Combined Heat and Power Generation and District Heating in Denmark: History, Goals, and Technology

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For more than 25 years Denmark has aggressively applied state-of-the-art energy production and management strategies and employed innovative technology to meet its national goal to make this North European country self-sufficient and secure in energy while meeting environmental goals. Over the past 20 years Denmark's energy consumption has remained relatively constant, despite a 50% rise in the Gross National Product. This has been due to better home insulation, more efficient fuel use including combined heating and power generation, and more energy-efficient industrial processes.[1]

This article briefly reviews the development of Danish combined heat and power (CHP) generation and energy policies; fuel sources; and the role of CHP generation. It also reports characteristics of the major heat transmission network, Centralkommunernes Transmissionsselskab I/S (Metropolitan Copenhagen Heating Transmission Company) that serves the Copenhagen area, and a major CHP station, Avedøre, that supplies heat to it, both visited by author Henry Manczyk at the invitation of the transmission network company President and Chief Executive of CTR, Mr. H. C. Mortensen, in September 2001.

Denmark is situated north of Germany, south of Sweden and Norway, and at the eastern edge of the North Sea at the straits leading into the Baltic Sea. It encompasses the largely rural Jutland peninsula on the west that extends from Germany; the large island of Funen; the larger island of Zeeland on the east on which the capital city of Copenhagen is located; and many smaller islands. Jutland and Funen are connected to the electricity distribution networks of Germany, Norway, and Sweden; Zeeland and the small islands nearby are connected with the networks of Germany and Sweden. Proposed electricity network connections across the "Great Belt," the strait between from Jutland and Funen and the eastern islands have not yet been constructed, effectively creating a division of the nation into eastern and western regions. The heating season in Denmark averages 3120 degree-days Celsius, (5616 degree-days Fahrenheit).

The nation's population of over 5 million is concentrated in the east, living in the urbanized areas on Zeeland around and west of Copenhagen. The nation has a light industrial base. The Danish public is accustomed to a high level of government regulation of the economy. About 50% of Gross Domestic Product is paid in taxes (1998) and half is spent directly by government. These factors combine to provide the Danish government the authority and resources to pursue an aggressive, innovative national energy policy.[2]

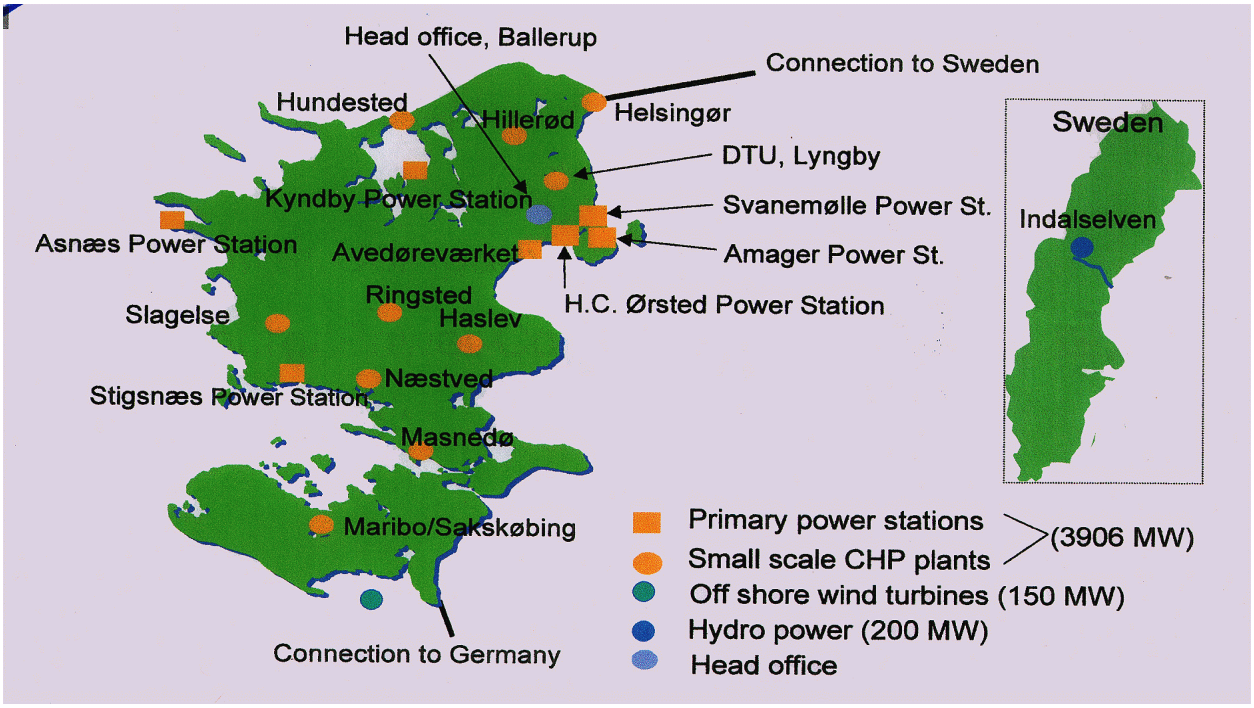
History of Combined Heat and Power Production and Energy Policy

In 1904 Denmark built its first combined heating and power generation (CHP) plant in Copenhagen to supply heat and electricity to a hospital. It began to expand in the 1920s and 1930s, producing heat for district heating systems and electricity.[3, 4] In the period of 1955-1973, more than 200 district heating networks were established all over Denmark.[5] Prior to 1950, all district heating was supplied with waste heat from municipal incineration and electricity production. Until the 1960s, the main energy sources for heat and power generation were coal, coke, wood and peat. During the 1960s, the consumption shifted from coal to fuel oil due to relatively cheaper fuel-oil prices.[5] In 1972 more than 90% of demand for energy was met using imported oil.[1]

Prior to the 1973 oil crisis there was very little government regulation of the Danish energy sector.[6] In 1973 all electricity in Denmark was produced by fossil fuels, 80% from oil alone.[1] In 1976 the government adopted

its first energy plan. It emphasized security of energy supply, energy savings, and oil substitution. It included exploiting surplus heat from power plants and enhancing combined power and heating in cities to meet a goal of supplying 25% of heat demand by 1995. As a result, the power industry changed from oil to coal as the primary fuel. In the early 1980s about 60 plants were converted to coal firing with an average payback of one to three years. As a result of the massive conversion,[5] coal usage has increased from 20% to 90% for generating power.[1] (This was advantageous because of better pollution control systems had become available for the new coal burners, the oil-fired plants were approximately 20 years old, and Denmark was using coal with less than 1% sulphur while its oil contained 1.5% sulphur.[5])

In 1979, the Danish government decided to exploit the oil and natural gas resources in the Danish sector of the North Sea.[5] The major market for natural gas was determined to be space heating, displacing oil. Denmark was divided into heating areas, one, west of the Great Belt, served primarily by natural gas, and one to the east of the Great Belt, served primarily by combined heat and power (CHP).[7]



Power and thermal generation in Eastern Denmark. *Courtesy of Energi E2 Company*

In the late 1980s the negative impact on the environment from the coal led to government support of research and development efforts by the utilities to reduce emissions of SO_2 and NO_2. In the 1990s, government directives were issued to switch toward more environmentally friendly energy sources such as biomass, natural gas and wind power.

