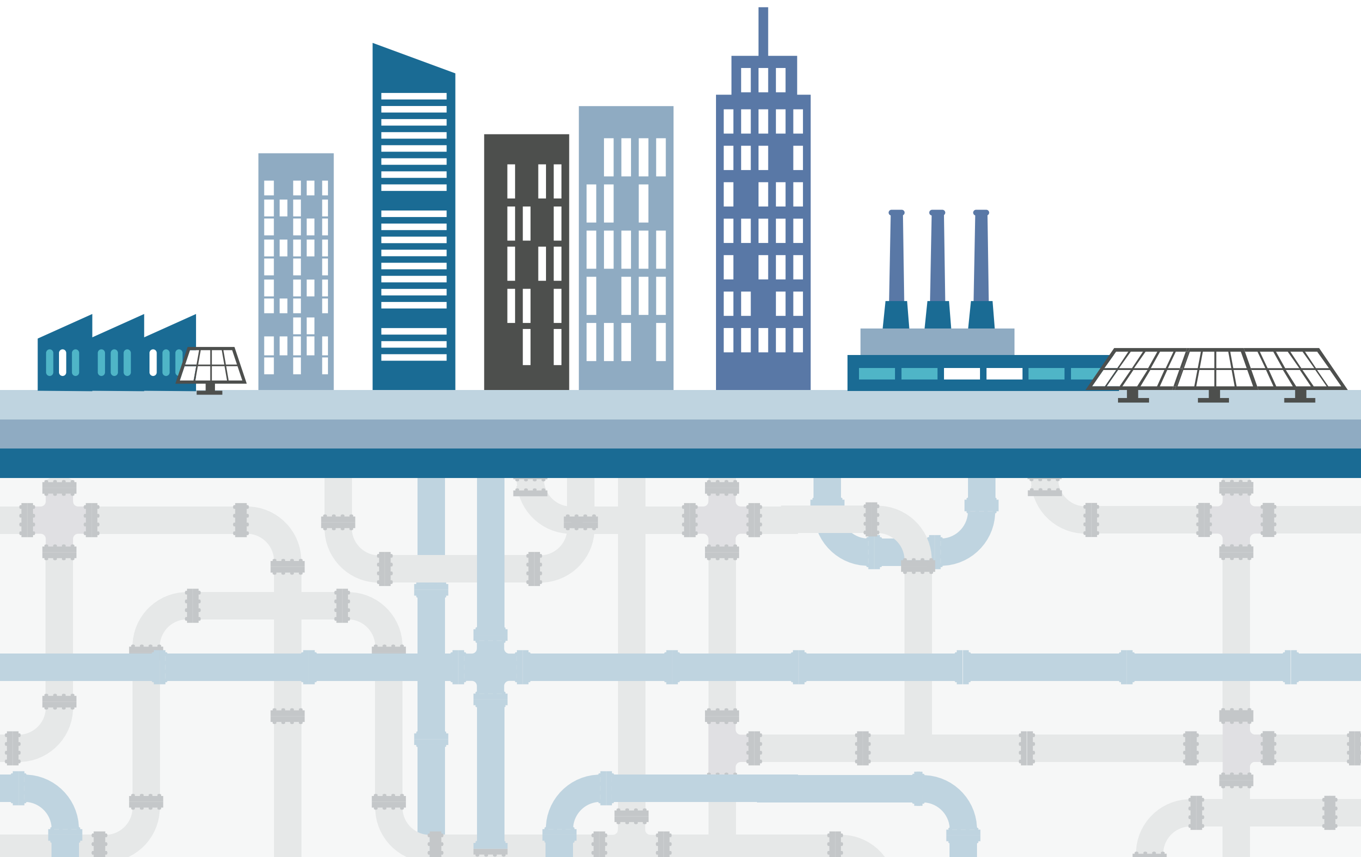
IRENA
International Renewable Energy Agency

RENEWABLE ENERGY IN DISTRICT HEATING AND COOLING

CASE STUDIES



REmap
A Renewable Energy Roadmap

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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SOLAR HEATING[1]

Case study 1: Graz, Austria: solar district heating at different scales

Graz has some experience of large-scale solar district heating facilities. However, the solar contribution to total demand for district heat has so far remained low. Additional projects are being implemented or in planning to eventually allow solar energy to play a major part.

District heat generation in Graz is mostly based on the combustion of fossil fuels in three large co-generation plants with a capacity of 230-250 MW_{th}. Several projects aim to increase the integration of industrial waste heat into the district heating system (Energie Graz, 2016a). Major changes in the district heating mix are expected in the future due to the anticipated mothballing of the combined-cycle CHP plant Mellach, whose profitability was compromised by low European power market prices (Energie Graz GmbH, 2016a).

In light of this uncertainty, a diverse set of new added district heating capacity is planned, predominantly sourced from renewable and especially solar heat. This has been motivated primarily by the predictability of costs using this approach. Local district heating networks in newly connected neighbourhoods operate at lower temperatures to facilitate the future integration of renewable energy (Energie Graz GmbH, 2016a).

Between 2002 and 2016, large-scale rooftop collector systems were installed on several buildings and connected to the district heating network. These systems have a combined collector area of over 15 000 m^2 and meet 0.6% of annual district heating demand. Since their peak output in summer is around half the baseload, there is no need for a storage tank

District heating in Graz

Inhabitants	Network length	District heating share	District heating produced	Peak load	Network temperatures
270 000	780 km	40% (61 000 apartments)	950 GWh*	423 MW_{th}**	Winter 120°C/ summer 75°C return 60°C

* gigawatt-hours

** megawatt thermal

Source: Energie Graz, 2016a

1 Throughout the report, solar systems refer to solar thermal installations only. Heat from heat pumps powered by photovoltaics is not considered.

Existing and planned solar district heating projects in Graz

System	Collector area (m²)	Storage volume (1000 m³*)	Capacity	Annual heat generation (MWh**)	Project cost (million USD)	Status
Fernheizwerk/ AEVG	7750	0	-	3000	-	Start of operation 2006
Andritz waterworks	3800	0	2.7	-	-	Start of operation 2009
Berliner Ring	2600	0	-	988	-	-
Merkur Arena	1407	0		540		Start of operation 2002
HELIOS	10000	2.5	10	-	4.2 incl. CHP	2016
Big Solar Graz	450000	1800	250	254000	200	Feasibility assessment

*cubic metres **megawatt-hours

Source: SOLID (2016c), Energie Graz, 2016a, Energie Graz, 2016b, AEE (2004), Papousek, 2016

