Technology Collaboration Programme
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IEA DHC

INTERNATIONAL ENERGY AGENCY
TECHNOLOGY COLLABORATION PROGRAMME ON
DISTRICT HEATING AND COOLING

SUMMARY FOR NON-TECHNICAL AUDIENCES

FLEXIBILITY AND DISTRICT HEATING VALUE CHAIN

ADVANCED ANALYSIS & COMPATIBLE PRICING

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Citation:

Please refer to this report as:

Rämä M, Hiltunen P, Sandvall A, Vilén K, Tunzi M, Yang Q, Salenbien, R. Flexibility and district heating value chain. IEA DHC Annex XIV programme project, final report, 2026.

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1 INTRODUCTION

The global heating sector is still based mainly on fossil fuels, and mitigating the natural gas dependency within the European heating sector has become a priority. district heating (DH) with its broad selection of low-carbon heat supply options, and building-specific heat pumps are the main solutions for the heating sector along the pathway towards clean and resilient energy systems. DH systems can also help in providing flexibility for the decarbonizing power system with increasing shares of variable renewable energy (VRE). This creates a fertile environment for electrification, but also requires flexibility from the systems. In fact, a flexible implementation of DH can boost its economic performance.

The project *Flexibility and district heating value chain – advanced analysis & compatible pricing (FlexVal)*, set out to investigate the impacts of measures that increase flexibility of DH systems such as thermal energy storages (TES), demand response (DR), flexible heat supply by heat pumps (HPs), excess heat (EH) recovery or combined heat and power (CHP). Also, DH network control strategies and topology design point of views are considered. The project in general emphasises a bottom-up perspective, and the impact of improving the demand side, i.e. building heat distribution, part of planning of low-carbon DH. This is an improvement to the traditional top-down approach where the feasibility of planning decarbonisation of DH is only considered from the heat supply perspective (Figure 1**)**.

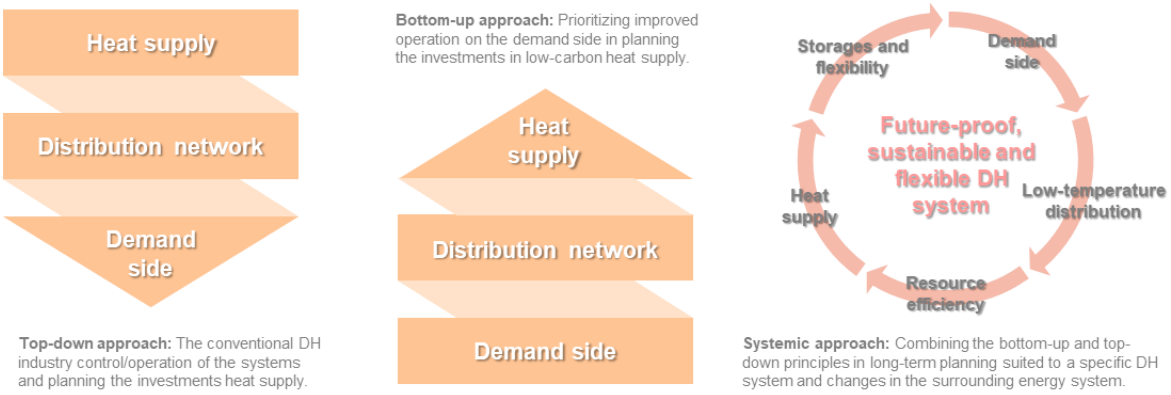


Figure 1: Summarising the top-down, bottom-up and systemic approaches describing the scope of work within the FlexVal project.

The research was carried out by four organisations, VTT Technical Research Centre of Finland in a lead role and looking into operational flexibility of DH within the Nordic energy system 2030, IVL Swedish Environmental Research Institute focusing on potential of district heating flexibility options in a long-term perspective, DTU Technical University of Denmark and the Civil Engineering Department studying future-proof design and operation of demand side components and the Flemish Institute for Technological Research VITO working on Flexibility from network design including operational aspects

2 LONG-TERM PERSPECTIVE ON THE HEAT ENERGY MIX INCLUDING FLEXIBILITY

The TIMES modelling framework [1] can be used to optimize energy systems over a mid to long-term horizon. The model is driven by exogenously defined demands for energy services and is based on a perfect-foresight, linear programming, bottom-up approach, where the objective function is the minimization of the total system cost. The energy system in question is represented by different processes that are connected by flows of commodities.

In this study, TIMES Gotland model is used to investigate the development of local district heating systems, considering the impact of the surrounding energy system. The objective function is cost minimisation. To represent the energy supply and demands in more detail in the model, the island is divided into six regions; HEM (Hemse), KLN (Klintehamn), LGN (Ljugarn), ROM (Roma), SLT (Slite) and VIS (Visby). Each region, in turn, is further divided into two or three areas (sub-regions), representing DH area (A1), next-to-DH area (A2) and rural (heat-sparse) area (A3). The model time horizon covers the period between 2020 (the base year) and 2050. Residential, commercial and industrial energy demand is considered as well as transportation demand, and fertilizer demand of the agricultural sector. A more detailed description of the model structure and input assumptions is provided in the full final report.