Energy plans have increasingly focused on security of supply, energy savings, environmental awareness, and global environmental goals, including active support for the Kyoto protocols. A key target is reduction of CO_2 emissions by 20% by 2005 compared to 1988. Danish policy emphasizes self-sufficiency for power and heat generation for the nation. It relies heavily on nationally-controlled fossil fuel and renewable fuel sources.

Among the methods employed by the government to advance its policies have been carbon taxes on all energy production. According to the October 1998 International Energy Agency review of Danish energy policy, "...The price of electricity to Danish households is the second highest of IEA countries, while the price to industry is about the middle of the range." Without the taxes, electricity prices are among the lowest in Europe.[8]

Energy tax revenues have been used to finance:

- Research, development, application, and subsidy of preferred technologies and fuel sources that pollute less than coal;
- Mandatory connection of new structures to district heating networks within districts;
- Conversion of the heating plants of existing buildings for connection to district heating networks;
- Restriction of residential use of certain heating fuels in district heating areas; and,
- Construction of combined heating and power plants.

Complementary measures include:

- Banning use of coal in new CHP plants (Denmark has no coal industry to oppose this measure);
- Voluntary agreements with companies to achieve specific objectives;
- International agreements for purchase of hydro power; and,
- Other measures to guarantee development of and market for otherwise uneconomic technologies.

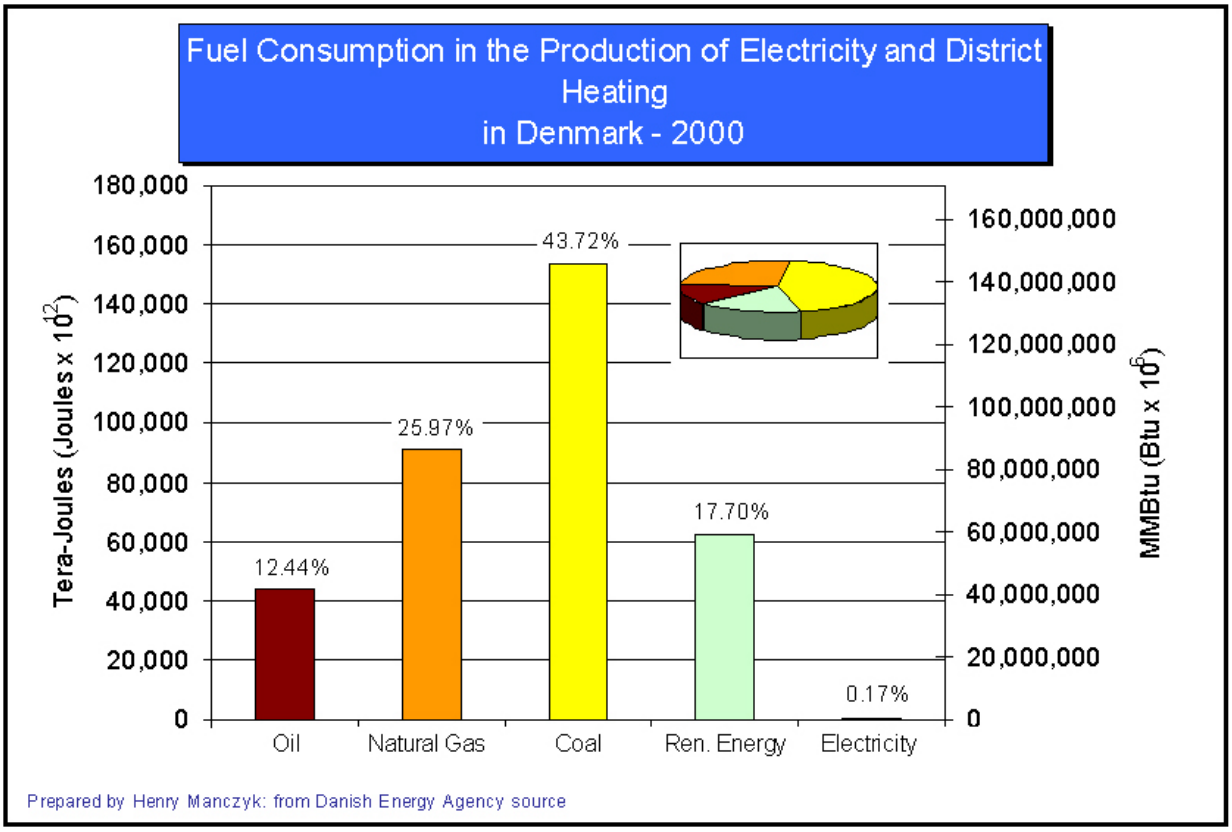
It has used price controls to provide utilities with cash for planned improvements, and to protect district heat consumers. Consumers are discouraged from use of electric heating. Gas and district heating are not permitted to compete, avoiding investments in duplicate distribution systems, etc.[8] The government is largely successfully working within the European Union to coordinate its national policy and EU policy to preserve Danish goals and methods of achieving them.

Resources and Sources

Denmark's energy production is based mainly on imported coal; oil and natural gas from the Danish region of the North Sea; wind energy; straw and other biomass fuels; solar energy; and some geothermal energy. Coal is the primary fuel for the production of electricity and heating and is wholly imported.[9] It is imported from Russia, Poland, Columbia, Australia, the USA, and South Africa (1996).[10] The maximum sulfur content of the coal is 1.2%.[11] In 1996 electricity generation consumed more than 90% of the coal imported. Coal provided fuel for 74% of the electricity and heat generation.[10] The Danish government's energy plan proposes replacement of coal for electricity generation by natural gas and, increasingly, renewables including wind power. In 1997 the Minister for the Environment banned coal use in new power stations; existing coal-fired units are to be converted by 2030. By 2030 no coal-fired electricity generation is to remain.