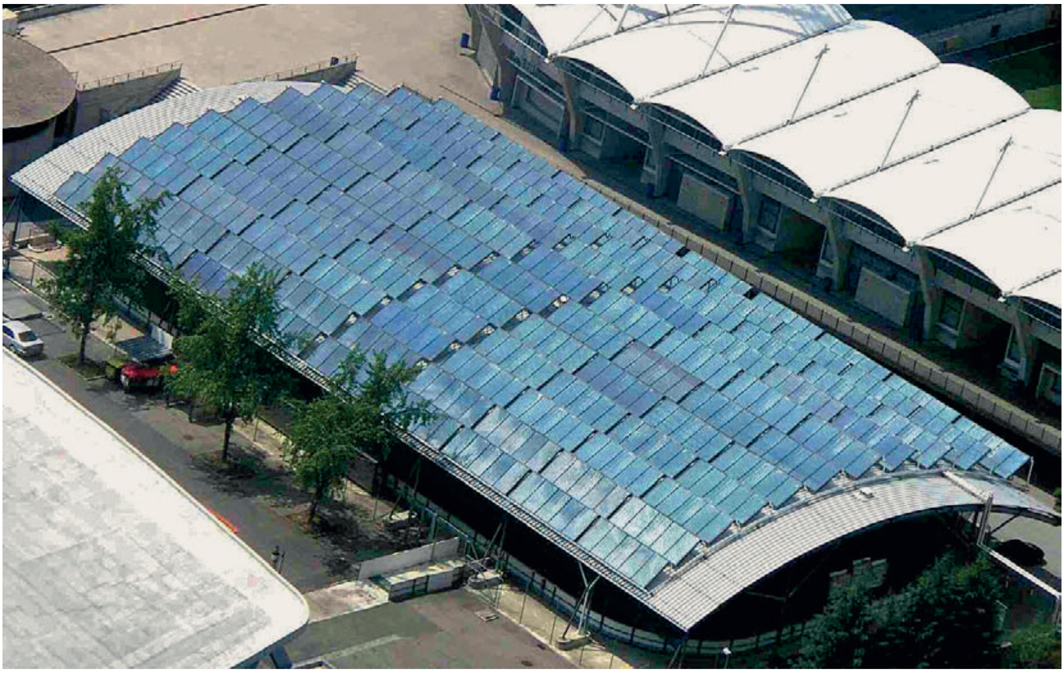
to make full use of the heat generated (Seidler, 2015). The installation Fernheizwerk/AEVG was expanded continuously and now hosts six different types of solar thermal collectors. This allows the scientific comparison of these systems under realistic conditions (SOLID, 2016c).

The new project HELIOS comprises 10000 m² of collector surface area (2000 m² in the first stage) and 2500 m³ of hot water storage used on weekly time scales. The solar system is installed on a retired landfill site. The landfill gas is combusted in a small-scale CHP plant to raise the water temperature in the tank (Energie Graz, 2016b). The greatest component of the investment cost is being paid from a grant by the Austrian state of Styria (Landesregierung Steiermark, 2015).

Specific proposals for using solar to deliver up to 20% of district heating have been brought forward and assessed in a feasibility study. The concept includes a collector field of 450000 m², seasonal pit storage with a volume of 1.8 million m³ and 96 MW of absorption heat pumps. The heat output will be fully dispatchable at 85°C. This system would have an annual yield of 254 GWh and maximum solar capacity of 250 MW. It has the recognised potential to make a significant contribution to district heating supply.

Simulations show that roughly 27% of the total heat generated can be put to direct use. The rest of the output is stored and supplied to the network with the help of heat pumps. The economic viability of this system has been judged positive if its composition is carefully balanced. Investigations have shown that the large size of the solar network is critical to the economic competitiveness of the project. It provides economies of scale as well as helping minimise heat losses from the seasonal storage facilities. The demand for space was estimated as 0.8% of Graz total urban ground area, approximately twice the size of the city's motorway junction. If compared to the ground area required to provide the same amount of heat with biomass, it is smaller by a factor of at least 30. Several suitable locations have been identified. (Papousek, 2016; SOLID, 2016b; Poier *et al.*, 2016).

Example of a solar district heating installation in Graz Merkur Arena



Source: SOLID GmbH/Wikimedia GNU Free Documentation License

Case study 2: Munich, Germany: rooftop solar thermal collectors connected to a hot water tank for seasonal storage

Construction of a new residential area incorporates a local district heating subsystem fed mainly from solar heat.

The residential neighbourhood Am Ackermannbogen was constructed between 2005 and 2007 on the site of former military barracks in central Munich. All dwellings were designed to meet low energy building standards and to limit annual final heat demand to 30-40 kWh/m^2.

A subset of buildings was selected for heat supply from an array of rooftop solar collectors with an area of 3600 m^2. A water storage tank with a volume of 6000 m^3 was erected above ground but later covered, forming a hill integrated into the urban landscape. The solar system satisfies up to half the heat demand of the buildings connected. It is used either directly or to heat the water in the storage tank to 90°C.

Thanks to the holistic way the neighbourhood was planned, the heating systems in the individual homes could be adapted to meet the requirements of the solar thermal system. Most importantly, the network return temperature is low, amounting to 30 °C.

The local centralised heating system is connected to Munich's district heating network. The heat from the city-wide system is used to drive a heat pump which has two effects. Firstly, it raises the temperature in the upper layers of the storage tank in order to meet residual heating demand. Secondly, it

Local district heating system Am Ackermannbogen

Number of apartments	Floor space	District heating share	Network temperatures	Connections
320	30400 m^2	100% (50% solar)	60°C supply/ 30°C return	Coupled by heat pump to city district heating network

Source: ZAE Bayern, 2010; Energieatlas Bayern, 2010 lowers the temperature in the bottom layers below the system's return temperature in order to maximise yield from the collectors.

If taking Munich's district heating supply as a reference, the Am Ackermannbogen network avoids 180 tonnes of CO_2 emissions per year. Together, the federal government and city of Munich met most of cost, which amounted to USD 4.5 million-5.7 million, or 4 million-5.1 million euros (EUR).

The planning, construction and evaluation of the system's performance was supported by an independent research institute. This consisted of feasibility assessments and system planning, the transfer of experience from previous projects, and continuous scientific monitoring of the system's performance. This was indispensable to the success of the project given its novelty (ZAE Bayern, 2010; Energieatlas Bayern, 2010).

Solar heating system Am Ackermannbogen: some technical and cost information

Collector area (m^2)	Storage volume (m^3)	Total project cost (USD)	Annual avoided CO_2 (tonnes)	Status
3600	6000	4.5 million to 5.7 million	180 (compared to district heating)	Completed 2007

Source: Energieatlas Bayern, 2010

GEOTHERMAL HEAT

Case study 3: Ferrara, Italy: district heating for the exploitation of geothermal resources

The Ferrara district heating system was set up in order to exploit the geothermal resources below the city, which still play a dominant role in the system. Significant expansion of the geothermal capacity is planned.