Investigated scenarios are Gotland 1) with (OS) or 2) without (NOS) additional offshore wind. Sensitivity cases for a both scenarios consider a capacity fee (DH_tariff), introduction of low-temperature DH (LTDH) and low-temperature DH with a bonus for improved cooling (LTDH_Tariff_Bonus).

The first very visible result is the impact of the surrounding energy system on the development of the DH systems. The overall outlook on heat supply in the OS and NOS scenarios vary greatly as visualised in Figure 2.

Other notable difference between scenarios and cases is the impact of capacity fee and introduction of low-temperature distribution. In both scenarios, the introduction of capacity fee reduces the demand for DH considerably. Low-temperature distribution clearly strengthens the future potential of DH, and also creates an incentive for electrification of the heat supply especially by HPs.

Concerning the TES, they are predominantly used significantly more in the future than during the reference year 2020. An increase of ~400-700% in discharged heat is observed in all scenarios and cases where DH still has a meaningful share in total heat supply, i.e. excluding the OS scenarios and cases with both the capacity fee and the low-temperature tariff bonus. The expected increase is pronounced especially during 2040 and 2055.

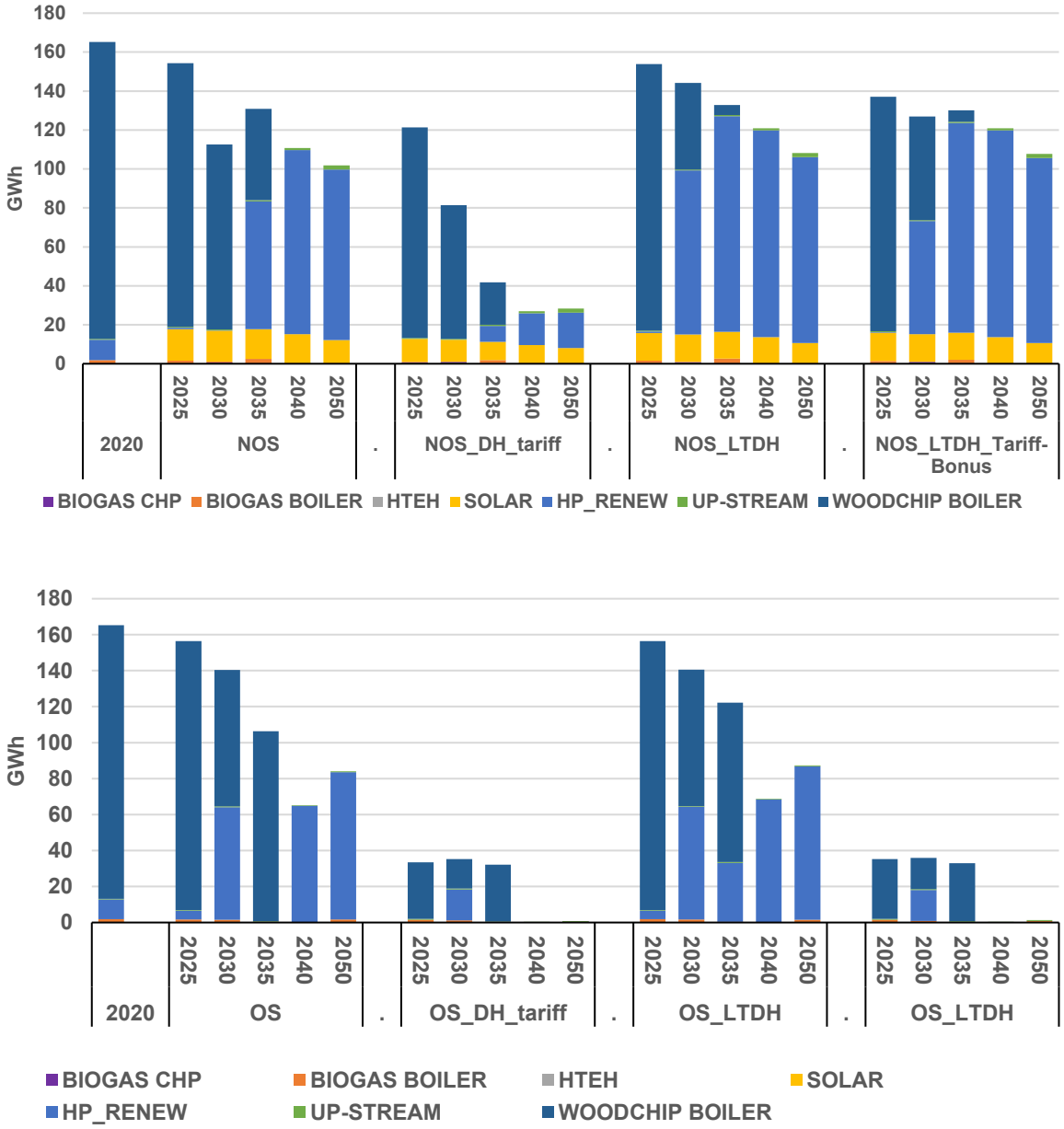
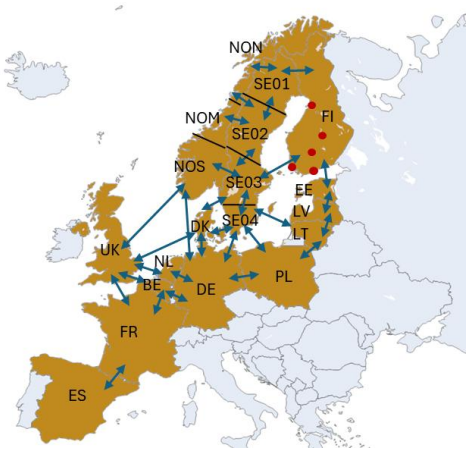