Fuel oil and natural gas are produced in the Danish sector of the North Sea fields. After Norway and the United Kingdom, Denmark is the third largest fuel oil producer in Western Europe.[9] In 1998 the International Energy Agency (IEA) reported that Danish oil reserves will last for 19 years at current rates of production.[12]

The IEA also reported in 1998 that, at the then-current 5.71 billion cubic meter annual production rate, natural gas reserves will last for 24 years, and will meet all domestic needs for 12 to 14 years (2010 to 2012), after which it is expected that Denmark will have to begin importing again.[13] Nevertheless, Denmark exports natural gas to Sweden and Germany (35% of production in 1996) and sells excess fuel oil on the spot market[9], assuming that reserves will increase as consumption increases.[1]



Fuel Type	TJ	MMBTU
Oil	43,708	41,427,190
Natural Gas	91,286	86,522,430
Coal	153,642	145,624,500
Renewable energy, etc	62,216	58,969,390
Electricity	598	566,795
Total	351,451	333,110,305

Denmark imports hydroelectric power from Sweden and Norway during the "wet" season, and, in return, supplies power to them during the "dry" seasons.[14] Sales of gas to Norway during its hydro power dry seasons, and purchase of Norwegian hydro power when gas is in high demand for heating in Denmark could help both countries control costs.[15]

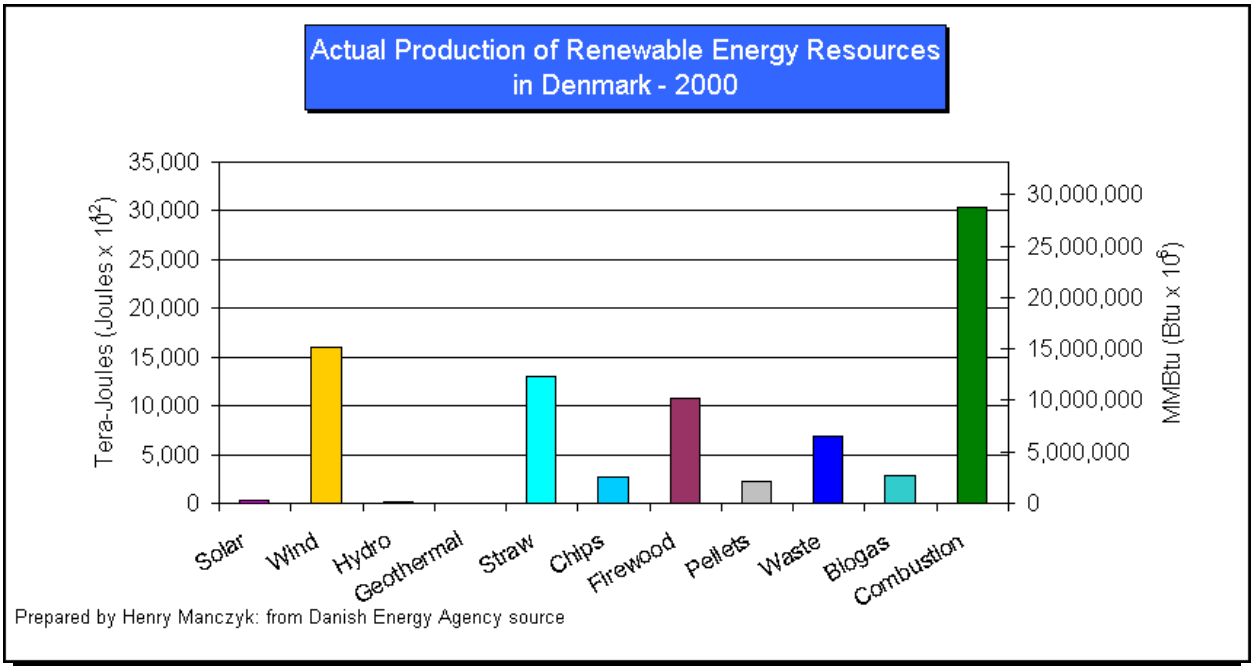
Danish energy policy set targets for recycling 54% of waste, incinerating 25%, and landfilling 21%.[16] In 1997 63% was recycled, 21% incinerated, and only 16% landfilled.[17]

Among Danish policy objectives is to expand "renewable" energy sources, primarily biomass and wind power, from approximately 8% of primary energy supply in 1995 [100PJ (9.478×10^{13} Btu's)] to about 12-14% by 2005 and about 35% by 2030.[18]

Biomass is the largest contributor to the Danish renewable energy production. It comes almost exclusively from agricultural and forestry byproducts and municipal waste. It includes industrial and municipal solid waste, wood chips and pellets, straw, energy crops, and biogas.[19]

In 2000, biomass contributed 45.1% of the energy production from renewable sources; waste combustion 35.6%; wind 18.7%. Solar, hydro, and geothermal sources contributed only 0.6%.[20]

Straw is the principal biomass source (15.3% in 2000[20]), and is usually supplied in 500kg (1,102 lbs.) bales. Transport from farm areas, site storage, and conveyance to boilers present technical challenges, although Danish utilities feel that these have been managed. Energy density of straw is only 10% that of coal. Chlorine and alkali content cause performance problems and slagging, fouling, and superheater corrosion, and the ash cannot be used in the cement industry. Dedicated boilers may be used to handle these problems. The price of straw was three to four times that of coal in 1998, in part because the Biomass Agreement (1993, 1997) requirement for utilities to use renewables such as straw and wood chips, gives farmers a strong price negotiating position.[18] In 1997 there were 59 straw-fired plants in operation in Denmark. The largest straw-fired plant, Avedøre 2, has a capacity of 48 MW_e and 47 MJ/s (1.605×10^8 Btu/hr) of heat. Preparations are being made to activate the new straw-fired boiler in the fall of 2002.

