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Energy Master Planning for Resilient Public Communities—Best Practices from Denmark

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ABSTRACT

When the oil embargo of 1973 occurred, Denmark, which until that time was totally dependent on imported oil, initiated a long-term energy policy with the support of a solid majority in the Danish Parliament that encouraged and adopted resilient and cost-effective energy solutions for the country as a whole. The Electricity and Heat Supply Acts of 1980 started a program of nationwide energy planning that aimed to replace oil and to cost-effectively improve the country's energy resiliency and energy efficiency.

The planning methodology took a team approach that involved the national energy Ministry, regions, and local authorities and utilities, and that established a playing field for regulated competition between the energy infrastructures of district heating and natural gas. In other words, Danish energy infrastructure was redeveloped as if Denmark were a campus.

As a natural result of this "campus approach," 100% of all investments in the infrastructure have been financed with the most competitive financing on the world market. Also, the power system, which is owned by state and consumer cooperatives, has been transitioning from centralized to local power generation; the use of underground electrical transmission and distribution cables has created one of the world's most reliable power sectors. Thus, emergency generators are only used for critical facilities. This process has helped create an environment that fosters innovation in state-of-the-art technologies and architectural design, which contribute to the International Energy Agency's "Energy in Buildings and Communities Program Annex 73," which focuses on developing guidelines and tools that support the planning of net zero energy resilient public communities and research performed under the Environmental Security Technology Certification Program (ESTCP) project EW18-D1-5281, "Technologies Integration to Achieve Resilient, Low-Energy Military Installations."

Four case studies illustrate this transition taking the first steps toward net zero resilient energy:

- *Case Study 1: The Greater Copenhagen district heating system, which supplies heat, 95% of which is generated from sustainable biomass-fired combined heat and power (CHP) plants and from waste for energy plants to an area of 754 million ft*^{2} *(70 million m*^{2}*) heated floor area. Ninety-nine percent of the heated floor area in Copenhagen is connected to the network.*
- *Case Study 2: The municipality of Taarnby, which uses optimal zoning of district heating and natural gas and a notable project in which heat pumps, 1222 tons cooling/ 22.2 MMBtu/h heating (4.3 MW cooling/6.5 MW heat) are used to integrate district heating and cooling, chilled-water storage, wastewater, and ground-source cooling.*
- *Case Study 3: The Technical University Campus in greater Copenhagen, which has established an infrastructure for heating and cooling in symbiosis with 33 MW gas-fired combined cycle (CC) CHP, 136.49 MMBtu/h (40 MW) electric boiler, and combined heating and cooling.*
- *Case Study 4: A typical district heating system or a campus supplied by a gas-fueled CHP plant, an electric boiler, a large heat pump, large-scale solar heating, and a heat storage facility that offers demand response to the power system for efficient integration of fluctuating wind and solar energy.*

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In this paper we will briefly describe the Danish legal framework for the heating sector and how it is administrated by local communities with the aim to meet the objectives in the most cost-effective way. The four case studies illustrate how the policy has been implemented to the benefit of the society and the consumers. The tradition of cooperation, consumer empowerment, and commitment from the cities has developed the district heating and cooling infrastructure in such a way that it is almost as if Denmark is one single campus.

INTRODUCTION

The oil embargo of 1973 gave Denmark a wake-up call. At that time, Denmark was wholly dependent on imported oil, and the ensuing oil crises stimulated the country to adopt a long-term energy policy that had the solid support of the Danish Parliament, and that encouraged and adopted resilient and cost-effective energy solutions for the country. A legal framework including The Electricity Supply Act of 1976 and the Heat Supply Act of 1979 began a dramatic transformation of the Danish heating sector into a system that reduces the country's dependency on oil and that increases the efficiency, resiliency, and cost-effectiveness of energy use throughout the country. The Heat Supply Act formed the legal framework for a national heat supply planning process in all public communities in cooperation with regional and national authorities.

The advent of democratic ownership structure of public utilities acting on behalf of the consumers and consumer cooperatives allowed project owners to proactively plan, implement, and operate the energy infrastructure to the benefit of the consumers. In this ownership structure, the board is elected not by shareholders, but by the consumers directly in the cooperatives and indirectly in the "not-for-profit" public utilities, which also make profit for the consumers. This ownership structure has stimulated cooperative efforts to identify the best solutions for each local community as if it were a campus.

In the first 20 years after the oil embargo, the main priority was to replace oil with an alternative fuel, and to increase the country's energy efficiency and resilience by increasing the market share of district heating based on waste heat and coal-fueled combined heat and power (CHP) and by introducing a new Danish natural gas infrastructure. In fact, this early planning process saw a marked competition between the district heating infrastructure and the gas infrastructure such that urban areas were divided into district heating and natural gas zones. Moreover, a ban on electric heating in new buildings and a minor investment subsidy to replace stoves with central heating in old apartment buildings stimulated efficiency in buildings. Today, more than 95% of all buildings are supplied with a centralized heating system at modest supply temperatures from 140°F to 194°F (60°C to 90°C).

The last 20 years have seen a further transition in which coal has been replaced with biomass. In the years to come, the energy systems will be integrated to include electricity, gas, and district heating and cooling combined with large thermal storage capacity, which will play an important role in the move toward a carbon-neutral society based on wind energy.

This paper describes the Danish regulatory framework and presents four cases that illustrate this transition from an oil-based society to one characterized by efficient, low carbon, resilient, environmentally friendly, cost-effective, and democratically developed energy markets. The four cases include:

- the Greater Copenhagen district energy system, which is probably the largest integrated system in the world,
- a new district energy infrastructure for the public utility of Taarnby, one of 20 municipalities in the Greater Copenhagen System,
- district energy in the university campus at the Technical University of Denmark, which is interconnected with the Greater Copenhagen System, and
- a typical minor district heating system integrating wind and solar energy.

In the past 20 years, the European Union (EU) has also formed a strong international energy policy and developed an efficient package of directives to improve the energy performance of buildings, to improve energy efficiency, and to encourage the use of renewable energy; these directives were inspired by the Danish Heat Supply Act and have yielded remarkable results. That is the first time in which district heating and cooling have been planned not only to provide buildings with cost-effective renewable and low-carbon surplus energy, which otherwise is wasted, but also to promote the use of CHP generating energy from waste. Accordingly, these Danish projects, which have been implemented in the past 40 years, are selected as demonstration projects in this paper, and to showcase this methodology to the EU and the rest of the world. The Greater Copenhagen district heating system, (represented by the first three cases), is the first of eight cases, which are included in the EU report for efficient district heating and cooling. The last case is the second of the eight cases in the EU report.

THE REGULATORY FRAMEWORK FOR ENERGY MASTER PLANNING IN DENMARK

As Denmark is a member of the European community, the Danish energy legislation must be consistent with the EU directives.

Energy Legislation in the EU

EU directives set the overall legal framework for energy planning in the EU member countries. The following energy-related directives for buildings, renewable energy, and energy efficiency are of importance to the regulation of energy planning for local communities.

The Energy Performance Directive for Buildings. Member states are obligated to set standards for buildings about cost-effectiveness, good indoor climate, and near-zero consumption of fossil fuels, including considerations of opportunities to deliver renewable energy to the buildings via district heating and cooling.

The Renewable Energy Directive. This directive falls in line with the building directive in terms of the obligation to consider transfer of energy to the buildings; it states that member states are obligated to increase the share of renewable energy and to plan for district heating and cooling, including considerations of opportunities to deliver renewable energy to the buildings via district heating and cooling.

The Energy Efficiency Directive. Similarly, this directive states that member states must increase the share of CHP and plan for district heating and cooling to transfer heat from CHP plants to buildings. This will reduce the losses from thermal power generation. Moreover, the member states shall consider the establishment of new power capacity near cities that will allow them to use the surplus heat from the power generation.

Energy Legislation in Denmark

Regarding the regulation of energy planning for local communities, the following energy-related legal acts for electricity, heat supply, and district cooling are of importance.

The Electricity Supply Act of 1976 gives the Minister the power to approve all new power generation capacity. Since this Act came into force, all new power capacity has been established as CHP plants, optimally located with respect to the heat market. That includes new CHP units at existing plants near cities where there is a potential for district heating. In 1985, this included approval of a new plant at a new site and a harbor for import of coal in a suburb of Copenhagen close to the heat market.

Today, the power sector is broken into a state-owned power transmission system, consumer-owned power distribution systems, and power producers operating in the Northern European Power Market, NordPool. All power plants, except one old peak plant, are CHP plants that generate heat for sale in hot-water district heating networks. Most plants are owned and operated by the district heating companies and municipal or state-owned utilities.