Figure 2: DH production in the NOS (top) and OS (bottom) scenarios. Abbreviations: High-temperature excess heat (HTEH), Sea water (RENEW), Heat pump (HP)

While the study presents a very specific case located in an island and that is potentially experiencing a remarkable change in local electricity production capacity, the results still highlight the importance of looking into the future developments within the surrounding energy system when evaluating decarbonization pathways for DH systems. Also, the impact of steering mechanisms is very visible providing food-for-thought on concreate measures for the DH operators.

3 OPERATIONAL FLEXIBILITY IN NORDIC DISTRICT HEATING SYSTEMS 2030

Here, the focus is on the potential of DH flexibility measures including demand response (DR), thermal energy storages (TES) and flexible heat supply, and assessing their systemic impacts on 1) Northern Europe energy system (right) and 2) specific DH system levels. The work is based on utilising the Backbone energy system modelling framework. The modelling approach considers the impact of different weather years as one of the sensitivity factors addressed. The overall aim is to provide a realistic representation of the changes the current operational environment.



As a starting point, insights from the industry were collected by targeted interviews. The discussions concluded that flexibility is becoming an essential feature of district heating systems, but no single solution stands out universally, as the most suitable measures depend on the local system and national context. While TES and DR are seen as promising and, in many cases, already implemented technologies, their wider deployment is still limited by challenges related to economic viability, scaling, regulation, and practical adaptation. The discussion also highlighted the growing importance of data, digital tools, and smart controls for improving system operation and enabling flexibility, although data access and integration remain obstacles. In addition, national market structures, taxation, and pricing models strongly influence what kinds of flexibility investments are feasible, and customer engagement is crucial, since the value and benefits of flexibility need to be clearly communicated.

Energy system level modelling (Northern Europe Backbone [2] model) showed that flexibility within DH systems supports the efficient operation of the wider energy system [3], but the benefits of additional TES and DR-based flexibility in the studied scale are modest and, more importantly, do not consider district heating operators' perspective as the modelled area is treated as if operated by a single stakeholder. This represents a need for a system-specific analysis. The overall finding on changes in DH supply presented in Figure 3 is that additional flexibility shifts biomass consumption from HOBs to CHP units and use EBs and HPs increases. The results also show the significant impact of the chosen weather year, emphasising the value of extensive model-based evaluation in e.g. feasibility assessments.

The system specific modelling task is carried out for a case system of Kuopio [4], a medium-sized city in Finland with ~125 000 inhabitants and an extensive city-wide DH system (1 TWh).