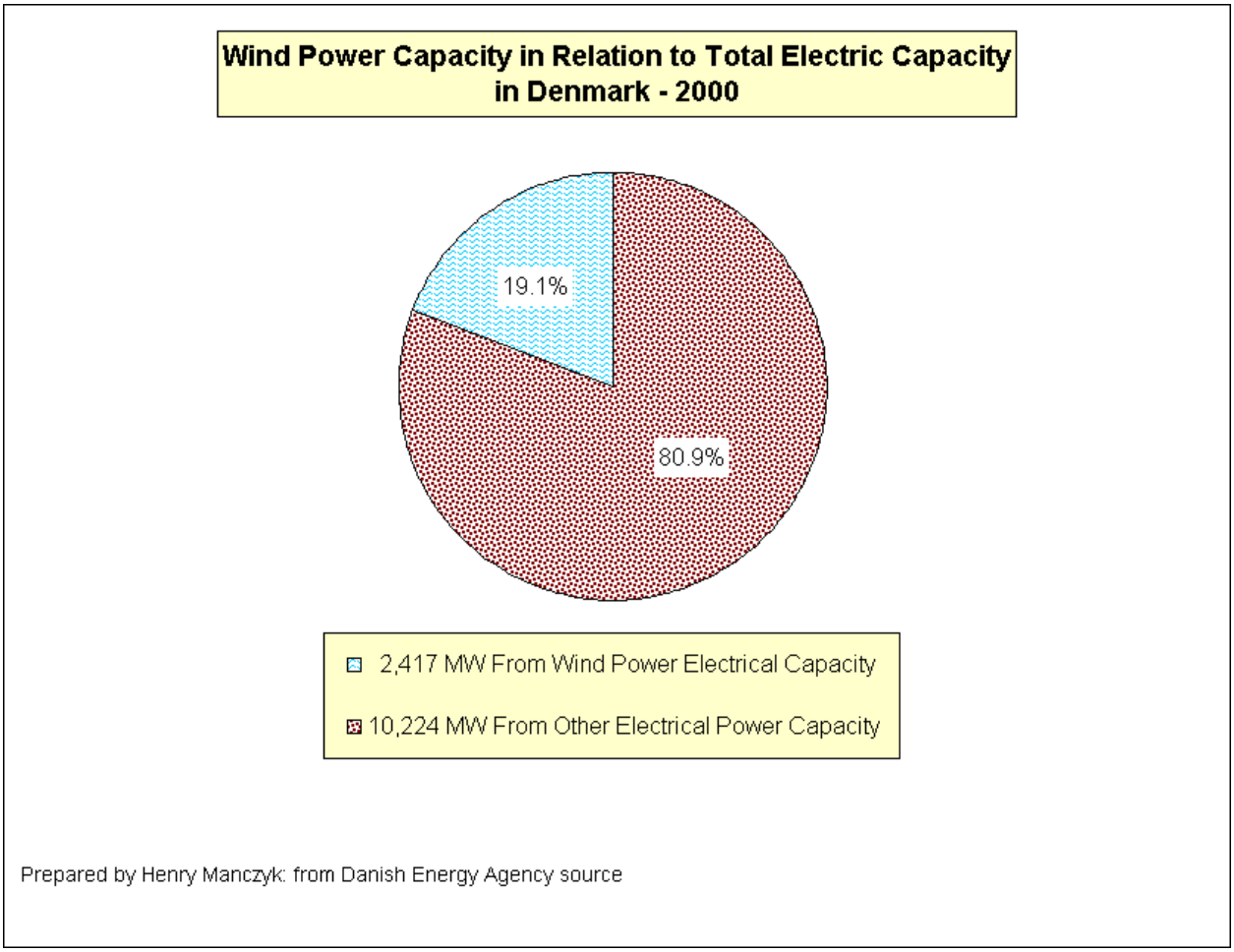


Fuel Type	[TJ]	[MMBTU]	%	Fuel Type	[TJ]	[MMBTU]	%
Solar Energy	331	313,727	0.39%	Firewood	10,743	10,182,399	12.59%
Wind Power	15,989	15,154,648	18.73%	Wood Pellets	2,257	2,139,223	2.64%
Hydro Power	103	97,625	0.12%	Wood Waste	6,816	6,460,321	7.99%
Geothermal	58	54,973	0.07%	Biogas	2,912	2,760,043	3.41%
Straw	13,053	12,371,857	15.29%	Waste Combustion	30,342	28,758,667	35.55%
Wood Chips	2,742	2,598,915	3.21%				

Total (Tera-Joules)	85,346
Total (MMBTU)	80,892,400

In recent years Denmark has developed wind power generation to produce 12-14% percent of its electricity consumption and has become the world's largest producer of wind turbines, supplying 50% of the world demand for the equipment.[21]

In 1990 the wind power was only 2% of Denmark's total electric capacity. By 2000 installed wind generation capacity had been increased to 2,417 MWe, 19% of the total Danish electricity generation capacity. Actual production in 2000 was 12.6% of Danish electricity consumption.[22] The national objective is that by 2030 the wind energy in Denmark will supply 40% to 50% of electricity consumption.[21]



Wind turbine installations are widely distributed through the country; offshore sites will be developed. A large reserve capacity is provided to accommodate the intermittent nature of wind conditions.

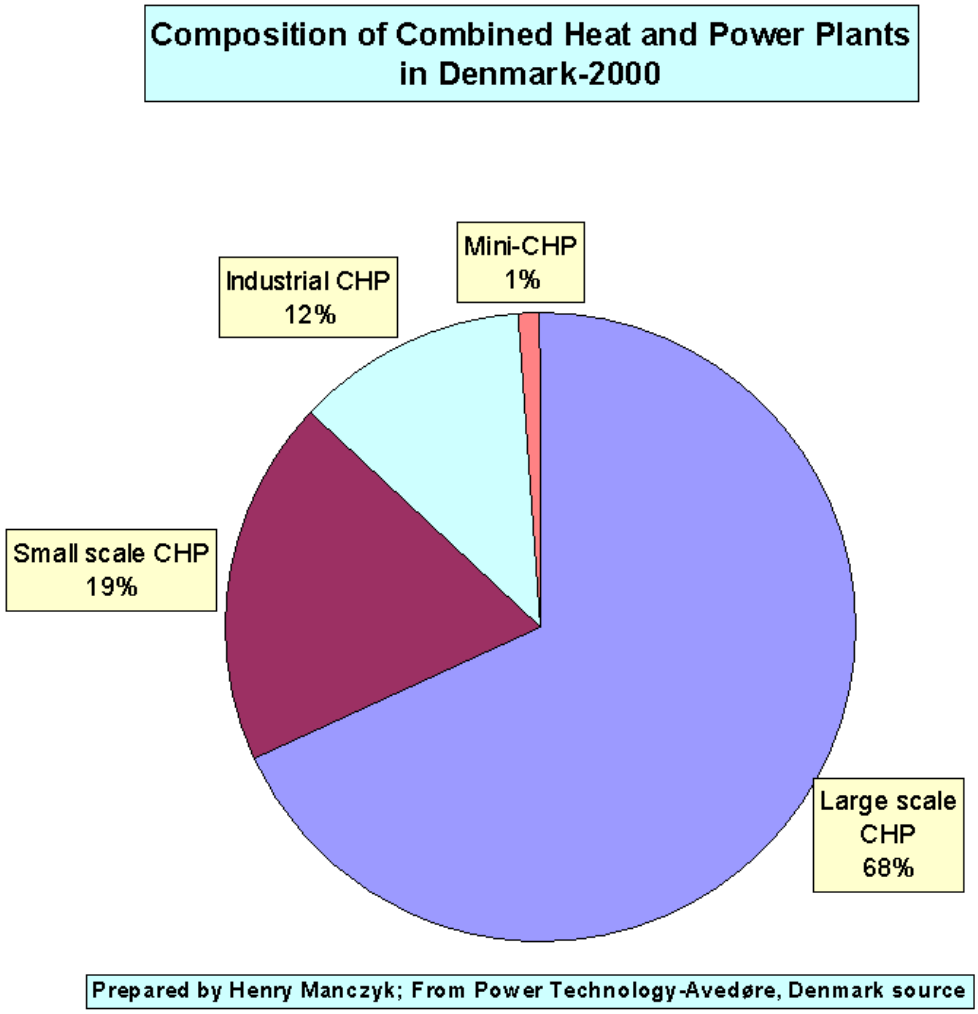
In 1985 the Danish Parliament foreclosed the option for use of nuclear power plants.[23]

Combined Heating and Power Generation and District Heating

Most electricity in Denmark is produced by large CHP plants that also supply heat to district heating systems and institutions in major cities. More than 50% of the space heating supply in Denmark comes from district heating systems. In 2000 combined heating and power facilities generated 60% of the electricity for domestic supply[24] and approximately 75% of the heat supplied to district heating systems.[25]

Because of the large number of large and small district heating systems serving Danish urban areas, combined heat and power (CHP) generation has become a major element of Danish energy and emissions control planning.

Under the Danish heat planning system, cities were divided into areas for central district heating and areas for individual natural gas supply. The urban areas of the eastern region of Denmark, in particular, were established as district heating-only areas. District heating was made a local natural monopoly, exempted from competition to ensure markets and economies of scale. 95-98% of the heat used in Denmark's 10 major cities' district heating systems is produced in CHPs fired by coal, natural gas, or municipal waste.[26] Government policy is to convert to natural gas and renewables and to abandon use of coal in all plants by 2030.