Ferrara's district heating system was set up to exploit a 100°C hot water source located at a depth of 2 000 m, which had been discovered previously when the region's potential for oil extraction was investigated. It was put in operation in 1990 and has a nominal capacity of 14 MW_{th}. In 2007, a municipal waste CHP plant (25 MW_{th}) was added to the system. This plant meets the rising demand for heat while the output from the geothermal well stays more or less constant throughout the years. In addition, a series of gas boilers is used to cover the peak load. All heat sources are to the west of the historic city centre. The hot water is both collected and transported to the demand centre through a single transmission pipe. A total storage capacity of 3 000 m^3 is available (Interreg, 2015, Gruppo Hera, 2015b, Gruppo Hera, 2015).

To develop the system for future needs, Gruppo Hera is aiming to expand the district heating network to cover heat demand from 37 500 apartments – equivalent to 40% of the city's homes. Two additional wells with a combined capacity of 14 MW_{th} are planned on the opposite side of the city. The old and new networks are to be connected at the distribution ends in the city centre. It is envisaged that heat from the new wells will be used to produce electricity in an organic Rankine cycle unit during the summer months. A 1 MW_{th} solar heating facility and additional natural gas plants will complement the mix (Gruppo Hera, 2015). By 2013, the entire cost was due to be met by the public utility Gruppo Hera. Applications for European Union funding were under consideration (Gruppo Hera, 2013).

District heating in Ferrara

Inhabitants	Network length	Number/ proportion of apartments connected	Renewable district heating produced in 2015	Installed capacity	Network temperatures	Annual CO_2 savings (tonnes)
130 000	56 km	22 000/ 23.5%	260 TJ* (73 GWh) geothermal	155 MW_{th}	90°C supply/ 60°C return	39 800

*terajoules

Source: Gruppo Hera, 2015 and GeoDH, 2015

Case study 4: Munich, Germany: range of geothermal district heating facilities

Munich contains one of the largest heating networks in Europe. The local utility aims to switch to 100% renewable district heating by 2040. Thanks to the excellent geothermal conditions below the city, this resource is bound to play a major role in achieving this goal.

The district heating system in Munich dates back to the beginning of the 20th century and has since been continuously expanded primarily by developing and interconnecting previously isolated systems (SWM, 2015).

Abundant geothermal water resources are available below the city and surrounding municipalities. The temperature range from the north to the south of the city amounts to 65°C-140°C at depths of 1500-4000 m respectively. To support its expansion plans, the local utility SWM has obtained mining rights for the whole city (SWM, 2015b).

District heating in Munich

Inhabitants	Network length	Network temperatures
1.4 million	800 km	Newer parts 90°C supply/45°C return; older parts based on steam

Source: SWM (2015)

Existing and future geothermal heating plants in and around Munich

Location	Temperature	Depth (m)	Capacity (MW)	Note	Status
Trade Fair City Riem, Munich	93°C	3000	13 MW_{th}	Covers 88% of the neighbourhood's heat demand	In operation since 2004
Sauerlach near Munich	140°C	5567	4 MW_{th}/ 5 MW_{el}	Power generation and district heat for local buildings	In operation since 2014
Freiham	80°C	2300	12 MW_{th}	-	Under construction until 2016
Sendling	>95°C	3700 to 4300	30 MW_{th}	Integration with a combined cycle CHP plant, replacing obsolete oil tanks	Start-up planned in 2019
Up to 5 additional plants	-	-	-	Currently seismic explorations	Start-up by 2025

Sources: SWM (2015), SWM (2015b), and SWM (2016)

Geothermal plant in Riem, Munich

Source: SWM/Thomas Einberger

The independent district heating system in Sauerlach 20 km south of Munich is operated by SWM, but is not connected to the rest of the network. The high temperature of the geothermal water enables electricity production as well as water to be heated for the district heating system. A biomass boiler is used as backup capacity, such that only renewable energy is used for the local provision of district heat.

In contrast to Ferrara, the Munich district heating network was only recently equipped with geothermal facilities. The lack of flexibility in the operation and design of the existing network raises additional barriers to these projects:

- **Availability of space**: Freiham and the Trade Fair City Riem are Munich's newest residential districts. This facilitates the integration of the geothermal plants into the urban environment. By contrast, shifts in the city's district heating mix allowed the retirement of some capacity in Sendling, which freed up construction space at its old heating plant. It is located close to demand centres and has an existing connection to the network.

- **Temperature in the network**: to optimise the use of this resource, SWM is encouraging customers to lower the return temperature. In new neighbourhoods, supply and return temperatures are planned at 60°C and 35°C, respectively. The geothermal facility at Riem illustrates the point: On inspection, the return temperature was

Drill bit and geothermal plant in Freiham, Munich

Source: SWM/Steffen Leiprecht

reported at 60°C. It stayed significantly above the design temperature of 45°C, so that the geothermal unit could not reach full heating capacity but remained 30% below the nominal value (SWM, 2015).

Further significant expansion of the district heating system is planned in the near future, with additional loads in the gigawatt range and a new network infrastructure of up to 100 km. The refurbishment of the steam-based system in the city centre was the main priority until 2010. However, these plans have been postponed to at least 2020 due to federal subsidies for expanding the network (Süddeutsche Zeitung, 2010, SWM, 2015 and SWM, 2015b).

BIOMASS: COAL CONVERSION AND CO-FIRING

Case study 5: Copenhagen, Denmark: Conversion of large CHP plants

The district heating system in Copenhagen has some of the most efficient CHP plants in the world. Due to the city's goal to become carbon-neutral by 2025, these plants are being modified to allow a larger fraction of biomass co-combustion or a complete switch to biomass.

The district heating system in Copenhagen is by far the largest in Denmark and extends beyond the city boundaries to include the neighbouring municipalities. Most heat generation is based on the combustion of municipal waste and a variety of fuels in several large CHP plants. Multiple stakeholders are involved in both operating the network and the connected power plants. The transmission grid is owned by three utilities and supplies heat to a number of distribution grids, which are in the hands of the municipalities or consumers (State of Green, 2015).

DONG Energy owns **Avedøre power station** east of Copenhagen's city centre. The plant's block 1 was built in 1990. Conversion to biomass started in 2015 at a cost of USD 112 million, or 740 million Danish Kroner (DKK). Once it had been completed in 2016, the plant was due to burn 1.2 million tonnes of wood pellets per year. The conversion of block 2 (570 MW_{th}/585 MW_{el}) was finalised in 2014 with the installation of an additional mill and a dock to service an increase in the biomass supply capacity. This enables the plant to reach full output through the exclusive use of wood pellets as fuel. The total cost, amounting to USD 15 million (DKK 100 million), was met by DONG Energy and heat transmission companies VEKS and CTR (Ingeniøren, 2014).