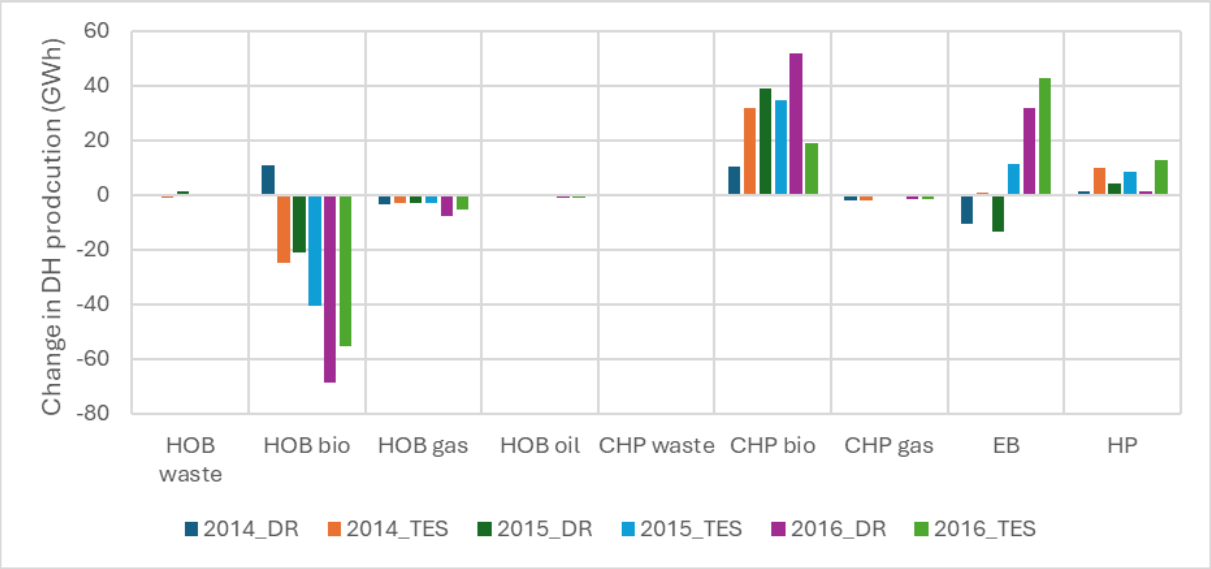


Figure 3: Changes in DH production (DR and TES vs. the reference scenario).

The scenarios were that there is 1) no TES or DR in the system (noTES), 2) TES is included (TES), 3) DR is included and 4) both DR and TES are included. Three climate and respective historical electricity price years (2022, 2023, 2024) were considered. The results show benefits of additional flexibility, but also (as in the energy system level investigation) that the operational environment can have a huge impact on the e.g. operational costs as depicted in Figure 4.

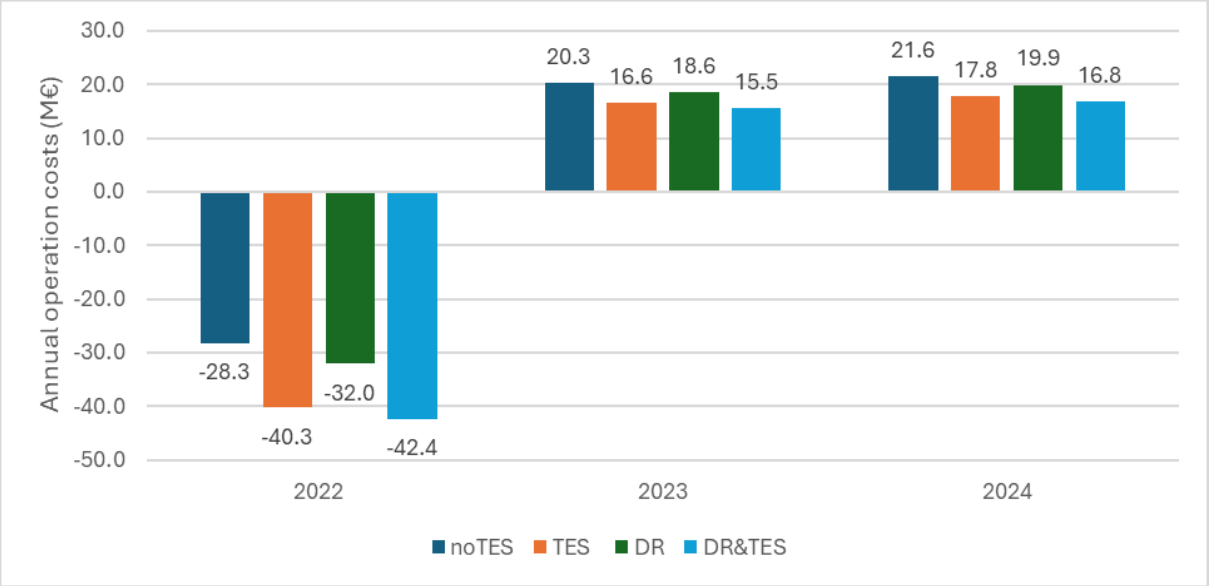


Figure 4: Total operational costs in each scenario and operational year.

As a conclusion, flexibility measures clearly improve the cost efficiency of DH systems, but the impact can be outweighed by changes in operational environment. However, ensuring a versatile heat supply portfolio (emphasising EBs, HPs and flexible CHP units) and improving flexibility by additional TES and DR capacity increases the robustness of the system.

4 FUTURE-PROOF DESIGN AND OPERATION OF BUILDINGS CONNECTED TO DISTRICT HEATING

This section aims to present the results of improving design, control and operation of space heating (SH) and domestic hot water (DHW) systems in buildings connected to DH networks. The objective was to document how low temperatures are already possible for the existing building stock and reflect on how this work relates to business models. The focus is on residential multi-apartment buildings with little or no renovation, and that have radiators as the heat distribution solution.