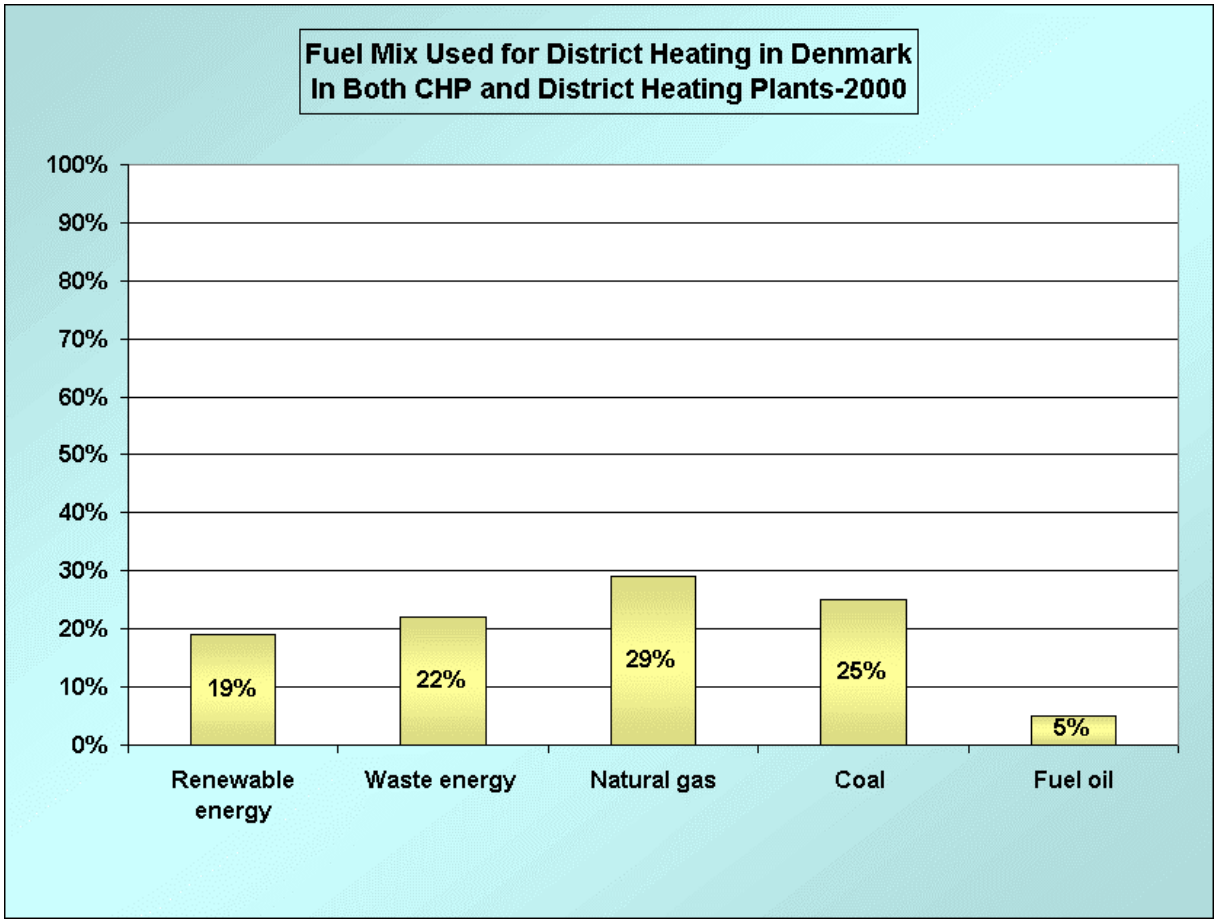
Energicenter Danmark reports that in 2000 75% of the total district heating supply of nearly 112,300 TJ (1.064 x 10^{14} Btu's) was produced as combined heat and power, an increase of about 20% compared to 1986. The remaining production sources were

Waste incineration plants	12%
Biomass heating plants	6%
Wood pellets at biomass heating plants	1%
Oil	1%
Natural gas	2%
Surplus heating from industries	2%

The fuel used for district heating on both CHP and district heating in 2000 was

Renewable energy	19%
Waste	22%
Natural gas	29%
Coal	25%
Oil	5%

("Fuel for CHP and district heating", November 2001[27])



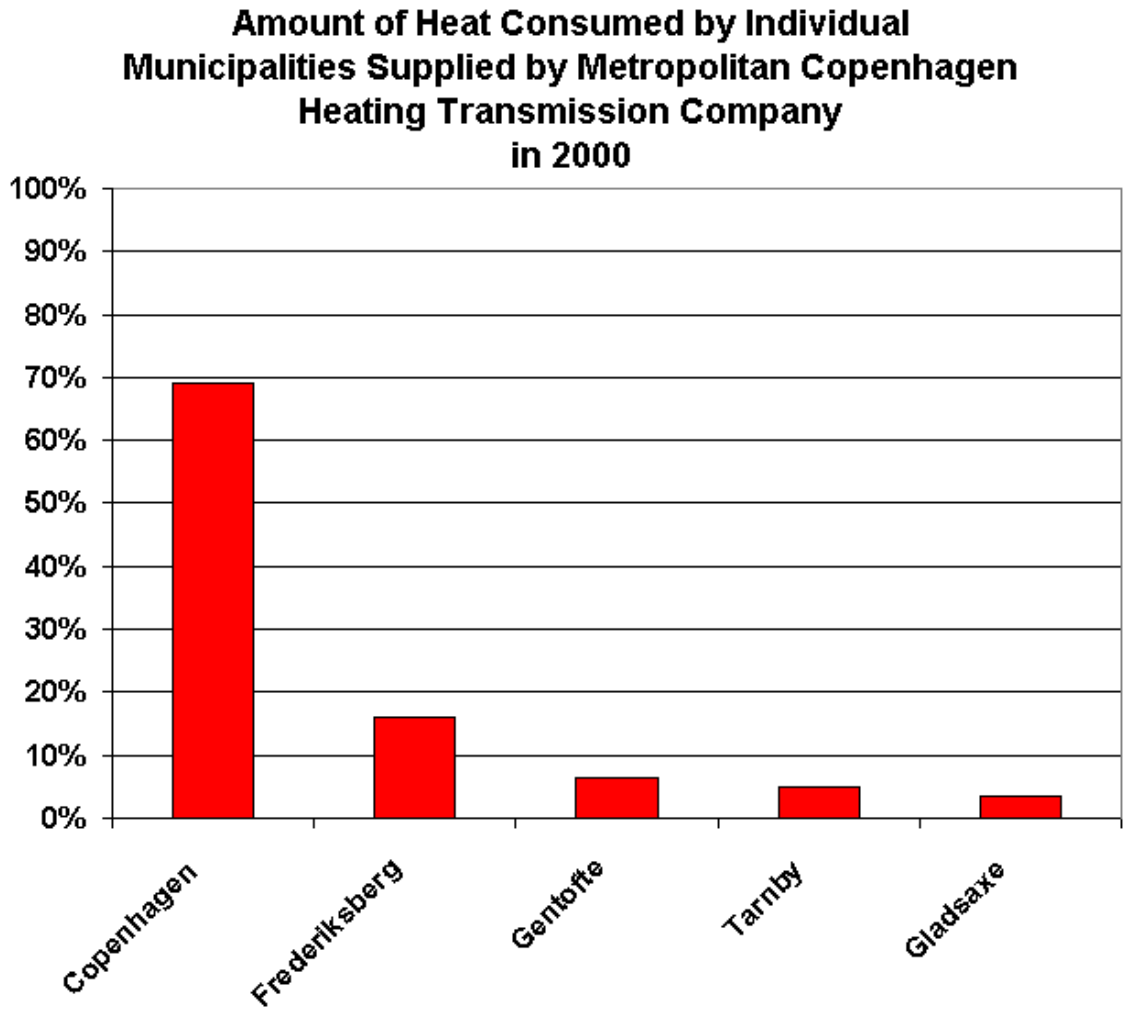
Prepared by Henry Manczyk from Energy Centre Denmark Source.