District heating in Copenhagen

District heating share	Network length	Floor area supplied	District heating produced	Storage
99% of all buildings in Copenhagen (560 000 inhabitants) and Frederiksberg (103 000 inhabitants)	180 km hot water transmission system; 21 distribution networks	75 million m^2	35 000 TJ 9 700 GWh	24 000 m^3 at the Amager power station

Source: State of Green, 2015

The **Amager power and heat plant** is south of Copenhagen and operated by HOFOR, Denmark's largest utility company. It covers almost 30% of Copenhagen's heat demand. The power station consists of two CHP plants. Block 1 (260 MW_{th}/80 MW_{el}) is generally used for the combustion of wood pellets or straw, with the option of using coal if there are biomass shortages. It was converted to biomass between 2004 and 2010 through the installation of a new boiler and turbine. The second block (331 MW_{th}/215 MW_{el}) continues to be fuelled by coal or oil. It is due to be retired and replaced in 2020 by a new block fuelled by biomass. The plant's proximity to the harbour infrastructure allows all fuel to be delivered by ship (Vattenfall, 2013; HOFOR, 2015; City of Copenhagen, 2015).

Due to the country's dependence on imports for its biomass supply, HOFOR views the combustion of this fuel as a transitional solution. It must ultimately be replaced by geothermal heat, large electric heat pumps and solar heating. The utility is therefore active in the development of relevant demonstration projects (HOFOR, 2015).

Heat tunnel connecting the Amager plant to the Copenhagen district heating system

Source: Wikimedia/Bill Ebbesen/CC-BY-3.0

Case study 6: Flensburg, Germany: Low-share co-combustion

Flensburg's utility is aiming for carbon neutrality by 2050. Technical barriers and rising biomass prices limit the amount of biomass used in a district heating system otherwise based on fossil fuel. Nevertheless, the technical constraints affecting the share of biomass usable in co-combustion are being explored.

Despite the city's small size, the district heating network is among the largest in Germany and covers almost the entire city's heat demand. Six boilers in a central CHP plant produce the bulk of the heat. A set of decentralised boilers is used only in case of outages. Bituminous coal is used as the main fuel for both the base and peak load units. Heavy fuel oil provides additional peak capacity (IFEU, 2013). In the short term, fuel diversification through the partial switch to gas, municipal waste and electricity is seen as the priority. It allows the utility to hedge against fuel price fluctuations and uncertain policy development (Flensburger Tageblatt, 2014; Hartmann, 2013).

Since 2007, small amounts of biomass (2% of fuel, or 20 GWh per year) have been mixed with the coal to cover the baseload. Up until now, only minor adjustments to the plant infrastructure have been required to enable co-combustion. These are related to biomass logistics (the installation of a pneumatic conveyor system) as well as plant automation. In the long term, it is envisaged that biomass would provide 30% of the fuel. Unless larger investments are made in plant adaptation, this is a technical limit due to the higher water content of biomass and consequently larger volumes of flue gas produced during combustion.

Studies have shown that co-combustion reduces emissions of sulphur dioxide. Some wood chips are available in the larger urban area of Flensburg. In addition, forest residues are imported from the Baltic states. Rising prices and lack of cost-competitiveness compared to hard coal are considered major obstacles. The price of carbon has been identified as a key parameter for the future viability of biomass use (IFEU, 2013).

District heating in Flensburg

Inhabitants	Length	District heating share	Sector share	District heat produced	Maximum district heating demand	Network temperatures	Storage
89 000	260 km primary transmission/ 340 km secondary distribution	98%	55% residential 26% services 19% industry	4 200 TJ 1.17 TWh*; trend: -1% per year	640 MW_{th}	80°C-130°C/ return: 60°C	28 000 m^3

*terawatt-hours, Source: Stadtwerke Flensburg, 2016; Hartmann, 2013; IFEU, 2013

Case study 7: Vilnius, Lithuania: Cost savings through switch to domestic biomass

In Vilnius, the switch from natural gas to local biomass is mainly motivated by the expected cost savings and age of existing capacity. For the same reason, and due to the extensive use of landfill sites, municipal waste is expected to play a major role.

The construction of the network in Vilnius started in the 1950s. The production of district heat relies on old Soviet CHP plants fired by natural gas. The country's dependence on imported electricity and fuel creates high costs. Switching from natural gas to domestic biomass been shown to allow for major savings of up to 34% (ENNEREG, 2013, World Bank, 2001, Stasiunas, 2009).

In an attempt to reduce dependence on foreign energy sources, there are plans to use Lithuanian biomass to provide the bulk of centralised heating (up to 70%) in Lithuania by 2021 (Rasburskis, 2016).

Thus far, the two main power and heat plants in Vilnius have been running on natural gas and heavy fuel oil:

Vilnius CHP Plant-2

Source: Wikimedia Commons/public domain

- A boiler in Vilnius CHP Plant-2 (932 MW_{th}/29 MW_{el}) was partly adapted to use a mixture of biomass and fossil resources (60% wood, 10% straw and 30% peat). For this purpose the old 60 MW boiler was modified at a total cost of USD 13.2 million (EUR 11.7 million). The modifications consisted of a new fuel handling system and a series of additional filters (Valentinas, 2014).
- The Vilnius Power Plant-3 is due to close in 2016. This is primarily motivated by the additional availability of low cost power from Sweden through the new NordBalt undersea power cable (Newsbase, 2016). Studies have shown that a new biomass-fuelled boiler (340 MW_{th}/180 MW_{el}) within the existing plant would be a viable option and could slash the heat price by 22%. A major share of the investment is to be paid from European Union funds (The Baltic Course, 2014).

District heating in Vilnius

Inhabitants	Length	District heating share	District heat produced	District heating capacity
540 000	460 km	90%	9 400 TJ/2 600 GWh in 2015	2 330 MW

Source: Rasburskis, 2016, World Bank, 2001

Case study 8: Borås, Sweden: Step-by-step fuel conversion of a heating plant

The main heating plant in the city of Borås has been converted from oil to biomass in several steps over the last decade.

Borås' largest heating plant is the Rya plant, which has a capacity of 180 MW. This includes 130 MW of biomass boilers, 40 MW of waste boilers and a flue gas condensation unit of 10 MW. Built in the 1960s as an oil plant with small amounts of feedstock from municipal solid waste, two oil boilers were converted in 1984 to burn a mix of 75% biomass and 25% coal. The additional installation of a dryer in 1994 enabled the conversion to 100% biomass. In Sweden, biomass is available in large quantities from forestry and is considered the cleanest fuel with the lowest climate impact. Ash from biomass combustion is returned to the forests as a fertiliser. During later years, waste-fuelled capacity has been expanded. In 2008, it supplied about 30% of the plant's heat generation, partly replacing biomass. (Ecoheat4eu, 2011; Borås Energi och Miljö, 2016; Borås Energi och Miljö, 2009)

District heating in Borås

Population	Network length	District heating share by inhabitants	Storage
66 000	300 km	53%	37 000 m^3

Source: Borås Energi och Miljö, 2009; Borås Energi och Miljö, 2016

STAND-ALONE BIOMASS

Case study 9: St Paul, Minnesota, US: Local biomass in a centralised heating plant

The system in St Paul, Minnesota, has been running since 1982 and continuously expanded. It delivers both heating and cooling services; cold water is generated through absorption chillers using heat from the heating plants. Both the network and the heat generators are owned and operated by a not-for-profit corporation founded by the city of St Paul.

