Popular summary in English

Climate change is one of the greatest challenges humanity is facing, and combating it requires a radical transformation of the energy system. This transition must combine net-zero greenhouse gas emissions with energy efficiency and sustainability. From a European perspective, it would also bring the added benefit of achieving energy independence and security of supply.

The ecological transition must reach all sectors of the energy system, including the heating and cooling sector. In Europe, this sector accounts for one third of final energy demand and it is still mainly covered by fossil fuels such as coal, oil, or natural gas. To replace these polluting sources, society has a broad range of technological alternatives. First, demand could be reduced through improved building insulation. However, beyond a certain point, demand reductions become prohibitively expensive, making it necessary to also substitute fossil-based heating and cooling with lower- or zero-emission sources. Among these alternatives are individual heat pumps, biomass, and district heating and cooling networks.

District heating and cooling systems consist of a network of pipes distributing heat and/or cold from one or more production plants to end users, mainly buildings in the residential and service sectors. Like electricity grids, these networks are characterized by their ability to integrate diverse heat and cold sources over time. They can also recycle waste heat from various sources that would otherwise be completely wasted. Another key advantage of district networks is their integration with the electricity system. Thermal storage in networks is significantly cheaper than electrical storage, and linking the two sectors via combined heat and power (CHP) plants, large-scale heat pumps, and electric boilers enables the system to capitalize on this cost advantage. In this way, surplus renewable electricity can be cost-effectively stored as heat, helping the integration of higher shares of renewable energy sources such as solar and wind.

Thanks to these benefits, several European countries have prioritized district networks, and in some, they cover more than half of heating demand in the residential and service sectors. However, their average share across the European Union is much lower, around 10%. Given the advantages of district systems, their further development could significantly aid the

ecological transition of the heating and cooling sector. Therefore, estimating their potential at the European level is crucial. As earlier studies have pointed out, the potential of district heating and cooling networks largely depends on the cost of the pipe infrastructure, which varies significantly depending on local conditions. Although detailed network costs can be estimated at the neighbourhood or city scale using hydraulic and structural models, applying these methods across broader regions, such as countries or the entire Europe, is not feasible due to the extensive data and computation required. Therefore, developing simplified models to estimate network costs at larger scales is essential.

District networks can also take different forms depending on parameters such as supply and return temperatures and the location of heat and cold production plants. These and other factors lead to a wide variety of network configurations, but they can generally be grouped into two main categories: warm or conventional networks and cold or ambient-temperature networks. In the former, heat is supplied at the temperature needed for space heating and domestic hot water. In the latter, heat is delivered at near-ambient temperatures, requiring end users to have heat pumps to raise the temperature to usable levels. Previous studies have argued that cold networks might be more cost-effective because they can use non-insulated pipes similar to those used for drinking water, thermal losses are negligible, and the same network can provide both heating and cooling through the bidirectional use of distributed heat pumps. However, very few studies have quantitatively compared the two configurations.

This thesis has addressed these two aspects of district heating and cooling systems. First, it investigated their potential at the European scale. As noted, this requires simplified models to estimate pipe network costs across large areas. One such model is that of Persson and Werner, which provides a first approximation of these costs. A key parameter in their model is the *effective width*, which indicates the required trench length in an area to be supplied by district heating. Previous studies had not determined reliable effective width values for all urban typologies, nor had they sufficiently accounted for the necessary connection length to individual buildings since most attention had focused on the distribution network.

This thesis carried out a detailed geographic analysis of two of the largest district heating systems in Denmark, which allowed the development of new equations for estimating *effective width*. These equations relate this parameter to urban density indicators such as the number of buildings and built area. The updated Persson & Werner model was then validated on several test areas and found to provide reasonably accurate estimates when used at aggregated levels and over large areas, but it showed limited accuracy at small scales.

Two further improvements were added to the model to account for the fact that not all buildings may be connected and that heat demand is expected to decline in the future. The enhanced model was applied to all the European Union to estimate the costs and thus the potential of district networks. One key finding is that these systems could cost-effectively meet one third of the Europe's residential and service sector heat demand by 2050.

The second part of this work examined the economic costs of warm and cold networks, both for heating only and for combined heating and cooling. This analysis is based on a detailed case study of Bilbao, which considered all key system components: heat/cold generation, distribution grid, and final-user connections. The results show that for heating-only systems, warm networks are more cost-effective due to the aggregation of demand (not all users require heat simultaneously), flexibility in energy sourcing, economies of scale in thermal storage, and lower electricity prices for industrial consumers, even when transport network costs are higher. These conclusions remain valid under varying economic conditions, including rising natural gas prices (e.g. due to the war in Ukraine) and high interest rates. However, when both heating and cooling are supplied, the costs of warm and cold networks are very similar. Warm systems require a parallel district cooling network, while cold networks do not require extra infrastructure, and the additional operating costs are minimal.

Finally, the case study focused on Bilbao also assessed how competitive district networks are compared to other low-carbon options like individual heat pumps and the predominant form of heat supply, natural gas. The comparison indicates that although both types of district networks are more cost-effective than individual heat pumps, they cannot outcompete natural gas, mainly due to the lack of a carbon pricing mechanism that would reflect its true social and environmental cost.