Copenhagen Heat Production and Transmission for District Heating

The Danish space heating industry has been segmented into three components: Supply, transmission, and distribution. CHP plants are the primary producers of heat for the customers served by the local district heating systems. Transmission companies have been established to convey heat from the production plants to the local distribution networks. Each component is subject to government regulation.

In the Copenhagen area two heating transmission companies purchase and convey heat from the primary power stations, incineration plants, and from other sources (for peak load or back-up supply) to the municipal and cooperative district heating companies within their territories. The transmission networks supply a maximum temperature of 120ºC (248ºF) at a pressure of 25 bar (362 psi), with a return temperature of 50ºC-60ºC (122ºF-140ºF), based on the optimal balance of heat energy allocated to the electrical and hot water generation at the CHP plants.[28]

The Metropolitan Copenhagen Heating Transmission Company (CTR–Centralkommunernes Transmissionsselskab I/S) serves the Copenhagen area. It was established in 1984 as a partnership of the City of Copenhagen and the four adjacent municipalities of Gentofte, Gladsaxe, Frederiksberg, and Tarnby. The main objective of the CTR transmission company is to utilize heat from refuse incineration and from CHP plants. The cost for the investment for its entire transmission net totals $425 million. CTR operates 54 km (34 miles) of hot water piping transmission, interconnecting various heat sources with the municipal district heating networks. This system is one of the largest of its kind in the world. It will be serving 275,000 households in 2002.[29]



Source: Facts and Figures about CTR. Metropolitan Copenhagen Heating Transmission Company

Copenhagen is the largest customer connected to the CTR transmission system; its district heating networks will serve 95% of the municipal needs by 2002, versus 65% in 1991. This results in a reduction of CO_2 emissions of 570,000 tons per year.[30] Connections to the district heating system will continue to increase to cover up to 98% of the users in the Copenhagen area.

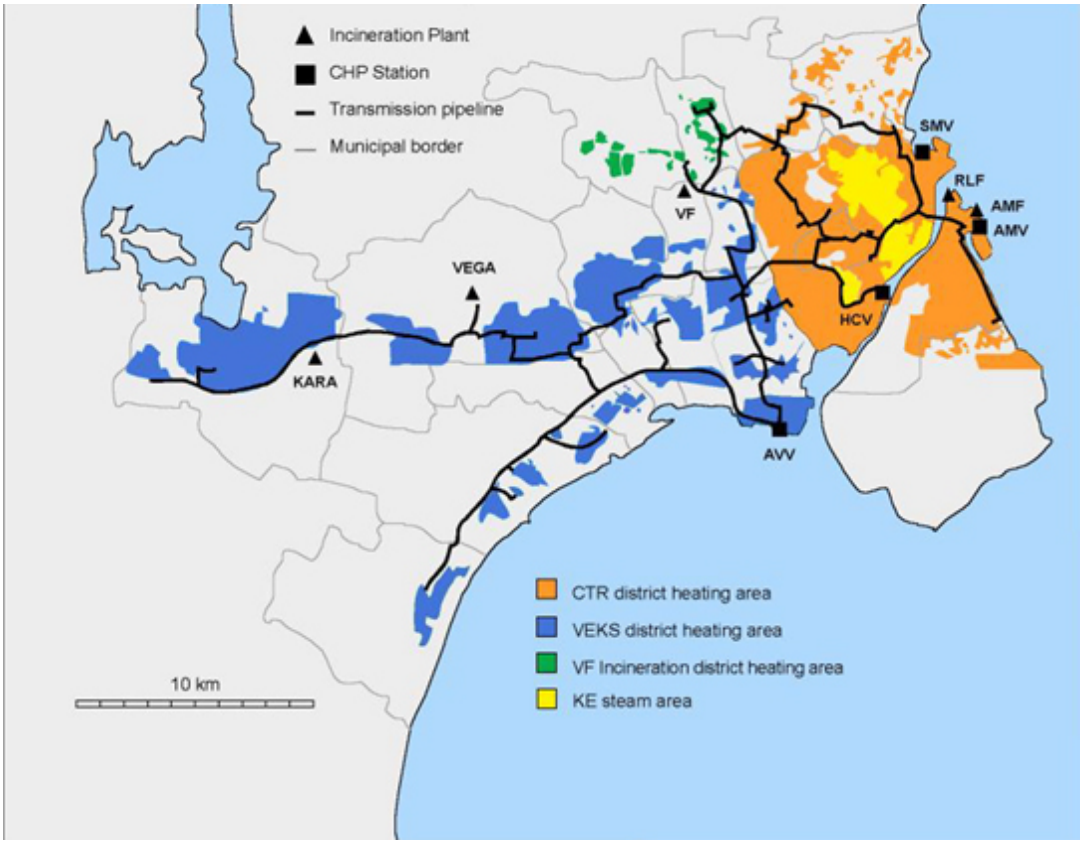
CTR purchases about 80-85% of its heat from CHP plants located in the Copenhagen region: Amagervaerket, HC Oerstedvearket, Svanemoellevaerket and from Avedørevaerket #2. Approximately 15% comes from incineration plants, primarily Amagerforbraending, Vestforbraending and Rensningsanlaeg Lynetten refuse plants. The rest of the heat is by means of natural gas and oil-fired heating plants.[28]

Another heat transmission company, "VEKS" (Vestegnens Kraftvarmesesskab I/S), serves 10 municipalities to the west of Copenhagen. It is interconnected with the CTR loop, permitting them to exchange heat. VEKS provides heat and domestic hot water to 125,000 households.[4] Most of the heat that VEKS company purchases comes from Avedørevaerket #1 and incineration plants.