The Heat Supply Act of 1979 was enacted to promote the most cost-effective heat supply for the society of Denmark, including consideration of the cost of climate gases and harmful emissions. Since its inception in 1979, the focus has also been to replace oil with natural gas from new natural gas infrastructure and to extend the existing district heating based on CHP and waste heat. Therefore, the Act specified a complex legal framework that encouraged municipalities, regions, and the Ministry to collaborate in the optimal zoning of district heating and gas networks. It also specifies the legal framework for investment in new heat production facilities for capacities above 0.85 MMBtu/h (250 kW).

Since 1990, municipalities have been solely responsible for heat supply planning. According to the current Act, they are obliged to work with heat supply planning in cooperation with local stakeholders to integrate heat supply planning into urban planning. This includes identifying opportunities for new projects and for improving the old plans (e.g., to shift from gas boilers to district heating). All of these projects will improve the cost-effectiveness of the heat supply in Denmark and thereby meet the objectives of the Heat Supply Act.

Briefly, the planning procedure after 1990 includes:

- Although the municipality is obligated to work with heat supply planning, it is no longer obligated to prepare heat plan documents; however, where there are many opportunities and stakeholders involved, the municipality may prepare its own strategic energy plan that describes the opportunities and cost-effectiveness for the society of relevant heat supply solutions. The outcome of this non-legally binding plan should be a ranking of activities and investment projects to be further elaborated by the local energy utilities that will implement the plan.
- The local energy utilities may also prepare a business plan that includes the cost-effective heat supply options for the utility. This plan could be incorporated into a municipal strategic energy plan, or it may be adopted by the municipality as its own strategy. The outcome of this plan will also be a ranking of activities and investment projects for the utility.
- In accordance with the Heat Supply Act, the energy utilities that will invest in a project must submit a project document (like a feasibility study) to the municipality.
- In principle, the municipality may encourage or order a utility to elaborate a project document (e.g., as described in a strategic energy plan), but typically the utility will submit a project document based on its own plan or without any overall plan if it is a standalone simple project.
- The project document shall describe the technical, institutional, and economic aspects of the project and prove that the project represents the most cost-effective solution for the society for heat supply compared to a realistic base case.
- The cost-benefit analysis in the document shall be based on a guideline and energy price forecast issued by the Danish Energy Agency; the document must also describe the profitability for both the utility and the consumers.
- A project document is required for the following investment projects:
  - all investments in district heating and gas networks for supply of more than one legal entity for heat supply (not process energy), and
  - investment in all heat production plants for all utilities and building owners, except for buildings with a capacity demand below 0.85 MMBtu/h (250 kW).

Project documents for campuses are therefore not required for local networks at the campus area (as the campus is one legal entity) but it is required for new heat production plants in case the capacity of the campus is above

0.85 MMBtu/h (250 kW), which it normally is. Thereby the campus is obligated to coordinate its production plan with the city in order to identify more cost-effective solutions for all local stakeholders.

The planning procedure for project documents, which are submitted to the municipality to meet the requirements of the Heat Supply Act, are:

- If the municipality finds that the project is likely to be approved, it starts the procedure. Otherwise the municipality may ask for further details or ask the utility to help the municipality to elaborate on a strategic energy plan that will give the municipality the needed background to better assess the project document.
- The municipality sends the project document to the public for a four-week hearing, and by mail directly to all local stakeholders, including utilities and landowners who may be affected by the project, in case the project proposes to install a trench on their land.
- The municipality assesses the project, including consideration of any comments from the public and local stakeholders.
- All comments are sent to the utility for its consideration and response.
- The municipality may find it necessary to call in the utility and to negotiate any opposition to the project.
- Note that the municipality's final decision is a legally binding document that gives the utility the right to a monopoly over the infrastructure including new-consumer connections to the network, but it is also an obligation to supply all consumers with heat.
- The decision may be appealed to the appeal board.

Accordingly, local community planning provides a marketplace in which the natural monopoly grids for district heating and natural gas compete to determine the most cost-effective long-term energy infrastructure and energy system design. In the first stage of the heat supply planning, both grids replaced oil boilers and electric heating. In new urban development areas, district heating networks compete against individual electric heat pumps. In the past two decades, district heating companies have submitted many project proposals to shift from gas to district heating, mainly in the most densely gas supplied districts. Most of these projects have been approved and implemented, but not without a dispute, and a few have been rejected by the municipality or the Appeal Board.

The Act also gave the municipality the option to require consumers to connect to the network and remain connected if it can be justified as cost effective for both the society and the consumers. In this context a consumer is the legal entity who owns a building or a complex of buildings, which has installed a centralized heating system supplied by an individual heat supply plant (e.g., an oil boiler), which can be replaced by a district heating consumer installation or a gas boiler. This instrument was used by many municipalities in the first stage of planning, but in recent years this instrument is rarely used. Only a few percent of all buildings are supplied by direct electric heating and stoves or heat pumps in each apartment.

The Heat Supply Act also regulates prices to protect consumers from abuse by the natural monopoly supply. For example, the energy supplier may only include necessary costs, including a reasonable interest on invested capital (which is only a few percent per year), in the price of heat. The legal framework also encourages strong financial competition, in that municipalities can guarantee loans to finance all investments in the energy infrastructure, such as district heating and natural gas distribution, that work to benefit consumers.

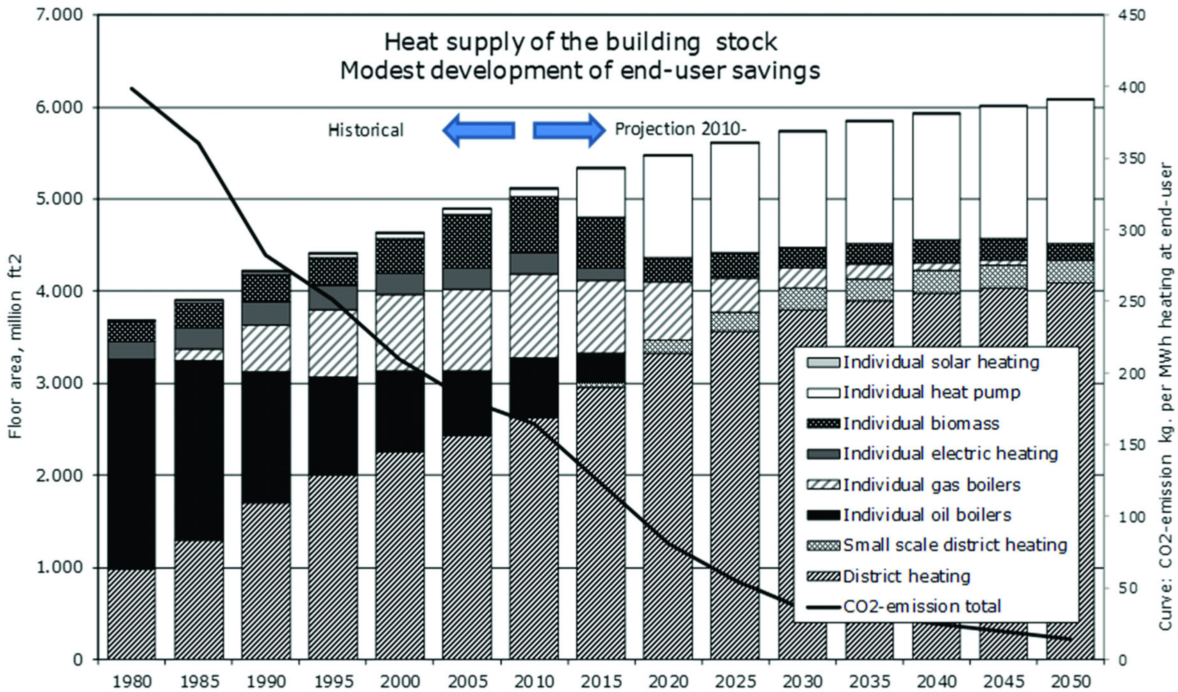
A consequence of price regulation is that municipally-owned district heating companies operate the district heating system on behalf of the consumers to minimize prices. This works hand-in-hand with the fact that most of the district heating companies are owned by the consumers as cooperatives, and that the Heat Supply Act specifies that, in case the heat supply network is put up for sale, it shall first be offered to the consumers or the municipality. In this way, the planning and ownership of local community energy systems is very similar to campus energy systems.