Viborg (Denmark) DH system and the local utility acts as a case example, and the location of the measurement activities and experimental work. Viborg has targeted low-temperature distribution as it is seen as a bottleneck for decarbonization by HP, EB and biogas boiler-based future heat supply when phasing out natural gas as the current, main heat supply option. Viborg has also introduced motivation tariffs (discount/penalty for the energy price) rewarding consumers that have efficient cooling and can cope with low supply temperatures.

One of the main results of the work is a methodology [5] for using heat cost allocator and energy meter data to improve the low-temperature operation within a building heating system. Based on this methodology, Figure 5 shows the evolution and impacts of gradually improved supply temperature curve-based control for single multi-apartment building while maintaining (more than) adequate comfort in terms of indoor temperature.

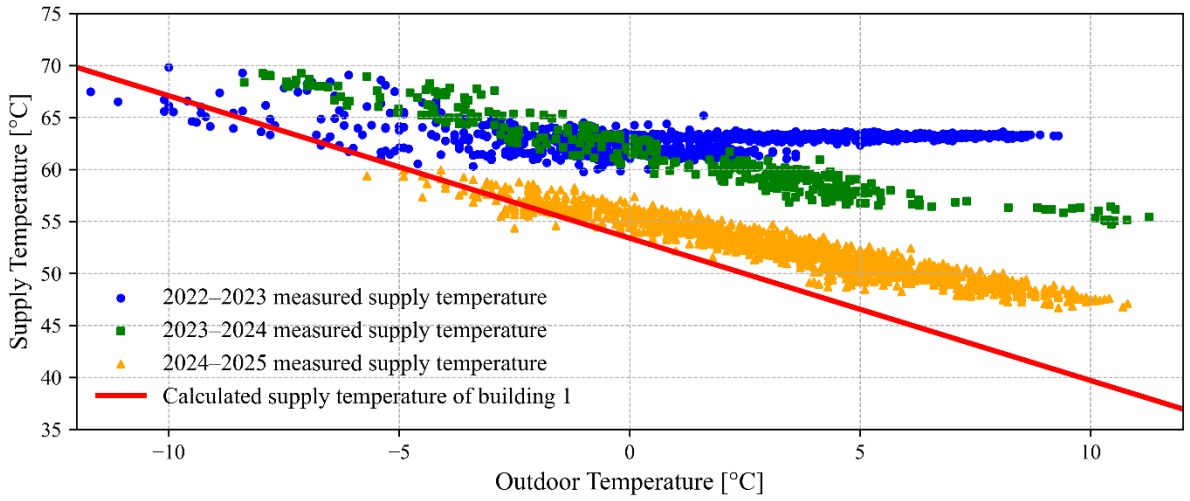


Figure 5: Calculated minimum supply temperature curve based on data from the 2021-2022 heating season compared with measured substation supply temperatures over heating seasons [6]

In addition to heat distribution systems in buildings, domestic hot water (DHW) supply remains one of the issues that can require or result in high DH temperature levels. A cascading DHW substation utilising aftercooling concept and a substation with a booster HP to offset circulation heat losses were studied. The analysis and field measurements, focusing on buildings equipped with radiator heating systems, confirmed substantial reductions in return temperature in the range of 3.0–5.8 °C and 5.4–6.7 °C for the aftercooling design under 3GDH and 4GDH conditions, respectively. For the DHW substation equipped with a booster heat pump, an average return temperature of approximately 27.9 °C was documented. While technically attractive, the additional investment costs and electricity consumption mean that this configuration should primarily target large buildings that currently act as bottlenecks for reducing network temperatures.

The economic assessment indicate that benefits of lowering operating temperatures depend on the market context. For space heating systems, motivation tariffs can effectively reward good performance and support sustained low-temperature operation. Nonetheless, the analysis also highlights clear challenges. Incentives (or penalties) are often distributed equally among tenants regardless of individual behaviour, and the link between user operation of radiators and elevated return temperatures is not always transparent to end-users. Also, building owners in rented properties may have limited interest in investing in system optimization if the bonuses are distributed to the tenants. These aspects can be clearly revealed through the current level of digitalization but require further discussion and regulatory adaptation due to their significant technical and economic impact.

The cost analysis of the DHW substation show (Figure 6) that traditional user-owned models often do not provide sufficient incentives for investment, whereas company-owned models allow district heating operators to capture system-level benefits more effectively, making the deployment of advanced DHW substations more economically viable – particularly in those critical buildings where temperature reductions create the greatest value.