A noteworthy addition to the system was the 1999 installation of a 65 MW_{th} (33 MW_{el}) CHP plant fuelled by municipal biomass. At an initial investment cost of USD 75 million, the plant supplies 65% of district energy demand. The construction of this plant was an important step towards greater energy self-sufficiency because the old coal and gas-fired heat-only boilers now only run during peak load hours. The fuel consists of wood waste from the city's metropolitan area. A total of 225 000 tonnes is burned in the plant's boiler, which corresponds to half the estimated available resource. The emission of 91 000 tonnes of carbon per year can be avoided when taking the operation of the coal boiler as a base line.

Given that the plant is close to the city centre, biomass delivery logistics are not easy because it needs 50 truckloads of biomass each day. Innovative approaches have been required to organise an efficient as possible delivery system. Specialist hoppers allow several trucks to discharge their load at the plant at the same time. The strategic location of the plant close to a series of arterial roads facilitates the logistics, and the deliveries increase local traffic by less than 1%.

At first, the reliance on several different businesses in the surrounding area for biomass supply created a barrier. Once chipping and screening equipment had been

District heating in St Paul

Network length	Floor area	Market share	Total capacity	Peak demand	District heating sold in 2015
32 km heating 10 km cooling	2.9 million m^2	80% downtown heating market 60% downtown cooling market 300 single-family houses	289 MW_{th}	190 MW_{th}	1 150 TJ (320 GWh)

Sources: Ever-Green Energy, 2016; IDEA, 2007; Biomassmagazine.com, 2010; DESP, 2016

Biomass CHP system in St Paul

System	Capacity	Fuel demand per year	Share in the system	Total project cost	Annual avoided carbon emissions (tonnes)	Status
Biomass CHP	65 MW_{th} 33 MW_{el}	225 000 tonnes wood residues	65% of heat 8% of capacity	USD 41 million	91 000	Completed 2004

Source: Ever-Green Energy, 2016; IDEA, 2007; DESP, 2016

installed, supply could be streamlined and could reach sufficiently high levels. When there is a shortage, wood is supplied from within the state of Minnesota. However, this results in increased harvesting and transportation costs.

The development of the local market and the establishment of the logistics allows the company to access sufficient volumes of biomass to investigate the additional use of biomass in co-combustion in the fossil fuel boilers (Ever-Green Energy, 2016; IDEA, 2007; Biomassmagazine.com, 2010; District Energy St Paul, 2016).

St Paul biomass-fuelled heating plant close to the city centre

Source: Wikimedia Commons/John Polo

Case study 10: Ulm, Germany: Replacement of fossil fuel plants

Two new co-generation plants started up between 2004 and 2013. Fuelled by local biomass, they replace large amounts of the previous fossil-based heat in the city's district heating system.

The district heating system in Ulm, Germany, supplies 2160 TJ (600 GWh) per year to a broad mix of customers. These are composed of private households (25%), industry (25%), and the tertiary (40%) and public sector (7%). Up until 2012, heat generation in Ulm's district heating system was largely based on the combustion of fossil fuels: at a central CHP plant, three boilers are fired with hard coal and two additional boilers with natural gas and oil. Peak load is covered through heat-only boilers using oil and gas. In 1997, a waste-fuelled CHP plant started up.

In 2004, the first biomass CHP plant was connected to the network, with a capacity of 40 MW_{th}. At a specific investment cost of EUR 925 per kW_{th}, it produces half the district heat despite representing only 8% of total heat generation capacity. Given that it operates as baseload capacity, major components in the fossil fuel plants have been replaced. A mixture of wood chips from both residues and dedicated fuelwood is combusted in the plant's boiler.

The success of the first biomass plant led to a second smaller facility at the same location. It operates around 4250 full load hours per year and is thus serving the mid-load range of demand, covering 85 GWh (14%) of heat generation. The plant requires 60000 tonnes wood per year, which is sourced within a radius of 70 km.

The electricity generated in the two biomass plants is subsidised in accordance with the German national feed-in tariff. The competitiveness of the biomass plants depends on this policy instrument when set against competing fossil fuel plants (Südwest Presse Online, 2013; IFEU, 2013).

District heating in Ulm

Network length	District heating share	District heating produced	District heating temperature
160 km	45% of space heating demand	2160 TJ/year (600 GWh)	4 different levels; hot water at 90°C-110°C; steam at 3 bar; return temperatures at 50°C-60°C

Sources: Südwest Presse Online, 2013; IFEU, 2013

CHP biomass system in Ulm

System	Capacity	Fuel demand per year	Share in the system	Total project cost (USD million)	Status
Biomass CHP 1	40 MW_{th}	N/A	50% of heat output, 8% of capacity	41	Completed 2004
Biomass CHP 2	20 MW_{th}	60000 tonnes wood chips	14% of heat	32	Completed 2013

Source: IFEU, 2013

Case study 11: London Olympic Park, Great Britain: Minor biomass share with possible future expansion

Minor amounts of heat capacity fuelled by biomass were combined with a natural gas CHP installation within a centralised energy system in London Olympic Park. Thanks to a dedicated legacy plan for the park, the district energy system is to be expanded in future.

The vision of the 2012 London Olympics was to become "the most sustainable Olympic Games of modern times" (Olympic News, 2013), which motivated the installation of a centralised heating system partly fuelled by biomass. Hot and cold water generated at two energy centres is supplied to the sports venues and Olympic village through a water network.

The King's Yard energy centre is equipped with a 3.5 MW biomass boiler and 40 MW of conventional boiler capacity. The heat output from an additional 3.1 MW_{th}/6.7 MW_{el} CHP system is partly used to drive an absorption chiller. Locally sourced woodchips and wood pulp are used as feedstock for the biomass boilers, which provide the baseload during the winter months.

The energy system was built, financed and operated by a private company. Applications during the competitive procurement process had to be based on a design provided by the Olympic Development Authority. In the initial plans, the heating system was to be based entirely on a biomass gasification and waste-to-gas scheme. Due to uncertainties related to future demand, none of the tenders proposed this approach. As a result, the Olympic Development Authority decided to generate heat largely from natural gas with minor elements of biomass. However,

District heating in London Olympic Park

Network length	Scope	District heating capacity	District heating network tempera-tures	Project cost	Storage
16 km heating/ 2 km cooling	Venues of the Olympic Park and commercial and residential buildings in neighbouring Stratford City	100 MW heat 18 MW cooling 3.5 MW electricity	95°C/55°C	USD 150 million (GBP* 113 million)	available

*Great Britain Pounds

Sources: McDonald, 2013; Olympic Delivery Authority, 2008; CEEQUAL, 2013

Biomass boiler integrated in a CHP system in London Olympic Park

System	Capacity	Role in the system	Status
Biomass boiler integrated in a CHP system	3.5 MW_{th}	Baseload	Completed 2009

Source: McDonald, 2013; Olympic Delivery Authority, 2008; CEEQUAL, 2013

the system design provides the flexibility to switch between biomass and natural gas in future (UNEP, 2015a).