The size of the transmission network and the variety of production facilities that supply it permit CTR and VEKS to estimate heating and electricity demand and optimize production based on price, environmental factors, and production facility priority. Because 95% of the heat which is procured by CTR is a product of surplus heat from the CHP stations and refuse incineration plants, the amount of fuel consumed to meet area

heating demands has been cut in half, also reducing pollution emitted. SO_2 emissions have been reduced to 33% of the pre-existing levels and CO_2 has been cut to half of its original level. NO_x emissions have been cut to 10-20% of their prior levels at plants fitted with nitrogen reduction equipment.[28]

In the year 2000, refuse incineration met approximately 20% of heat demand in the CTR and VEKS area, equivalent to a heat supply for 70,000 households.[31]



Hot Water Distribution System in Copenhagen Region
Courtesy Metropolitan Copenhagen Heating Transmission Company

Avedøre Power Stations

Two of the most modern plants from which CTR purchases its heat (via the VEKS network) for the Copenhagen region are the CHP Avedørevaerket plants #1 and #2. They are located 10km south of Copenhagen on reclaimed land on Koege Bay.[32] Among the companies constructing and owning the plants are Sjaellandske Kraftvaeker, (which as SK Power Company, has merged with EK Energi Power Company and KE Produktion of Denmark to form "Energi E2"[33]) and Vattenfall AB of Sweden.[32, 34] Avedøre 1 is a typical modern CHP plant; Avedøre 2 is an early example of the planned future development of major Danish plants. (Unless noted in the text, the Avedøre plant data are drawn from brochures and technical presentation materials graciously supplied by Mr. Thomas Scott Lund of Avedøre plant management, primarily source[34].)

Avedøre 1

Avedøre 1 CHP station was commissioned in 1990, producing electricity for eastern Denmark and heat for one of the largest district heating systems in Northern Europe. It is a base-load facility producing up to 250 MW_e or, in cogeneration mode, 215 MW_e electricity and 300 MJ/s (1.025×10^9 Btu/hr.) heat for district heating. It provides 12% of electric demand in eastern Denmark and district heat for about 100,000 homes.

The plant mainly uses coal, consuming around 600,000 tons annually. Coal is delivered to the station three times a week, by sea, by barges carrying about 9,500 tons of coal each. The coal yard has a storage capacity of 800,000 tons of coal. At its highest peak the plant uses 85 tons per hour. Coal is fed on conveyors to silos for pulverization where it is blown to the furnace and is ignited in low emission NOx burners. The plant is also designed to use fuel oil for fuel flexibility, as much as 50 tons per hour.

Avedøre Power Station 1. Fired with coal and fuel oil. *Courtesy Avedøre Power Station.*

The high-pressure steam at 250 Bar (3,625 psi) and 545ºC (1,013ºF), is then fed to the steam turbine, generating 132 Kv for delivery to the high voltage grid. The turbine plant is a combination of a high-pressure turbine with two intermediate-pressure turbines and one low-pressure turbine. The intermediate pressure turbine supplies steam to district heat exchangers.

The station has two heat accumulator tanks for collecting up to 44,000 cubic meters of water (11,600,000 US gallons) of surplus hot water in periods with low district heating demand and reserve it for periods of high demand. Their discharge capacity is 330 MJ/s or (1.126 x 10^6 Btu/hr.).[29]

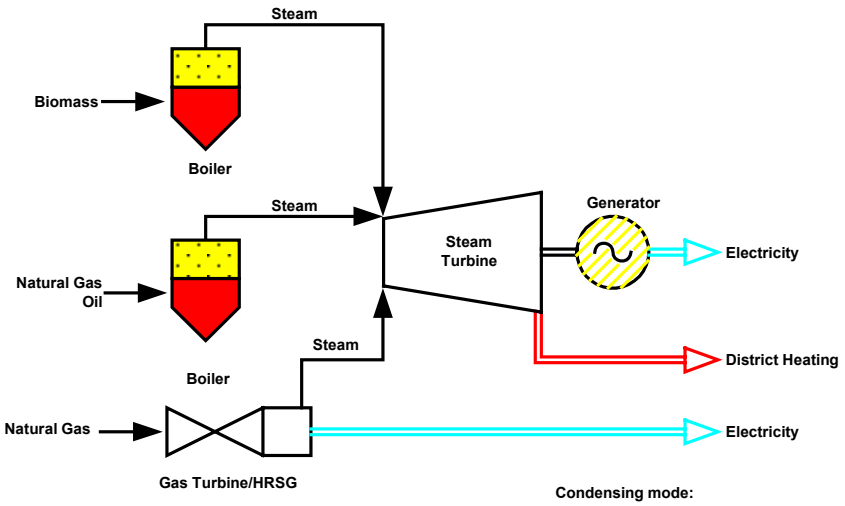
Avedøre I controls emissions using an electrostatic precipitator and a wet method, lime water scrubbed desulphurization plant. The scrubber process produces about 3.5 tons of gypsum per hour from the lime water and sulfur.

Avedøre 2

In the mid 1990s the Avedøre owner, Sjaellandske Kraftvaeker, proposed that a second Avedøre plant be constructed. It would meet projected additional electricity and district heating demand and replace aging, more polluting facilities. Following the Minister for the Environment's 1997 ban on coal use in new power stations, the application was approved on the basis that production would be based on natural gas and biomass. The main furnace design was therefore modified for natural gas firing and a biomass unit was incorporated. This advances the government's plan to eliminate coal-fired electricity generation by 2030 and its objectives for use of renewable energy sources. [33, 34]

The Avedøre 2 CHP plant has the capacity to supply 180,000 homes with heat and 800,000 households with electricity, about 20% of the electricity demand in eastern Denmark. Its capacity is 570 MW_e or, in cogeneration mode, 485 MW_e of electricity and 570 MJ/s (1.947×10^9 Btu/hr.) of heat for district heating. The new CHP station is a multi-fuel plant, capable of burning natural gas, biomass and fuel oil. It is rated the most flexible and energy efficient plant of its kind in the world. About 85% of the total fuel consumption at the Avedøre CHP station will be natural gas, amounting to 600 million cubic meters annually.