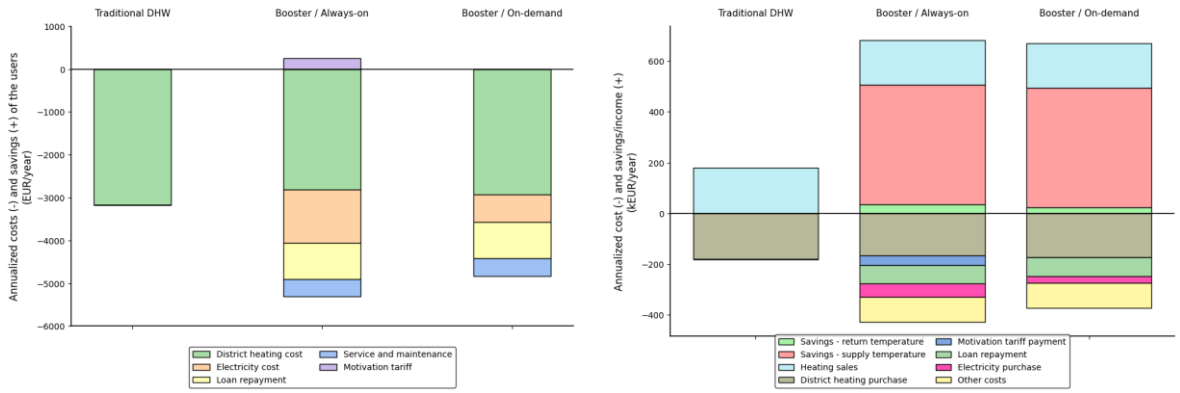


Figure 6: Comparison between annualized costs and savings/income for end-users' ownership (left) and company ownership (right) business models for booster HP substations.

5 FLEXIBILITY FROM NETWORK DESIGN INCLUDING OPERATIONAL ASPECTS

An important although often overlooked contribution to flexibility of systems is the way a network is designed. Operational aspects are crucial for the day-to-day efficiency and interactions, but the impact is also influenced by the optimality of the design. Traditional methods rely heavily on established guidelines and are primarily driven towards so-called peak based conditions: a network must guarantee energy supply under worst case conditions and is dimensioned accordingly, often including extra redundancy. This redundancy can be exploited to provide flexibility. However, this comes with a hidden surplus capital investments and operational losses, and ultimately an impact on feasibility. It is the aim of this chapter to investigate how an optimal design of networks can be influenced, when a priori smart control strategies are considered, i.e. designing the network specifically for the modus operandi.

VITO has been developing the frameworks of STORM and PathOpt for the past years. STORM represents a district energy controller [7], optimising the operation of the buildings, districts and the network by peak shaving, interaction with the electricity market and network balancing, and PathOpt, a topology design toolbox for optimisation of network topologies [8] considering specific geographic conditions. In this work [9], [10], both frameworks' principles are combined.

A fictive case in the Belgian city of Menen was created to investigate the impact of peak shaving on the optimal design of a network. Even though large-scale uptake of DH in Belgium is rare, potential is there. In the case of Menen, this holds true as a historic city centre with typical entangled street pattern and high building density has a water treatment facility representing a heat source. Area and the selected case study zone, is shown in Figure 7.

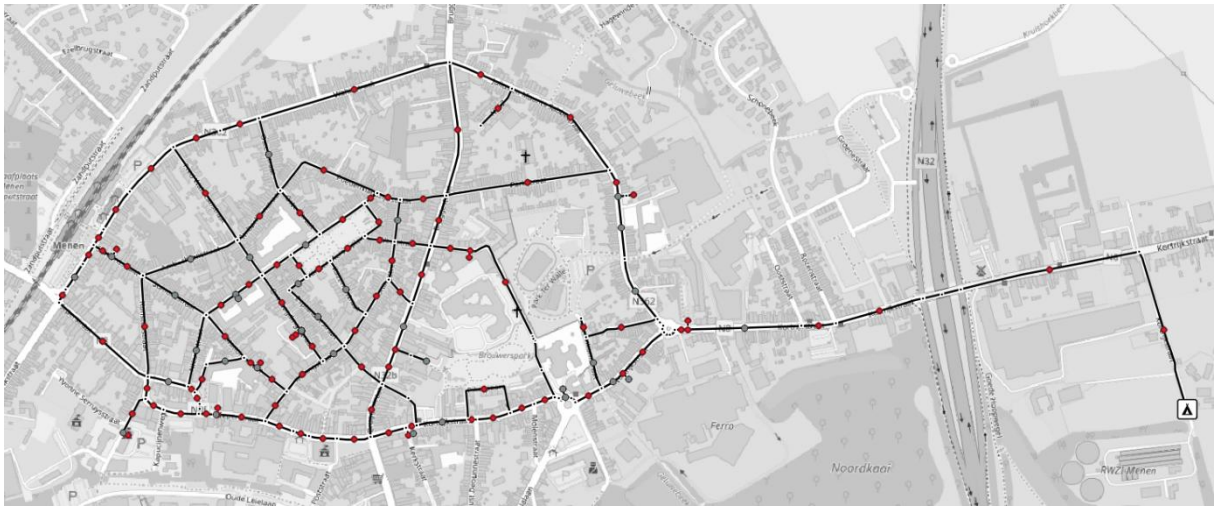


Figure 7: Case study project zone. Menen, a historical city centre near a wastewater treatment facility eastward of the city.