The District Cooling Act is not regulated in the same way as the Heat Supply Act because the supply of cooling is regarded as a commercial service to building owners. The district heating companies can establish a district cooling system, including a heat pump for combined heating and cooling, but in a separate business and without the option of loan guarantee.

The building code is also important as it regulates the HVAC installations and, for example, sets design criteria for temperatures. Currently, the return temperature for heating new buildings (to district heating network or to local production) must not exceed 104°F (40 °C) at a supply temperature of not more than 140°F (60°C). Similarly, the return and supply temperatures for the cooling system are 59°F (15°C) and 50°F (10°C), respectively. Moreover, the building code includes a ban on oil boilers to new buildings in zones that are planned for district heating or natural gas.

Figure 1 shows the infrastructure and the successful end-use equipment transformation of the heating sector from mainly oil boilers to a combination of district heating and building-level gas boilers and heat pumps.

To date, the market share of district heating has developed according to the plan although heat pumps to buildings outside the district heating and gas zones lags behind this prognosis. Recently, the large tax on electricity has been reduced significantly to encourage installation of large heat pumps for district heating and small ones for single-family houses without district heating. In the longer term, the heat planning will go for an optimal division of the market between district heating, hybrid installations (gas boiler in serial connection with a heat pump) and building-level heat pumps. The main reason for the dramatic reduction in CO_2 emissions up through 2010 is the use of CHP (hot water, not steam) and waste heat in district



Source: Heat Plan Denmark study (2010).

Figure 1 *The heat market and CO_2 emission from heating from 1980 to 2050 in Denmark.*

heating; the further reduction is mainly due to conversion from fossil fuel CHP to biomass CHP, large heat pumps, and large-scale solar water heating. In the long term, a significant part of the heat to the district heating systems and hybrid installations will be generated by wind energy. Due to having back-up from large thermal storages and gas, this integrated energy system can respond quickly to fluctuations of wind energy and utilize existing capacity in the power grid more efficiently.

CASE STUDY 1: GREATER COPENHAGEN DISTRICT HEATING SYSTEM IN 20 MUNICIPALITIES

The Electricity Supply Act and the Heat Supply Act gave the local governments the power and obligation to plan for heating in cooperation with the energy utilities and the Ministry. This initiated business plans and urban plans for cost-effective, low-carbon heating in all municipalities in Denmark, in particular the 20 municipalities in Greater Copenhagen, which had large potential for energy efficient and cost-effective projects. The Energy Agency assumed the responsibility to coordinate this work in Greater Copenhagen and formed a committee including all major stakeholders (municipalities, the region, power utilities, and the gas utility) with the objective to identify the most cost-effective solution for the region. This also initiated the formation of utilities.

The municipalities established new municipally-owned district heating utilities to supplement the existing municipal and the consumer-owned distribution utilities, and they formed two heat transmission companies to transmit heat from the existing and new power plants, and to take care of the optimal heat load dispatch.

Along with that, the Minister approved the new power capacity in eastern Denmark to be CHP plants at two sites in Greater Copenhagen, including a new power plant (Avedore) at a new site close to the heat market in the western suburbs.

Parallel to this, the municipalities had already formed a new municipally-owned company to distribute natural gas from a new natural gas infrastructure based on Danish natural gas.

In the 1980s, heat supply planning, which divided the urban areas in district heating and gas zones, was undertaken using an interactive process that included the Energy Agency, the region, and all municipalities and utilities. The municipalities prepared heat plans for district heating and for natural gas in cooperation with the utilities to be approved by the Minister, and the municipalities approved project proposals from the district heating utilities and the gas utilities.

Since 1990, the municipalities have been fully responsible for an ongoing process of planning the heat supply, including improving the heat supply whenever possible, as required by the legal framework.

In 1980, the main objectives of heat supply planning were to replace oil with alternative fuels, to improve energy resiliency, and to ensure the payback of the natural gas infrastructure. These early objectives prioritized gas supply in the northern suburbs and in industrial areas; conversion from steam to hot water was not seen as urgent, but the steam system was not further developed. After 2000, the focus shifted to the

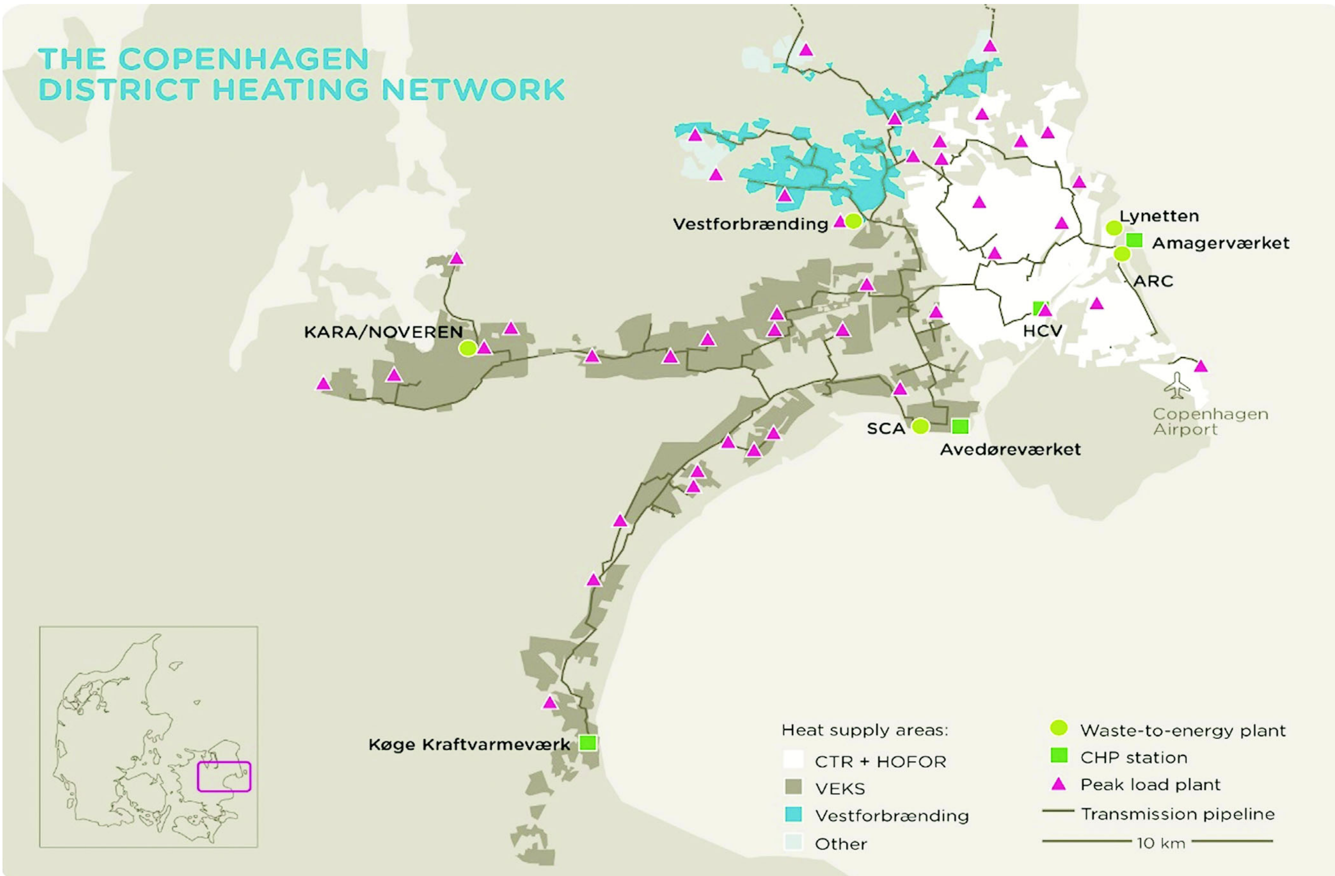


Figure 2 *The Greater Copenhagen district heating system in 2019.*

long-term objectives of promoting low-carbon energy. Therefore, planning has continued to replace large gas boilers with district heating and to shift from steam and super-heated water to low temperature hot-water district heating, 230°F (110°C) and lower.

There is no single source for all data to the system, as it is developing in time and space. Recently, the system has been interconnected with two heat transmission systems north of the main area via the transmission system of Vestforbrending (Figure 2). Thereby, surplus heat capacity from the waste incinerators can be transmitted over long distances to cover the base load in the summer.