There was explicit emphasis on building flexibility into the facility design so that heating and cooling capacity could be expanded once the sports event was over. In the long term, 10 000 new homes are to be supplied by the energy centre. This will mean installing several new engines and boilers fuelled by both natural gas and biomass. Further expansion opportunities have been identified in the surrounding districts (power-technology.com, 2012; UNEP, 2015a; McDonald, 2013; Olympic Delivery Authority, 2008; CEEQUAL, 2013).

SOLAR COOLING

So far no district energy system has been built to incorporate solar cooling. However, solar cooling has successfully been employed to satisfy the demand of single buildings and groups of buildings. It is a modular technology and can thus be readily scaled and connected to a larger network. Solar district cooling services can thereby be provided either by cooling water at a central location or operating decentralised absorption heat pumps using heat from a solar district heating system.

Case study 12: Phoenix, Arizona, US: Desert Mountain High School

Large parts of school building roofs in Arizona's Desert Mountain High School were covered with double glazed collectors, and racks were used to provide additional surface area above the car park. A lithium-bromide chiller with a capacity of 1750 kW provides cooling. During the summer months the solar system meets the school's entire cooling demand albeit at lower activity levels. During the school year the old electric chillers complement the supply.

The solar cooling system is owned by a dedicated energy service company, SOLID DMHS, which sells cooling as a service to the school. In addition, subsidies per metered unit of energy are paid by the local utility company to compensate for the savings from deferring grid investment (SOLID, 2014; SOLID, 2015; SOLID, 2016a; SDH, 2014).

Properties of particular large-scale solar cooling systems

	Commissioned	**Collector surface**	**Collector capacity**	**Chiller capacity**	**Peak coefficient of performance[2]**	**Total cost (USD million)**	**Storage**
Desert Mountain High school	2014	5 000 m^2	3 500 kW	1 750 kW	0.7-0.77 (thermal)	10	34.5 m^3 hot water
United World College South East Asia	2011	3 900 m^2	2 730 kW	1 500 kW	0.8 (thermal)	5	60 m^3 cold water/ 7 m^3 hot water
Sheikh Zayed Desert Learning Center	2012	1 108 m^2	N/A	400 kW	N/A	N/A	5 m^3 cold water/ 26 m^3 hot water

Source: SOLID, 2014; IEA SHC, 2012; SOLID, 2016a

2 The coefficient of performance is defined as the number units of work required to produce a unit of useful cooling or heating.

Case study 13: Singapore: United World College of South East Asia

The solar cooling system at the United World College of South East Asia in Singapore is based on solar collectors on the roofs of the university buildings. The system uses enhanced flat plate collectors, which perform better than single glazed collectors while avoiding part of the cost premium of double glazed collectors. Built by the same Austrian company as the system at Desert Mountain High School, the financing approach is very similar (IEA SHC, 2012).

Case study 14: Al Ain, UAE: Sheikh Zayed Desert Learning Center

The Sheikh Zayed Desert Learning Center was constructed as a part of the Wildlife Park & Resort, and serves as a museum. Unlike the systems in Phoenix and Singapore, the solar cooling facility in Al Ain was installed during the construction phase. This meant integration could be optimised by using the cooling capacity for concrete core activation, for instance. The solar system is owned by the Al Ain Wildlife Park Resort (SOLID, 2013; SOLID, 2016a).

NATURAL WATER COOLING

Case study 15: Paris, France: Large cooling network sourced by the river Seine

An extensive district cooling network has been installed underneath the city of Paris. It allows cold water from the river Seine to be used to supply space cooling to the city's buildings.

Since 1991, Paris has been relying on centralised cooling solutions to bear part of its space cooling load. Today, three networks are in operation, the largest of which is at the very core of the city. In all, eight centralised cooling plants with capacities ranging between 8 MW and 52 MW are connected to the network, and 45% of installed capacity comes from cold water in the Seine. In winter, when the river temperature reaches 4 °C, the water can be used directly through heat exchangers. Otherwise it is used to cool electric chiller condensers. As they have priority dispatch, the natural water cooling plants take around 75% of the annual cooling load in the system. Strict regulations limit the impact of the cooling system on the river; the temperature of the rejected water must not exceed 30 °C. In addition, the maximum deviation of the system from the river temperature is set at 5 °C-10 °C depending on the plant.

Cooling plants have been built underground to minimise space demand (*e.g.* Canada Energy Plant) or integrated into existing buildings (*e.g.* Palais de Tokyo). Extensive infrastructure below cities acts both as an obstacle and advantage for expanding the district cooling network. Synergies have been discovered *e.g.* by using the sewage system

Natural water cooling plants in Paris

Plant	Capacity	Combined share in the system	Avoided CO_2 emissions
Canada	52 MW	75% of cooling, 45% of capacity	50% (all district cooling, compared to distributed solutions)
Tokyo	52 MW		
Bercy	44 MW		

Source: Mairie de Paris, 2007; Climespace, 2016

District cooling in Paris

Inhabi-tants	District cooling network length	District cooling distribution	District cooling capacity	Network temperatures	Storage
2 240 000	73 km	470 GWh	330 MW	1°C-4°C 12°C-14°C	140 MWh at three locations

Source: Climespace, 2016; Mairie de Paris, 2007 to lay additional cooling pipes cost-effectively while avoiding street-level excavation and resulting disruption to traffic. In another example, a cooling plant was installed in partnership with the operator of the Paris metro system.

The whole Paris district cooling system produces half the carbon emissions of stand-alone systems. This corresponds to 20 600 tonnes CO_2 equivalent per year (Mairie de Paris, 2007; Climespace, 2016).

Case study 16: Bahrain Bay, Manama, Bahrain: Shallow seawater cooling in new development

The centralised cooling system in the new development Bahrain Bay expels part of the heat into the warm surface seawater. Capacity utilisation was negatively affected by the 2008 financial downturn, which brought construction to a standstill.

Bahrain Bay is a new real estate development at the Manama waterfront in Bahrain and is being built on three reclaimed islands. The first anchor development is the headquarters of a bank and was completed in 2012. A large hotel followed in 2014.

The cooling system is based on 18 centrifugal chillers using seawater on the condenser side. Much of the heat is rejected through nine cooling towers. That way, the temperature of the water is raised by only 3°C before being rejected into the sea, as demanded by environmental regulations.

The system makes use of natural filtering through a series of layers of sand and rocks under which the intake pipe is buried. Due to the extensive tidal range in the region, water intake is not always possible. Cold water tanks compensate for this, ensuring the continuous operation of the system for six hours under full load conditions. Titanium components allow direct seawater use while minimising corrosion.