A total of three scenarios were studied: scenario with original demands and the corresponding network topology and sizing, scenario 1 with all consumers with a targeted 20 % peak demand reduction and finally, a scenario 2 with 5 largest consumers with a 30 % peak demand reduction. In all cases, the network topology, pipe sizing, production capacity and total cost of ownership were optimised over a long lifetime.

Figure 8 represents the network topology for scenario 2 with the 5 largest consumers identified. This optimised topology can be compared to Figure 7 and its potential pipeline routes.

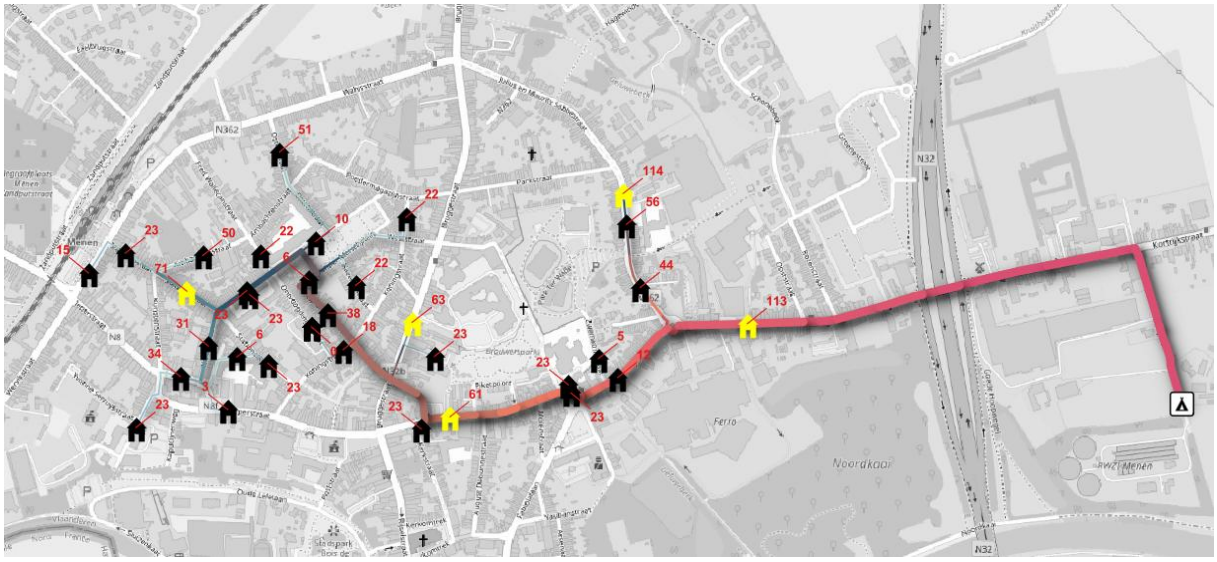


Figure 8: Optimal network topology for a scenario where the 5 largest consumers are intelligently controlled and have their peak power reduced by 30%.

The total cost of ownership (TCO) for scenarios with demand reduction were 10% and 4.6% lower than without the demand reduction. The impact on capital investments for the network was negligible.

The study showed the relevance of the network design phase for the operation of the system in order to avoid compensating for rigid designs later through operation. The main results showed that including operational flexibility assumptions in the design phase can reduce overdimensioning. When peak demand is lowered through control, required pipe diameters and peak production capacity decrease, and the total system costs can be reduced. However, the results also revealed a trade-off: although total cost of ownership and capital expenditure may decrease, the resulting cost per delivered megawatt-hour can increase, especially in low-density networks where heat losses become more dominant. Thus, designs optimised for flexibility are not automatically optimal in terms of unit heat cost.

Another key finding was that targeted flexibility (on smaller number of large consumers) is often more effective than uniform control (across all connected buildings). Overall, it can be said that flexibility from network design is real and significant, but highly context-specific.

6 JOINT ANALYSIS AND OVERALL CONCLUSIONS

Study on **long-term perspective on flexibility** showed that flexibility measures significantly influenced the long-term, cost-optimal development of district heating systems. Their effectiveness depended heavily on the broader energy system. Pricing mechanisms for DH also strongly shaped system operation and the results.

As a summary, flexibility-oriented investments and tariff reforms had been crucial for decarbonised, cost-efficient district heating, but their design needed to be tailored to local conditions currently and what is expected of the future making long-term perspective a relevant task.

Work on **Operational flexibility in Nordic DH systems** assessed district heating as a source of flexibility from both energy system and operator perspectives. District heating played a role in balancing fluctuating electricity production from renewables, although in the scale studied (capacities for TES and DR) the overall impact on an energy system level was small.