The following list include data used to estimate the system, assuming that, in 2022, facilities that provide the hot-water supply will include the remaining old steam system in the center of Copenhagen that will have been converted to hot water, and all heat supply from CTR, VEKS, HOFOR, and Vestforbrending:

- One million people are roughly supplied from the interconnected system
- 754 million ft^2 (70 million m^2) is the total heated floor area (gross)
- Almost all buildings larger than 5382 ft^2 (500 m^2) in Greater Copenhagen
- Around 50% of garden house districts are also supplied with district heating
- 98% of all buildings in the district heating zones are connected to network.
- 32 million MMBtu (9.5 million MWh/a) are supplied to end-users (buildings)
- 5 million MMBtu (1.5 million MWh/a) are heat losses in transmission and distribution networks
- 37 million MMBtu (11 million MWh/a) are supplied to the network
- 93 mi (160 km) of heat transmission lines, up to 230°F (110°C), have a heat loss of around 1%
- 3204 mi (5500 km) heat distribution lines have a heat loss of around 15%
- Three 6.3 million gallons (3 × 24,000 m^3) heat storage tanks storing heat up to 230°F (110°C)
- Operating temperature of 149°F to 210°F (65°C to 105°C), depending on the heat load need for temperature to buildings
- Return temperature of 104°F to 140°F (40°C to 60°C), depending on the performance of the buildings
- The total heat production of 37 million MMBtu (11 million MWh) is divided among the following main sources:

- Waste incineration, mainly in CHP mode = 30%
- Biomass CHP, partly with flue gas condensation = 65%
- Peak and spare capacity from boilers = 5%
- Heat pumps, mainly in combination with cooling = <1%
- Roughly 825,000 MWh electricity is generated from waste incineration combined with heat.
- Roughly 3,080,000 MWh electricity is generated from biomass combined with heat.

The peak and spare boilers include mainly gas/oil boilers and a mix of electric boilers and wood pellet boilers. It is difficult to estimate the exact amount of fuel resources needed to generate the heat and the CO_2 emission reduction as it depends on the baseline. This is illustrated in Table 1 in a very simplified energy balance for heat and electricity comparing Greater Copenhagen district heating with two base cases without district heating and thereby also without CHP. In Base Case 1, the electricity is generated by power only plants fired with waste and biomass, and the heat is generated by building-level gas boilers. In Base Case 2, all electricity and heat are generated by gas. The calculation is based on average data for efficiencies and lower calorific value for biomass and gas.

This comparison is a good indicator for the advantage of district heating, as district heating is important for efficient, cost-effective, and the environmentally acceptable use of CHP as well as biomass and waste as a resource. Many cities

Table 1. Simplified Energy Balance for the Greater Copenhagen Hot Water District Heating System

Scenario	Units	Greater Copenhagen District Heating (DH) (Biomass + Waste + Gas)	Base Case 1 Power Only, no DH (Biomass + Waste + Gas)	Base Case 2 Power Only, no DH (Gas Only)
End Use and Losses				
Heat demand	million mmBtu/y	32,400	32,400	32,400
Heat losses in networks	million mmBtu/y	5100		
Heat Production	million mmBtu/y	37,500	32,400	32,400
Heat production				
Waste-fired CHP	million mmBtu/y	9400		
Wood-fired CHP	million mmBtu/y	26,200		
Large gas-fired boilers	million mmBtu/y	1900		
Small gas-fired boilers	million mmBtu/y		32,400	32,400
Total heat production	*million mmBtu/y*	*37,500*	*32,400*	*32,400*
Electricity Production				
Waste-fired CHP	MWh/y	825,000		
Wood-fired CHP	MWh/y	3,080,000		
Waste-fired condensing	MWh/y		1,100,000	
Wood-fired condensing	MWh/y		2,805,000	
Gas-fired condensing	MWh/y			3,905,000
Total electricity production	*MWh/y*	*3,905,000*	*3,905,000*	*3,905,000*
Resources and CO_2 Emissions				
Waste resources		Incinerated	Incinerated	Landfilled
Wood resources	GWh/y	10,780	7013	0
Gas resources	GWh/y	550	9500	18,178
Fuel consumption	*GWh/y*	*11,330*	*16,513*	*18,178*
CO_2 emission	*Mill.tons/y*	*0.1*	*1.9*	*3.7*

in which there is a heat demand and/or high building density are supplied with gas, or even oil, like in Base Case 1. The table illustrates that these cities have the opportunity develop two main projects in parallel: one main project is to develop district heating, and another main project is to shift from fossil-fuel-power-only plants far from the cities to nearby waste and biomass-fired large power plants, from which low-temperature heat can be extracted (power extraction plants that can operate in back-pressure and in condensing mode, as well as all combinations of heat and power) and offer cheap heat as a base load to a growing heat market.

The result of the comparison can be summarized roughly as follows. The waste resource from the whole region (almost twice the district heating zone) is used for energy generation in the project and in Base Case 1, whereas it is dumped at landfills in Base Case 2. Going from Base Case 2 to Base Case 1 will reduce the CO_2 emissions from 3.7 to 1.9 million ton per year, but with very little efficiency improvements as the saved gas energy is replaced by almost the same biomass energy. Going from Base Case 1 further on to the project almost eliminates the CO_2 emission, as well as the local pollution from heat generation. Moreover, 31 million MMBtu (9.0 million MWh) gas is replaced by only 13 million MMBtu (3.8 million MWh) biomass. Thus, the annual fuel saving is 18 million MMBtu (5.2 million MWh), taking into account all losses in district heating network and in cooling towers at the power-only plants.

To complete the energy balance in this comparison, we could summarize all the thermal losses in the district heating project and the two base cases roughly as follows:

- The project: 5 million MMBtu (1.5 million MWh) due to heat losses in the hot-water network
- Base Case 1: 23 million MMBtu (6.7 million MWh) due to losses in cooling towers
- Base Case 2: 29 million MMBtu (8.4 million MWh) due to losses in cooling towers and landfills

Thus, we can conclude that the rather small heat losses in the hot-water district heating system are not a problem in case the heat is generated by energy sources, which otherwise would be wasted in cooling towers or in landfills.

In the coming decades, it is expected that the market share of heat pumps and electric boilers will increase significantly as wind will be a dominating energy source for Denmark and as biomass is expected to be a limited resource in the long run. The first heat pumps are already being installed in combination with district cooling and use of surplus heat from data centers and industries, for example. Also, electric boilers are being installed for three reasons: to provide peak capacity for heating, low price electricity in case of surplus of wind energy, and regulation services to the power grid. By 2030, it is anticipated that the two oldest of the biomass (wood-pellet-fired) CHP units will be at end of useful life, and it is more likely that a total capacity of at least 680 MMBtu/h (200 MW) heat pumps and 1700 MMBtu/h (500 MW) electric boilers plus more heat storage capacity will be installed as an alternative to reinvestment in these old CHP plants. Moreover, the plant infrastructure can be used to serve large heat pumps, electric boilers and plants for generating renewable fuels. In regards to the newest wood-chip-fired fluidized bed CHP plant with flue gas condensation, it is expected that it will be in operation for at least 35 years.

In Greater Copenhagen, the district cooling market has only developed in the past 10 years due to legal constraints, but currently it is growing rapidly in the city center area and in combination with new urban developments. So far, most of the production has been based on compressor chillers and seawater cooling. In several new small district cooling systems, the production is based on combined heating and cooling, and it is foreseen that the market for combined production of heating and cooling in combination with ground-source cooling and other heat sources will increase dramatically and boost the overall development of large heat pumps as previously mentioned.

Due to the regulatory framework, all projects forming the system have been cost-effective for the society, the utilities, and the heat consumers. The final end-user price is significantly lower than the base case for all consumers according to statistics from the Danish District Heating Association.

CASE STUDY 2: DISTRICT ENERGY IN THE MUNICIPALITY OF TAARNBY, CENTRAL MUNICIPALITY IN GREATER COPENHAGEN

Taarnby Municipality is the owner of Taarnby Forsyning public, which in 1980 only owned and operated services for wastewater and water in the municipality. In 1980, the municipality was supplied entirely by oil boilers and was one of the 20 municipalities in Greater Copenhagen, which could be part of the integrated system. Therefore, Taarnby Municipality took part in the planning process, which proved that it would be cost-effective to supply the larger buildings in the municipality with district heating and the rest with natural gas.

District Heating in Taarnby

To implement the Heat Supply Act, to be project owner, and to the benefit of the heat consumers in the municipality, in 1982, the Taarnby Public Utility formed a business unit for district heating and joined the CTR company as co-owner. The Taarnby Municipality could thereby develop a new district heating system connected to the CTR heat transmission system in the northeastern end of the municipality.