The entire system has a coefficient of performance of 4.4 on the average. Other cooling systems based on a body of cold natural water take a much higher share of the cooling load directly through the cold water. However, in Bahrain the use of seawater has the additional benefit of reducing freshwater consumption for the cooling circuit.

The completion of Bahrain Bay was delayed after the financial downturn, which stalled many of the building projects included. Before the central hotel was completed, cooling plant operation was limited to the intermittent use of one of the 18 chillers (Veolia Middle East, 2016; McElroy, 2014; Bahrain Bay, 2010).

District cooling in Bahrain Bay

Network length	District cooling capacity
5 km	155 MW (45 000 RT*)

* refrigeration ton, Source: Veolia Middle East, 2016

Artist's illustration of Bahrain Bay

Source: Wikimedia Commons/Bahrain Bay/CC BY-SA 3.0

Case study 17: Geneva, Switzerland: Lake water cooling

A combined DHC system was installed in Geneva to supply the buildings of several of the international organisations residing in the city. The system relies on lake water used for both cooling and heating. It is extracted at the lake floor, where the water temperature is more or less constant throughout the year.

The lake water cooling and heating project in Geneva was primarily driven by the cooling demands of the buildings used by international organisations residing in the city. Since most of them had previously been heated by heavy fuel oil, a switch to a lake water heating and cooling system was bound to have positive effects on the local environment. The total cost of the project amounted to USD 34 million (33 million Swiss Francs). It was implemented and monitored with the participation of a large number of organisations, including the state government, local utility and research institutes.

The system is fed by a central pumping station where water from the lake is collected in an underground basin. It is extracted from a depth of 37 m where water temperatures are relatively stable throughout the year at 6°C-9°C. The return pipe releases the effluent 4.5 m below the water surface. The network has a maximum altitude gain of 75 m. Pumping energy is recovered by turbines operating before the water discharge. A proportion of the water returned irrigates a park next to the pumping station, which yields substantial drinking water savings.

In the connected buildings, the water serves both heating and cooling needs, depending on the time of demand. For cooling purposes, heat is transferred from the building's internal hydraulic circuit to the lake water using heat exchangers. For heating purposes, the heated water in the return pipe serves as a heat source on the evaporator side of the building's heat pumps. The environmental impact on the lake is minimised and monitored. The main concern is the discharge of the relatively cold effluent in the lake's warm surface layer. However, given the limited need for

District cooling in Geneva

Inhabitants	Network length	District cooling distributed	District cooling/district heating capacity	Network temperatures
190 000	6 km	95 TJ (26 500 MWh)	16.2 MW/3 MW	6°C-9°C

Source: Brasier, 2013

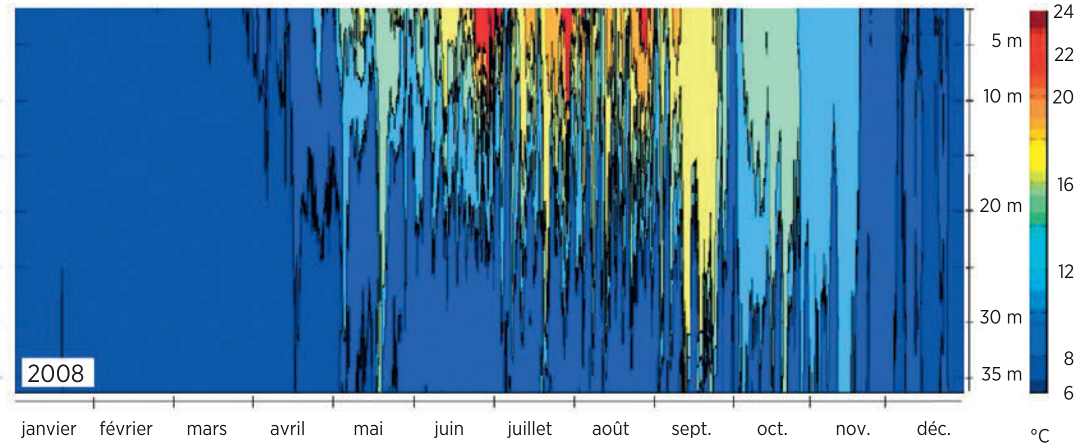
Lake water cooling system in Geneva

System	Capacity	Total energy supplied	Total system cost (including network)	Annual avoided CO_2 (tonnes)	Status
Lake water cooling	16.2 MW cooling	95 TJ (5.5% for heating)	USD 34 million	6 000	In expansion

Source: Faessler et al., 2012; Brasier, 2013; Viquerat (2012) cooling services in the Swiss climate, resource constraints are not a major concern in the design of the system. To minimise the impact on the lake's ecosystem, the water flow at the inlet is limited to a certain speed. Since the lake water enters the district energy network directly, chlorine is added to extracted water to avoid the growth of biofilms inside the system.

In 2015, 11 new and ten old buildings were connected to the network, consuming an estimated 95 TJ (26 500 MWh) of thermal energy (5.5% for heating). A significant expansion is planned before 2022. A second inlet pipe and a new pumping station will produce enough capacity to supply both the city's airport (80 MW) and several commercial buildings and hotels in the town centre (Faessler *et al.*, 2012; Brasier, 2013).

Lake water temperature as a function of depth throughout the year



Case study 18: Honolulu, Hawaii, US: Deep seawater cooling

A deep sea district cooling network is being constructed in Honolulu, Hawaii. The direct use of the water in a tropical environment means the inlet pipe has to be placed significantly below sea level to access sufficiently low temperatures.

The aim of the planned deep seawater cooling system is to supply space cooling to office buildings and condominiums in central Honolulu. Given the State of Hawaii's energy dependence and reliance on imported oil for cooling, the system is expected to provide significant cost savings. It is scheduled to start up in 2017 at a total cost of USD 250 million. The project was on hold in 2015 until the operating company could obtain binding contractual agreements to cover 59% of the total load.

A total of 70 MW (20 000 refrigeration tons) will be supplied through an inlet located 534 m below sea level, where the water temperature is about 7°C. To reach this depth, a pipe 7.6 km in length with a diameter of 1.6 m is laid on the seabed. Heat is transferred from the closed district cooling system to the seawater through a heat exchanger. Supplementary chillers in the cooling station ensure a constant water temperature in the distribution system (Pacific Business News, 2015; Makai, 2015; Honolulu Seawater Air Conditioning, 2011).

Planned district cooling system in Honolulu

District cooling capacity	Inlet pipe length	Inlet depth	Network tempera-tures	Estimated total cost	Inlet water tempera-ture	Status
70 MW (20 000 refrigeration tons)	7.6 km	534 m	6.7°C	USD 250 million	7°C	Completion 2017

Source: Pacific Business News, 2015; Makai, 2015; Honolulu Seawater Air Conditioning, 2011

Downtown Honolulu, part of which is to be supplied with seawater cooling

Source: Wikimedia Commons/Hakilon/ CC BY-3.0

POWER-TO-HEAT

Case study 19: Aarhus, Denmark: Electric boiler and heat pump for district heating

Wind power in western Denmark already makes significant contributions to the electricity mix. In Aarhus, two pilot projects make use of excess wind power for heat generation.