Modelling in Northern Europe showed that extra demand response or storage improved system performance and lowered costs, but benefits of additional capacity diminished e.g. in Finland, where thermal storage capacity already exists. At the operator level, demand response and storage provided savings and improved system robustness.

As a conclusion, operational flexibility has become central to DH systems given the continuing growth of wind (and solar) power and has the potential to grow in importance.

Future-proof buildings connected to DH had the focus on the building level, arguing that buildings are a vital but often overlooked source of flexibility (directly and indirectly) and efficiency in DH. Many obstacles to low-temperature DH originate from operational inefficiencies and misaligned incentives rather than technical limitations.

Analysis of large apartment buildings pointed out faults such as poorly functioning radiators and inadequate control strategies that often result in higher supply temperatures. Digital tools and metering data can address these issues without major retrofits, highlighting the strong role of digitalisation for low-cost improvements. Advanced domestic hot water substation concepts using aftercooling and booster heat pumps can offer technical solutions for retrofitting.

Economic analyses found motivation tariffs encouraged better operation but were generally insufficient as incentives for major building level investments. Alternative business models, such as utility- or company-owned substations, can enable operators to gain benefits quicker or more likely.

In summary, future-proof district heating depends on building-level measures. Digital diagnostics, improved control, and innovative substations enabled low-temperature operation

and flexibility, but broad adoption requires incentives and ownership structures that are aligned with system-level benefits.

By employing the STORM energy controller and PathOpt optimisation tool, the study on **Flexibility from network design including operational aspects** showed that peak-based design resulted in oversized pipes and higher costs. Including smart strategies like peak-shaving reduced total cost of ownership.

Case studies revealed that while optimised design did not alter network routing much, it improved cost efficiency. However, lowering peaks could increase unit energy costs, highlighting the need for tailored optimisation rather "rule-based" solutions.

As conclusions, combining advanced control with design optimisation is especially valuable for new or expanding district heating systems. Building flexibility into infrastructure early avoids rigid designs and improved long-term performance.

As an overall conclusion for the entire project, four main learnings can be drawn:

1. Building-level actions are in key role
2. Flexibility is a systemic feature of DH coupled with the energy system
3. Solutions are strongly context-specific
4. Anticipating future development is crucial

Buildings play a central role in unlocking flexibility and efficiency across district heating systems. Lower return temperatures, improved controllability, and demand response at the building level are targeted. Improved control through digitalisalisation and technical solutions such as advanced substations, are available but extensive retrofits are not always needed.

Flexibility in district heating is based on operating a system and its assets in an optimal manner. The strong increase of variable renewable energy sources (wind, solar) and the electrification of DH heat supply have resulted in a situation where storages and flexibility are becoming very attractive. This also has implications for pricing (incentives for increasing e.g. building-level flexibility), and network design and its operation, i.e. towards low temperature levels.

The effectiveness of the measures depends strongly on local context, including electricity market conditions, taxation, regulatory frameworks, and the maturity of the district heating sector. There is also a mismatch between modelled system-level benefits and operator-level incentives. As a result, policy design, regulation, and taxation are important factors in determining whether flexibility solutions are adopted at scale.

The benefits of flexibility are maximised when it is considered early in design, rather than retrofitted later. Networks designed with operational flexibility in mind avoid over-dimensioning, and buildings prepared for low-temperature operation enable long-term efficiency gains at low additional cost. However, future-proof district heating requires both strategies.

ABBREVIATIONS

Abbreviation	Meaning
4GDH	Fourth Generation District Heating
AMB	Ambient air (heat source)
ASHP	Air Source Heat Pump
CHP	Combined Heat and Power
COP	Coefficient Of Performance
CO_2	Carbon dioxide
CTES	Cavern Thermal Energy Storage
DH	District Heating
DHC	District Heating and Cooling
DHN	District Heating Network
DHW	Domestic Hot Water
DR	Demand Response
EB	Electric Boiler
EED	Energy Efficiency Directive
EH	Excess Heat
ENTSO-E	European Network of Transmission System Operators for Electricity
EPBD	Energy Performance of Buildings Directive
FGC	Flue Gas Condenser
HCA	Heat Cost Allocator
HDh	Heating Degree hours
HEX	Heat Exchanger
HOB	Heat-Only Boiler
HP	Heat Pump
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
LTDH	Low-Temperature District Heating
LFO	Light Fuel Oil

O&M	Operation and Maintenance
OPEX	Operational Expenditure
OS	Offshore wind scenario
PLR	Part-Load Ratio
PTES	Pit Thermal Energy Storage
Ref.	Reference scenario
SH	Space Heating
sTES	Seasonal Thermal Energy Storage
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage
TCO	Total Cost of Ownership
TRV	Thermostatic Radiator Valve
VOM	Variable Operation and Maintenance
VRE	Variable Renewable Energy

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