The border between the Taarnby Municipality and the neighboring municipalities and the market share of the district heating and the established district heating zones and networks are in the planning stage (Figure 3), which includes:

- large buildings, supplied with district heating in 1985,
- medium-sized buildings, planning to shift from gas to district heating in 2020-2030, and

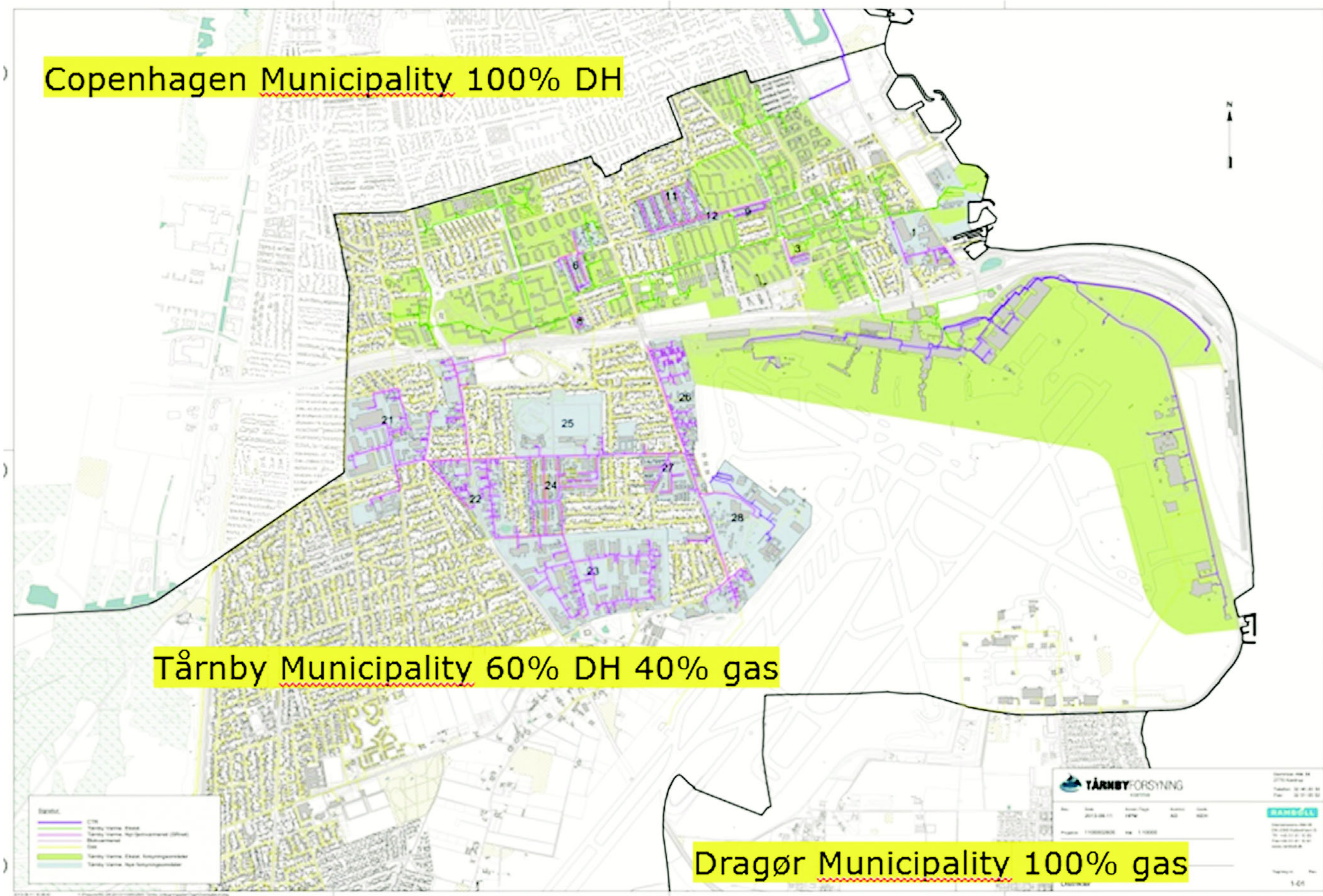


Figure 3 *Map of Taarnby Municipality, including zones of district heating and district heating pipes.*

- single-family houses, with an option to shift from gas boilers to district heating to small heat pumps or to hybrid solutions of heat pumps and gas boilers in 2030 to 2050.

The data listed in Table 2 summarize the main results of the heat supply planning, specifically, the heat demand in the zones and the necessary investments in the district heating network required for the system to reach the consumers. The investment in district heating network divided by the total annual heat sale appeared to be a very good "investment indicator" of the cost-effectiveness of district heating compared to gas boilers; this figure was used as the first screening tool by the Energy Agency and the municipality in the planning in all 20 municipalities to compare districts and rank them. The operating and maintenance costs of district heating and building-level boilers were relatively small and not as important for the optimal zoning as the investment in the network. The data listed in Table 2 show that the calculated heat losses could also be used as an indicator. They also show how the connection of the airport campus improves the indicator and how the planned extension can be ranked. District heating is significantly more competitive than individual heat pumps for the planned apartment buildings in the new urban developments. The indicator will be higher for the remaining districts with small houses, which are not included, and the planning of the long-term zero carbon heat supply will have to wait until overall conditions change over the next 10 to 20 years. The electric energy consumption for circulating the water in the district heating network is not used as a parameter, as it is insignificant, but it is included as a minor part of the operation and maintenance cost in the economic assessment.

The technical data for the district heating can be summarized as follows:

- 612,000 MMBtu (180,000 MWh) maximal design heat demand in a normal year
- 3000 max load hours measured and estimated based on actual consumption and weather data
- 205 MMBtu/h (60 MW) maximal design capacity to the network
- 205 MMBtu/h (60 MW) capacity of heat exchanger from CTR
- 205 MMBtu/h (60 MW) capacity of oil-fired backup boiler at the airport

Table 2. Investment Indicators from the Heat Supply Planning

Development of Taarnby DH Districts	Annual Heat Demand, MMBtu	Network Investment, 1000 US $	Network Investment/Demand, US $/MMBtu	Heat Loss, %	Alternative Individual
First network in 1985	395,000	40,200	102	6.8%	Gas boiler
Campus in long-term development	188,000	11,800	63	5.6%	Oil boiler
Total average including campus	583,000	52,000	89	6.3%	
First expansion 2020	105,000	6800	64	5.0%	Gas boiler
New urban development	19,000	2800	147	10.4%	Heat pump
Second expansion 2025	38,000	6500	171	11.0%	Gas boiler
Total average without small houses	745,000	68,100	91	6.6%	

- 22.2 MMBtu/h (6.5 MW) planned heat capacity from new heat pump for combined heating and cooling
- 132 consumers, including the Copenhagen Airport campus
- 612,000 MMBtu (180,000 MWh) annual heat production
  - 580,000 MMBtu (170,000 MWh) annual heat sale
  - 34,000 MMBtu (10,000 MWh) annual measured heat loss in the city network, equal to 5.3%
  - 44,000 MMBtu (13,000 MWh) losses including airport network measured, equal to 7%
  - 31,000 MMBtu (9000 MWh) annual heat loss for new pipes, calculated
  - 41,000 MMBtu (12,000 MWh) annual heat loss including the network of the airport for new pipes, calculated
- 17.4 mi (28 km) DH network, DN20-DN500 + 6.2 miles (10 km) airport campus network
- Normal supply temperature 167°F to 205°F (75°C to 95°C)
- Normal return temperature 122°F (50°C)
- Preinsulated pipes from 1985 with surveillance system
- Remaining lifetime of the network: approximately 50 years or more.
- Heat exchanger between district heating and campus is removed
- Heat exchangers between the integrated network and all radiator systems in buildings

The data show how the system has total backup capacity and how the measured heat losses of the old network is only slightly larger than the estimated heat losses of new pipes.

The cost of heat for the consumers is lower than the cost of individual heating with gas boilers or heat pumps.

The project is a good model for modern district heating, and it has been in successful and efficient operation for more than 30 years. It has also proven that it is a good idea for city district heating companies and campus owners to cooperate to find the best common solutions. The project has demonstrated that municipally-owned utilities operating vital infrastructure in their cities can identify the cost-effective energy solutions and implement them to the benefit of consumers, in fact acting as if the whole municipality were one campus. Therefore, the case is a good story for campus-owners.

District Cooling in Taarnby

By maintaining close contact with the urban development department, Taarnby Public Utility was able to screen the potential for district cooling and prepare a feasibility study for district cooling in a new urban development area between a new metro station and the sea north of the airport, benefiting from the synergies within the utility.