The city's use of variable renewable electricity for heating – together with other measures – is motivated by the municipality's ambition to become carbon neutral by 2030. There is also a national target to meet 50% of electricity demand with wind power. This calls for innovative approaches to integrating it into the grid.

Heat generation in Aarhus is based on combusting a mix of residues from agriculture and coal in the two-unit Studstrup CHP plant; by 2015, engineers had nearly finished converting it to the exclusive use of wood pellets (DONG Energy, 2015a). For improved flexibility, the plant is equipped with a pressurised storage tank of 33 000 m^3.

In 2015, a 80 MW electric boiler was installed at the Studstrup plant at a total cost of DKK (Danish Krone) 72 million (USD 11 million). Choosing a site containing an existing plant produces important synergies: firstly, grid connection with a high voltage is available. Secondly, the plant's pressurised storage tank can act as a buffer between heat generation and demand. Thirdly, wind power production is greatest in winter and thus well correlated with heat demand in Denmark. This means the electric boiler is expected to primarily replace oil-based peak load boilers installed at the same power plant. (DONG Energy, 2015b)

The aim of improving the value of excess wind power also motivated the installation of an electric heat pump in the new harbour district Aarhus Ø. Seawater is used as a heat source. Its temperature in winter is thereby lowered from 4 °C-6 °C to 0 °C-2 °C (with up to 14% ice in the discharged water) (COWI, 2015). The whole system required USD 22 million (DKK 148 million) investment, including the transmission pipe, heat exchangers and sea water pump (City of Aarhus, 2016). The inherent modularity of the heat pumps

District heating in Aarhus

	Inhabitants	Network length	District heating produced	District heating share	Network temperatures
Old system	320 000	130 km (transmission only)	10 600 TJ 2 900 GWh	95%	-
New system Aarhus Ø	75 000 by 2030	-	-	100%	65°C/40°C

Sources: City of Aarhus, 2016

Studstrup CHP plant with new biomass silo under construction

Source: DONG Energy A/S

allows capacity to be continually expanded. A decision on the installation of the full 14 MW will be taken after the performance of the initial 2 MW is assessed. This is planned to start up in 2017. At their full planned capacity, the heat pumps will be able to take the entire heat demand of the neighbourhood, thereby replacing oil boilers (City of Aarhus, 2016; COWI, 2015).

Case study 20: Lemgo, Germany: power-to-heat for ancillary services

While the district heating system is dominated by natural gas co-generation plants, the viability of electric boilers is being explored. Due to regulatory restrictions, the use of boilers is largely limited to ancillary services instead of the direct use of surplus wind power.

Lemgo's district heating network dates back to the 1960s and is primarily fuelled by natural gas. Most of the installed capacity consists of large natural gas CHP plants and boilers. However, the baseload is covered by 12 small-scale gas CHP plants installed in 2005, each with a 2 MW capacity. The connection of these facilities has greatly improved the efficiency of the system, and large cost savings have been achieved thanks to their modularity (IFEU, 2013).

A 5 MW boiler electric has been running since 2012. The total cost of the system amounted to USD 930 000 (EUR 900 000), including the replacement of the boiler house. The boiler is connected to the local 30 kilovolt grid to avoid transmission constraints while operating at maximum capacity. This connection has increased costs significantly (IFEU, 2013).

By concentrating heat production during the night, the system avoids the fixed capacity rates of grid use. This is facilitated by the availability of storage capacity. It has been estimated that the boiler can compete with heat production from the CHP plants during 500 full-load hours of the year (IFEU, 2013).

The direct use of power curtailed due to surplus wind turbine output or grid congestion is not an option at the moment. Instead, the boiler's operating schedule is determined by the prices in several markets for electricity and ancillary services as well as the marginal costs of the other boilers and CHP plants in the district heating system.

Bids for the provision of negative operating reserve capacity are submitted to the secondary control reserve market. This is independent of the demand for heat. The system's storage capacity thus plays a

District heating in Lemgo

Inhabitants	Length	District heating share	Trend	District heating produced	Maximum district heating load	Network temperatures	Storage
41 000	58 km	40% of the low temperature heat demand	2005-2012: -10% expected trend: -2% per year	600 TJ 165 GWh	60 MW	105°C (90°C) Return: 60°C	2 700 m^3

Source: Kraftwirte, 2014 and IFEU, 2013

pivotal role in matching power supply and heat demand. The replacement of heat from the highly efficient small-scale CHP plants during the summer months is not considered desirable. Because of this, high bids are submitted during that time, which limits the revenue to the payments for the balancing capacity.

The electric boiler operates at up to 1500 full-load hours and contributes 27 TJ (7.5 GWh) to total heat generation *i.e.* 5% of total heat supply in 2012. Experience has shown that the income generated by providing ancillary services is key to the economic success of this investment (stadt+werk, 2013; IFEU, 2013).

Case study 21: Hohhot, Inner Mongolia, China: direct use of otherwise curtailed wind power

In Inner Mongolia, high amounts of wind power and limited transmission capacities create very high curtailment rates. When the old centralised heating systems in the city of Hohhot were upgraded, electric boiler capacity was installed to put this surplus power to use.

Centralised heating in Hohhot developed as a series of small-scale distribution networks fed by relatively inefficient isolated coal boilers. The Low-Carbon District Heating Project has been proposed with the aim of modernising the systems and reducing their environmental impact. It consists of expanding and interconnecting the network infrastructure, installing cleaner plants fuelled by natural gas and investing in 50 MW of wind-powered electric boilers (Asian Development Bank, 2014; Asian Development Bank, 2016).

The Inner Mongolia Autonomous Region has a quarter of all Chinese wind power capacity (22.3 GW by the end of 2014). Transmission constraints and the high penetration of CHP plants means up to 45% of potential electricity generation is curtailed (UNEP, 2015a). To counteract this inefficiency, the Chinese National Energy Administration encourages wind power for heating. The city of Hohhot is the main urban centre in the Inner Mongolia Autonomous Region and has a developed district heating network. It is therefore the test bed for the first large-scale implementation of this power-to-heat scheme, whose completion is due in 2020.

Otherwise curtailed electricity is sold at an "affordable cost" to the local heating company. The grid operator receives payment for the transmission. Almost 400 TJ of heat is to be generated this way each year, corresponding to 2.8% of annual planned district heat generation (Asian Development Bank, 2014; Asian Development Bank, 2016).

District heating in Hohhot

Inhabitants	Length	District heating share	District heating produced	District heating capacity	Network temperatures
1.9 million (urban, 2012) 883 500 affected	79 km (primary network, proposed)	95%	14.4 PJ	1 422 MW (proposed)	Transmission: 135°C/75°C; distribution: 95°C/65°C

Source: Asian Development Bank, 2016

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