Avedøre 2 - Plant Configuration



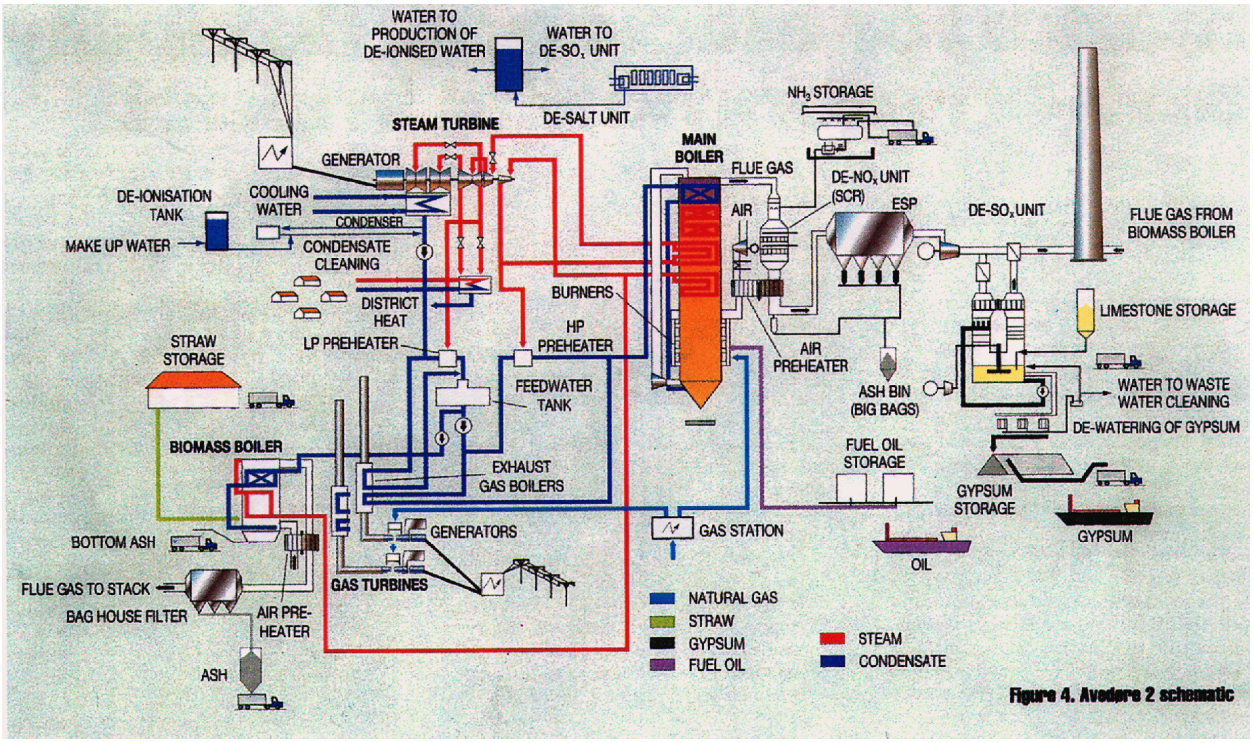
Prepared by Henry Manczyk, from Power Technology-Avedøre, Denmark source

The biomass plant contributes 48 MW_e of electricity and 47 MJ/s (1.605×10^8 Btu/hr.) of heat. The fuel is mainly straw, but the plant can also can burn wood chips. When it is in full production, it consumes 25 tons of straw per hour. Each bale of straw weighs about 500 Kg (1,102 lbs.). The fuel consumption from biomass, approximately 10% of total fuel consumption at the plant, will be about 150,000 tons of straw, or 120,000 tons of straw and 50 tons of wood chips per year.

In 1994 SK Power entered a long-term cooperation agreement with the Swedish energy company Vattenfall AB, a member of the joint venture building the Avedøre 2 plant. The agreement gives Vattenfall the right to up to 200MW_e of the Avedøre 2 production and SK Power the right to 200MW_e of hydropower from the

Indalselven installation in northern Sweden.

The plant came on line in January 2002. Avedøre 2 replaces five older technology, 1950s and 1960s coal-fired plants with a more efficient, less polluting facility.[32]



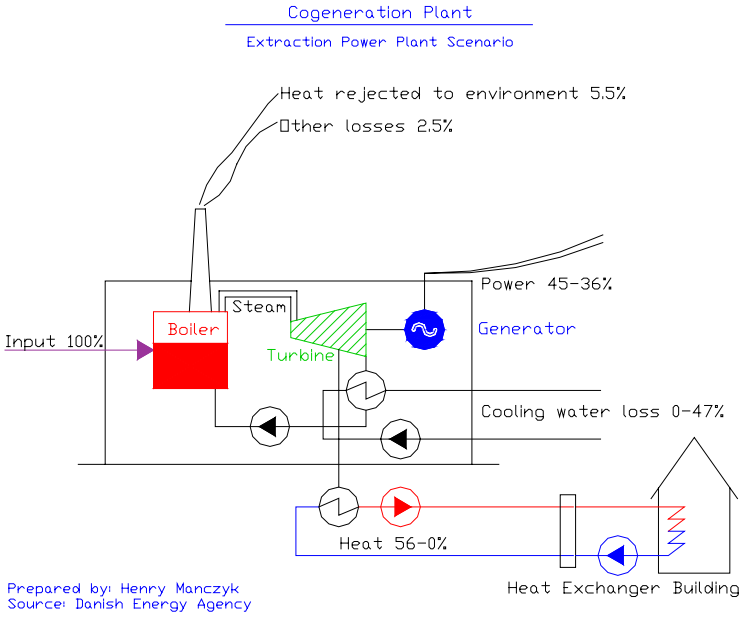
Avedøre 2 CHP Station. Courtesy of Avedøre CHP Station

Avedøre Results

The cogeneration of heat and electricity results in considerable savings and enormous environmental benefits for the entire metropolitan area. In cogeneration mode the installations have a maximum potential fuel efficiency of 92% at the Avedøre I plant and 95% at the Avedøre 2 plant.

By replacing the older coal-fired plants, the Avedøre 2 power station is expected to achieve emission reductions of 10% in CO_2, 20% in NO_x, and 30% in SO_2.

Together, Avedøre I and II stations produce heat for 280,000 homes, primarily in the greater Copenhagen district heating area. Electricity is supplied to 1.2 million homes, supplying 30% of the consumption in Eastern Denmark.[32]



Goal Achievement and Future Prospects

Over the past 20 years the Danish GNP has increased 50%. Through its energy policies, technology development and application, however, it has held its energy consumption approximately constant.[1]

Denmark is increasingly opening its energy market, creating new challenges to maintaining its accomplishments. Because the EU has adopted similar environmental provisions, particularly in support of provisions of the Kyoto treaty, the situation is largely hopeful for Denmark.

A new liberal/conservative government was elected in November 2001. It is more oriented to the free market than prior governments, and it intends to cut back on public spending. It has also dropped plans to develop three offshore windpower parks, and some point out that the new government may recommend plans of nuclear energy in Denmark which was dropped from the overall energy program in 1985. At this time, it is not clear how its policies will affect Denmark's long-term energy and environmental goals.[38]

Denmark has made excellent progress in meeting its 1998 goal of reducing CO_2 emissions by 20% from its 1988 level by 2005 is well along: by 2001 it had already achieved an 11% reduction.[35]

Denmark energy agencies report that by 1997 the nation had achieved self-sufficiency in all fuels.[1] Although it has dramatically increased the role played by renewable energy sources, particularly wind power, its oil and natural gas reserves are dwindling, despite efforts to improve its extraction from the North Sea field. Imported fuel sources will probably become increasingly important once again.

The technologies employed in Denmark have been demonstrated as technically and operationally feasible and, because of the high level of government involvement in all aspects of the energy sector, cost effective within the Danish market. It has become an internationally competitive leader in wind power generation. It has highly developed heat and power generation from biomass. Its use of combined heating and power generation in proportion to its total capacity is the highest in the world.

Denmark has demonstrated that energy and environmental objectives including those in global environmental agreements can be achieved given national policy to do so.

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