The study showed that it was profitable in the long-term to establish traditional district cooling based on the same technology that would otherwise be used in individual buildings, and that the profitability would be further improved if heat pumps were installed and chilled-water storage were used to establish a symbiosis between heating, cooling, and electricity. Moreover, it turned out to be very profitable to use the excess capacity of the heat pump to increase the heat production based on ambient heat in the treated wastewater, located just north of the new urban development area, thereby including wastewater in the symbiosis. Potential ground-source cooling might even improve the system for two reasons. The cost of capacity of the ground-source cooling is lower than the cost of chiller capacity, and the ground-source cooling including a warm and a cold well (aquifer thermal energy storage [ATES]), will reduce the necessary heat generation from the heat pump in summer (while heat prices are low) and increase the efficient heat generation in winter (while the temperature of the ground water is larger than the temperature of the wastewater).

The heat pump will be connected to the treated wastewater to use available capacity to generate heat for use in the district heating network in an optimal way, considering electricity prices and heat production prices in the Greater Copenhagen district heating system.

Figure 4 *The district cooling project stage 1.*

To implement the project, Taarnby Public Utility established a new business unit for district cooling and entered agreements with the first largest consumers. The project for the heat pump was approved in accordance with the Heat Supply Act and the bank accepted the district cooling part for investment such that the business unit could start the project implementation in 2019 and start operation in 2020.

Figure 4 shows the first stage of the new urban development area to be supplied with district cooling. The wastewater treatment plant and the planned district cooling plant with chilled-water storage (green roof) are shown in the upper left corner. Of the three existing buildings in the district only the Blue Planet aquarium had a cooling demand. This building had installed a chiller with connection to seawater, but it is expected that it will be included in the project due to problems with their seawater cooling. The open area left of the new buildings is reserved for the second stage of the urban development. The first buildings in the second stage, further to the west, will be connected already in 2020.

The district cooling plant for combined heating and cooling will be situated at the wastewater treatment plant, where there is just enough available space. As Figure 4 shows, a roof covers the water basin to keep the odor of untreated wastewater from affecting the neighborhood.

Table 3 lists the main characteristics of stages 1 and 2 of the project.

In many ways, this project is a front-runner. It integrates district heating, district cooling, electricity, ground-source cooling, a chilled-water tank, and heat from the treated wastewater, and it improves the efficiency of heat generation in the integrated district heating system in Greater Copenhagen, which already has a zero-carbon base load generation. Moreover, it was the first project in the new business unit in which the utility was able to eliminate several bottlenecks by establishing a system of parallel processing.

Monitoring this case study will undoubtedly yield important lessons learned that may be passed to other district heating and cooling companies. In fact, Taarnby Forsyning has partnered with the Danish District Heating Association in a research and development (R&D) project to transfer lessons learned from heat pump projects to the entire sector.

The project has also demonstrated that a municipally-owned utility operating a vital infrastructure in the municipality can identify cost-effective energy solutions in symbiosis with relevant sectors, and can implement those solutions in a way that improves both heating and cooling for all consumers by treating the whole municipality as one campus. By extension, this case study serves as an effective model for campus owners as well.

CASE STUDY 3: DISTRICT ENERGY AT THE TECHNICAL UNIVERSITY OF DENMARK IN LYNGBY-TAARBÆK MUNICIPALITY, NORTHERN SUBURB OF GREATER COPENHAGEN

In the 1960s, the Technical University of Denmark (DTU) moved to a new campus site, where it established a utility infrastructure. All buildings were connected by walkable tunnels, which included vital parts of the infrastructure,

Table 3. Principal Characteristics of the District Cooling Project

Parameters	US Units	Stage 1	Stage 2	Parameters	EU Units	Stage 1	Stage 2
Additional Information				**Additional Information**			
No. of buildings	No.	3	11	No. of buildings	No.	3	11
Total floor area	ft^2	594,000	1,836,000	Total floor area	m^2	55,000	170,000
Energy				**Energy**			
Cooling demand	MMBtu	11,935	30,690	Cooling demand	MWh	3534	9094
Cooling capacity demand	TOR	1,221	2,897	Cooling capacity demand	MW	4.3	10.2
Expected capacity to network	TOR	1,221	2,613	Expected capacity to network	MW	4.3	9.2
Heat pumps cold capacity	TOR	1,221	1,306	Heat pumps cold	MW	4.3	4.6
Storage tank capacity	TOR	341	710	Storage tank capacity	MW	1.2	2.5
Ground-source cooling	TOR	0	568	Ground-source cooling	MW	0	2.0
Total installed cooling	TOR	1,562	2,613	Total installed cooling	MW	5.5	9.2
Heat pumps heat capacity	MMBtu/hr	23	23	Heat pumps heat	MW	6.7	6.7
Heat from combined H&C	MWh	13,640	37,510	Heat from combined H&C	MWh	4,000	11,000
Heat from wastewater	MWh	139,810	132,990	Heat from wastewater	MWh	41,000	39,000
Total heat generation	*MWh*	*153,450*	*170,500*	*Total heat generation*	*MWh*	*45,000*	*50,000*
Investments				**Investments**			
Building	1000 US $	556	556	Building	Mill.DKK	4	5
Ground-source cooling	1000 US $	0	1,397	Ground-source cooling	Mill.DKK	0	9
Heat pump	1000 US $	5,968	6,433	Heat pump	Mill.DKK	38	41
Wastewater heat exchanger	1000 US $	238	238	Wastewater heat exchange	Mill.DKK	2	2
Chilled-water tank	1000 US $	635	635	Chilled-water tank	Mill.DKK	4	4
District cooling grid	1000 US $	1,604	2,187	District cooling grid	Mill.DKK	10	14
Consumer connections	1000 US $	339	807	Consumer connections	Mill.DKK	2	5
Connection to DH network	1000 US $	476	476	Connection to DH network	Mill.DKK	3	3
Total investments	*1000 US $*	*9,816*	*12,729*	*Total investments*	*Mill.DKK*	*62*	*80*
NPV Benefit, Including Environmental Costs				**NPV Benefit, Including Environmental Costs**			
Society	1000 US $	9,524	16,349	Society	Mill.DKK	60	103
District cooling business	1000 US $	2,698	8,254	District cooling business	Mill.DKK	7	52
Consumers	1000 US $	794	1,270	Consumers	Mill.DKK	5	8
Internal rate of return	%	13%	41%	Internal rate of return	%	13	41

Figure 5 *The DTU Campus area.*

including a heating network and a power grid owned by the university.

In the first stage, heat was generated by three 34 MMBtu/h (10 MW) heavy fuel oil boilers, and all power was supplied from the grid. Around 1985, the power utility established a coal-dust-fueled CHP plant, and shortly after the heavy oil was converted to natural gas. In 1998, the CHP plant was upgraded to a 38 MW electricity, 102 MMBtu/h (30 MW) heat natural-gas-fired combined-cycle (CC) CHP plant with a 2.1 million gallon (8000 m^3) heat storage tank. A heat transmission system was established at that site to supply DTU and a local district heating plant (Holte District Heating north of DTU) from the CHP plant. The annual heat demand supplied from the transmission system was 200,000 MMBtu (60,000 MWh) to the DTU campus and 340,000 MMBtu (100,000 MWh) to Holte District Heating.

DTU has its own microgrid for electricity, which is connected to the high voltage grid parallel to the CHP plant. There is no need for power backup to the DTU microgrid as the Danish power grid is very reliable. However, if the microgrid were not reliable, DTU could in principle use the plant as a backup, or DTU could contract with the owner of the CHP plant to provide this backup service.

All boilers at DTU and Holte District Heating remain as backup capacity to be able to heat as before in case the CHP plant is out of operation. Thus, the total installed capacity of the CHP plant, the heat storage tank and all the boilers are almost twice the maximal hourly demand of DTU-HF on the coldest day. In 2000, DTU established a district cooling network in the tunnels to supply all cooling end-users from the three largest chiller plants in the existing buildings.

