOP = 6
- electricity price of 100 €/MWh typical of large consumers (i.e. the utility company)
- operation variable between 3,000 and 6,000 hours. In the first case, waste heat is recovered only during winter season, while in the second case, it is harvested through most of the year.

Consequently to these hypotheses, the cost related to recovering waste thermal energy into the network, varies between 8 and 17 €/MWh. The cost related to the electricity consumption is in this case equal to 16.7 € per MWh of thermal energy delivered to the network,

Overall, the cost of the waste heat harvested in the network ranges between 25 and 33 €/MWh. In addition to this, the investment cost related to the installation of the network pipelines ranges around 12 €/MWh (based on data reported in section 4).

The above costs do not yet account for the investment related to the installation of the Prosumer substation.

The total cost of a domestic substation with heat pump and thermal storage tank can range around 800 - 1000 €/kW of thermal capacity set up, <u>if the substation is installed on site</u>, compared to around 200 €/kW for a small 10 kW unit down to 50 €/kW for a large 500 kW substation.

Table 5 shows the economic assessment for a 20 kW thermal capacity substation installed in a typical 10 dwellings multifamily building (100 m^2 and 7000 kWh/y heating demand each).

In this business case, the utility company managing the network bears the investment with a horizon for the return of the investment of 10 years and an 8% interest rate, which is a suitable investment also for an ESCO. The same also pays for the operation costs (electricity consumption) of the substation, with a rate of 100 €/kWh. The operation hours calculated are 3500 per year, while the SCOP considered is equal to 4 (corresponding to a lift between about 15 °C and 50 °C, i.e. conservative scenario).

The cost of the thermal energy provided from the network to the house substation (left column "network side") varies between 51 and 64 €/MWh, while the cost of the electricity is 33 €/MWh (both parametrised to the MWh of thermal energy from the network to the substation). The same costs parametrised to the thermal energy provided from the substation to the building amount to about 38 to 48 €/MWh for the thermal energy and 25 €/MWh for the electric energy (right column "building side").

Summing heat harvesting, distribution and delivery to the final customers, the overall cost of heat provided from the network to the building substations can be calculated accounting for:

- Cost of energy harvest = 25 to 33 €/MWh
- Cost of energy distribution = 12 €/MWh
- Cost of energy delivery to houses = 84 to 97 €/MWh

Table 5 - LCoE of the waste heat delivered from the network. 800 €/kW investment cost for the substation in the left table. 1000 €/kW investment cost for the substation in the right table

Investment per kW	800		€/kW	1000		€/kW
Capacity	20		kW	20		kW
Maintenance	2%		-/year	2%		-/year
Investment Cost	€ 16,000.00		€	€ 20,000.00		€
Maintenance Cost	€ 320.00		€/year	€ 400.00		€/year
interest rate	8%		-	8%		-
Investment Horizon	10		years	10		years
Annualised Investment	€ 27,044.72		€	€ 33,805.90		€
Annuity	16.9%		-	16.9%		-
Operation hours	3500		hours/year	3500		hours/year
SCOP	4		-	4		-
Cost of electricity	100		€/MWh	100		€/MWh
	network side	building side		network side	building side	
Cost of heat (Investment)	€ 51.51	€ 38.64	€/MWh	€ 64.39	€ 48.29	€/MWh
Cost of heat (electricity)	€ 33.33	€ 25.00	€/MWh	€ 33.33	€ 25.00	€/MWh

Therefore, in the scenarios presented, the cost of heat distributed to the substations can vary between 121 €/MWh and 142 €/MWh. The cost of the energy “seen” by the customer (parametrised to the building heating demand) varies between 91 and 106 €/MWh.

Although higher than natural gas delivery or conventional DH energy costs, thy span in the same range. Moreover, these values include already the revenues related to the installation of the substations (8% over 10 years), the electric energy driving the substation and the maintenance services offered by the network manager (utility company, ESCO, etc.).

This solution is well representative of ESCOs or aggregators investing in the installation of the substations at customers’ homes and offering a full-service including energy delivery and systems maintenance. The ESCO or aggregator would profit from the efficient operation of the plant and of optimised purchase of electricity from the grid and DH energy from the network.

Once more, the highest costs are related to the installation and operation of the substations at the building side. Slightly better performance can be obtained if the network temperature is increased compared to this simulation; still the trends remain unchanged. On the contrary, much better performance could be obtained by working on reducing the substation initial cost.

A prefabricated substation that is standardised and manufactured in a factory to be plug-and-play mounted on site, can reduce the initial investment by 1.5 to 2 times. In this case, the cost of delivering energy to the houses would shrink to around 60 to 70 €/MWh (parametrised to the building heating demand).

Generalising the above results to the entire set of scenarios assessed, depending on the temperature levels of energy source and network, the cost of heating and cooling can largely vary (factor 2). Moreover, better performance is obtained if the utility company managing the network also provides electricity to the single substations: in this case, customers handle only one contract covering their heating and cooling uses, while the specific electricity price is lower than what the single customer can negotiate.

As limited investments are involved in connecting substations to the network, business cases can be defined where private producers/prosumers bear these costs: the utility company can hence be the owner of the main network, while substations are private owned.

Heat costs in the range of 15 to 40 €/MWh have been calculated in the most suitable cases of waste heat recovery. The same values can also be met with renewable heating through geothermal/ground water and direct solar thermal energy integration.

The largest portion of heat cost to the final customer is related to the installation of the substations connecting the network to the single buildings: overall final costs of heat between 80 and 120 €/MWh (parametrised to the building heating demand) if on site substation assembly is accounted for.

Space cooling offered as a commodity or allowing to gather rejected heat for free during summertime is suitable both in northern and southern countries. Hence, waste heat from single households is a viable solution to partially balance DHW loads and improving the economic feasibility in case the space cooling service is paid by the consumer.

FLEXYNETS KEY RECOMMENDATIONS ON BUSINESS MODELS	
BENEFITS	DRAWBACKS
• Heat recovery at very low costs or even sold as a cooling service • Utilities can consider offering multiple services (e.g. heating, cooling and electricity), thus) enlarging their business portfolio and/or enabling more flexibility in their operation strategies.	• Higher risk related to multiple producers to be connected and managed • More elaborated contracts (heating and cooling plus services)