From 2014 to 2020, several projects were planned and implemented to upgrade the system and to integrate it into the Greater Copenhagen district heating system (see Case Study 1), including large buildings around the DTU campus. Moreover, DTU has prepared a long-term vision for further development of the campus energy up to 2050. The following projects have been implemented from 2014 to 2020:

- The local heat transmission system has been connected to a heat transmission system north of the system (NORFORS) to transfer efficient surplus heat from a waste-fired CHP plant in the summer season and to serve as a backup in case there is a breakdown in the NORFORS transmission system. The heat supplied from this system is primarily heat that would otherwise be wasted or that could be produced by feeding more waste into the incinerator.
- DTU established an economizer to extract heat from the flue gas by reducing the temperature of the flue gas from around 248°F to 140°F (120°C to 60°C), thereby increasing the efficiency of the boiler plants from around 88% to 98% based on lower calorific value. The economizer generates 10 MMBtu/h (3 MW) at maximal

boiler load. To avoid corrosion in the stack, three stainless steel tubes were installed in the tall stack.

- The tariff for sale of electricity from the CHP plant to the public grid changed from a fixed three-part feed-in tariff to the NordPool market price. Previously, the CHP plant was paid this fixed feed-in tariff, although the NordPool market price in general was lower. Thereby the plant suboptimized the production for the society and generated a loss, which was paid for by electricity consumers who were obligated to pay for this feed-in electricity. From the moment the payment shifted to the NordPool market price, the plant generated electricity efficiently and operated within the limits of the regulated electrical generation market. This lower price of electricity caused the combined production of heat to be reduced from around 90% to 10% of the annual demand, as the CHP plant was only in operation at high prices. The rest of the heat was supplied from efficient gas boilers at DTU and from the surplus waste heat in the summer period. To compensate for this reduced income, the CHP plant was paid a capacity payment equal to the lost revenues.
- The district heating company Vestforbrending, which is part of the Greater Copenhagen district heating system, developed district heating in the local municipality Lyngby-Taarbeak, including a DN350 interconnection district heating pipe to the local transmission network and thereby to DTU.
- Vestforbrending can supply efficient renewable heat from the Greater Copenhagen district heating system. Thus, the waste- and biomass-fueled CHP plants are base load DTU. However, since the system has limited transmission capacity and is connected to many consumers, it is used at full capacity in the coldest 5 to 6 winter months so the plants at DTU must supplement their energy supply in the winter period.
- Starting in 2020, the CHP plant, the storage tank, and the local transmission system is owned by Vestforbrending, and the total surplus capacity of the CHP plant, the storage tank, and the boilers at DTU can be transferred to Vestforbrending as peak and spare capacity. This will open the system to connection with many more customers, thereby avoiding investments in new boiler capacity in the municipality.
- The total operation and production of heat from the CHP plant at DTU, the heat from NORFORS, and the heat from the Greater Copenhagen district heating system can be optimized.
- A 40 MW electric boiler was established in 2020 at the CHP plant and connected to the high voltage grid using the available power cable to the CHP plant, which normally is used to transfer power to the grid. This electric boiler has several purposes: 75% of its output can be used as peak capacity for heating, the boiler can offer regulation services, and can use surplus low-cost electricity from wind. This setup will allow the CHP and the electric boiler to operate from 100 MMBtu/h (33 MW) of production to 136 MMBtu/h (40 MW) of consumption within a few minutes.

The long-term strategy at DTU is to expand the floor area from 4.3 million ft^2 (0.4 million m^2) in 2019 to 13 million ft^2 (1.2 million m^2) in 2050 and to provide heat capacity for the campus system that will supply all new buildings design with low-temperature heating systems. However, building regulations and need for thermal comfort and process cooling are also expected to cause the district cooling demand to grow significantly. To meet the increasing cooling demand, DTU plans to install a heat pump for combined heating and cooling.

The operator currently uses the optimization tool Mentor Planner (Danfoss n.d.) based on electricity price and weather forecast, to optimize the production of the CHP plant, the electric boiler, the gas boilers, and the heat storage tank on a weekly, daily, and hourly basis. In the future, this optimization tool will be even more important as it will need to integrate the interaction with the electric boiler and the heat pumps, also to further optimize operations based on price signals from the Greater Copenhagen district heating system.

In the next stage, DTU may establish a chilled water-tank and install more heat pumps in combination with ground-source cooling (ATES).

CASE STUDY 4: TYPICAL SMALL DISTRICT HEATING SYSTEM IN DENMARK INTEGRATING FLUCTUATING RENEWABLE ENERGY

There are more than 300 small district heating systems in small Danish communities that operate their own networks and produce their own energy. Almost all of them are owned by the consumers in cooperatives and managed with the objective to deliver resilient, cost-effective heat to the owners at the lowest cost.

Most of these cooperatives have been developed and established over the past 50+ years. The first business model was to use cheap heavy oil instead of individual boilers and stoves fired with coal or light oil. Beginning in 1979, a second business model was adopted, which involved shifting from oil to alternative heat sources. Some cooperatives managed to use local resources like biomass while others had to use natural gas from the new national gas project, which was primarily approved, not to achieve optimal cost-effectiveness, but to increase the resiliency of the national energy supply. Cooperatives were not allowed to use coal, but were required to shift from oil to gas. Often, they just shifted from oil burners or gas or to dual fuel burners at the boilers for better resilience. Later, they were required to invest in gas-fired CHP plants (mainly gas engines) with heat storage tank. They typically installed gas engines in the range from 1 MMBtu/h to 34 MMBtu/h (1 MW to 10 MW) heat to cover 50% of the peak load capacity, which gave them the ability to supply up to 90% of their annual production in an optimal way relative to the electricity tariff.

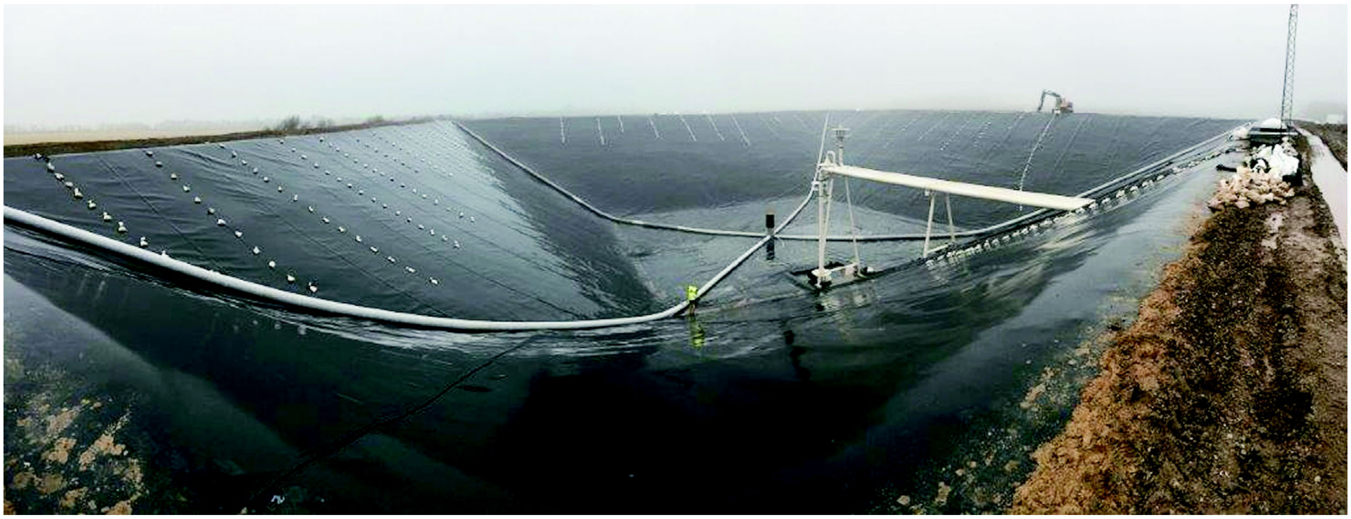


Figure 6 *The heat storage pit under construction at Toftlund district heating.*

The typical pressure less heat storage tank, maximum 205°F (95°C) had several functions. It enabled the company to optimize the electricity production, it maintained the pressure in the network, it offered storage volume for makeup water, and it could offer peak capacity leveling the daily heat load fluctuations on cold days. The companies played an important role in quickly replacing the use of oil as a primary fuel and in creating revenues that allowed the gas company to repay loans assumed to fund the gas project.

Around 2000, when the gas project became financially stable, the direction of energy policy changed to focus more on the environment and on a long-term goal of becoming independent of fossil fuels.

One Danish district heating company, Marstal District Heating, was a principal driver in the development of cost-effective, large-scale solar water heating; in the past 10 to 15 years, many companies have subsequently installed solar water heating, electric boilers, and large heat pumps to supplement or even replace their CHP plants, as there is no longer a market for backup capacity for the power system. However, several companies kept their CHP plants, as the market was expected to develop some kind of incentives for backup capacities because of the growing market share of wind energy. Along with that, electric boilers may have an increasing role to play. They can use surplus electricity at zero or negative prices thereby avoid curtailing wind energy, and they can enter the day-ahead market for down regulation and even up-regulation, e.g. from 50% to either 0% or 100% load. Solar heating can typically deliver 20% of the annual heat production with help from the existing heat storage tanks. In 2019, more than 100 companies have installed around 15 million ft^2 (1.4 million m^2) of solar heating panels cost-effectively when compared to gas prices at the world market price. The cost of solar water heating at individual buildings, for example, would cost six times more than heat from these large plants. Large-scale solar water heating based on this concept has now been established in such locations as Norway, China, and Chile (for low temperature industrial processes).

Marstal District Heating was later the driver in developing seasonal heat storage pits in combination with more large-scale solar heating to increase the share of solar heat up to 50% to 60% of the annual heat production. In 2019, there are five of these heat storage pits in Denmark, one in China, and several more planned in other countries.

The most adoption of this technology was the installation of three plants in the Municipality of Haderslev in Denmark (in Vojens, Gram, and Toftlund). The plans were financed based entirely on projected cost-effectiveness (without direct subsidy), although they do benefit from the Danish tax on gas, which encourages energy efficiency by doubling the price of gas. The newest plant is owned by the consumer-owned district heating company in Toftlund. Figure 6 shows the storage pit under construction.

The Gram consumer-owned district heating company, which has built one of these plants, is the second of eight demonstration projects described in a report from the EU (Galindo et al. 2016). The town of Gram in Denmark is a small community where the heat consumers are co-owners of the consumer-owned district heating company Gram Fjernvarme Amba. Figure 7 shows the solar water heating plant and the storage. In the back-ground, it is possible to see the town and the thermal heat storage tank at the gas-fueled CHP plant.

The overall technical parameters for the typical small district heating companies with heat storage pit (in this case, Gram) for a normal year with stable heat losses are:

- 2500 inhabitants in the town, almost all supplied with district heating
- 1200 buildings connected

Figure 7 *The solar water heating and heat storage pit at Gram district heating.*

- a 13 mi (21 km) heat supply network in preinsulated pipes
- a 32 million gallon (122,000 m^3) heat storage pit
- Heat demand at consumers: 68,000 MMBtu (20,000 MWh)
- Heat production to the network: 96,000 MMBtu (28,000 MWh), generated in a typical year as follows:
  - 474,000 ft^2 (44,000 m^2) solar panels, 61%
  - 34 MMBtu/h (10 MW) electric boiler, 15%
  - 3 MMBtu/h (0.9 MW) heat pump, 8%
  - Industrial surplus heat, 8%
  - 5 MW electric, 20 MMBtu/h (5 MW electric, 6 MWth) CHP gas engine, 8%
  - Gas boilers for spare capacity, 0%

This architectural design for storage and production incorporates several synergies:

- Heat storage acts as a repository for heat energy generated by fluctuating heat sources (solar and other production); the stored heat can be used to diminish the effects of vacillating electricity prices caused by the fluctuating wind and solar PV power production.
- The heat pump and the electric boiler use the power cable that was installed for the CHP up to its capacity.
- The electric boiler can be used to generate heat when the price of electricity is low, and its use can be regulated to match any load.
- The CHP generates heat only when the price of electricity is high.
- Heat pumps generate heat continuously except when the price of electricity is high or when capacity in the power grid is constrained.

Figure 8 shows the measured distribution of the annual generation where solar heating provides a large share of energy generation in Toftlund as predicted in the simulation models. The next stage in the green transition will be to replace heat from gas boilers with heat from large electric pumps and electric boilers. In district heating companies with heat storage tanks where solar heat covers only around 20% of the heat, a larger share is attributed to the use of heat pumps, electric boilers, biomass-fired plants, surplus heat, and gas boilers. The combination of these various energy-generation technologies with heat storage allows these companies to vary their demand for electricity significantly based on fluctuations in electricity prices so that when electricity prices rise, as seen from the power grid, it appears that they are drawing power from a large battery.

CONCLUSION AND LESSONS LEARNED

The four case studies demonstrate how the Danish energy policy developed over time and how this policy and the regulatory framework has been adopted in various parts of the society: a metropolis, a city, a small town, and a university campus. The planning and implementation has been the responsibility of local city councils and boards of directors for companies elected by the consumers, either directly in cooperatives or indirectly via municipalities. They have all been acting in the

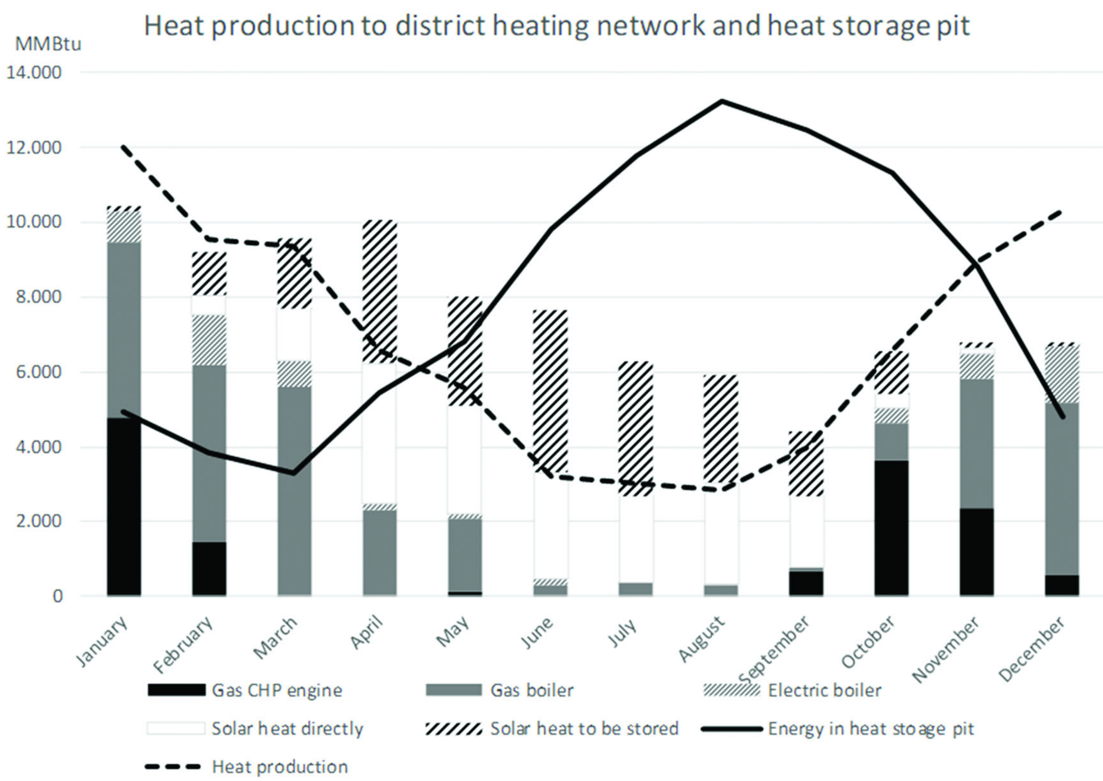


Figure 8 *Measured annual heat production monthly at Toftlund.*

interest of their owners, which are the consumers, but also with an obligation to go for least-cost solutions for the society as a whole in order to stimulate cooperation across boarders and sectors. The role of the government has been to set the overall energy policy objectives and to guide the local decision makers by means of legal framework, planning assumptions, and tax incentives (e.g., tax on CO_2 emissions, electricity, and fossil fuels).

This model of local engagement has also stimulated innovative solutions and smart sector integration, which is important for developing cost-effective resilient energy services in all climate zones. The preinsulated pipes, large-scale solar water heating, and heat storage pits are technologies developed in Denmark and now transferred to other countries and other climate zones.

The four case studies are included in the two of eight case studies in the EU report for efficient district heating and cooling, which can be replicated in the EU, but they can also inspire other communities.

ACKNOWLEDGMENTS

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- The Danish Energy Agency: https://ens.dk/en
- The Danish District Heating Association: https://www.danskfjernvarme.dk/sitetools/english
- The heat transmission company CTR: http://www.ctr.dk/en/home.aspx
- The heat transmission company VEKS: https://www.veks.dk/en
- The waste management and district heating company Vesforbrending: https://www.vestfor.dk/
- The public utility Taarnby Forsyning: http://www.taarnbyforsyning.dk/
- The DTU Campus Lyngby: https://www.dtu.dk/english/about/campuses/transforming-our-campus.

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