Copenhagen Energy Vision

A sustainable vision for bringing a Capital to 100% renewable energy

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AALBORG UNIVERSITY

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A sustainable vision for bringing a capital to 100% renewable energy

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Abstract

The short-term goal for The City of Copenhagen is a CO_2 neutral energy supply by the year 2025, and the long-term vision for Denmark is a 100% renewable energy (RE) supply by the year 2050. In this project, it is concluded that Copenhagen plays a key role in this transition. The long-term vision of 100% RE can be achieved in a socio-economic and resource efficient way in Denmark, but local involvement is required to ensure the implementation of a Smart Energy System approach.

A Smart Energy System perspective, which considers electricity, heating and transport, is applied in this study using the EnergyPLAN model. The model simulates the electricity, heating, cooling, industrial, and transport sectors on an hourly basis and enables the identification of new synergies between the sectors to 1) improve the efficiency of the energy system and 2) accommodate the short-term fluctuations in renewable energy production.

Based on results at the national level, some key recommendations can be made for Copenhagen, the Greater Copenhagen Area and national policymakers. For example, key technologies that will be necessary in Copenhagen in the coming years are heat savings in buildings, large-scale heat pumps, flexible fuel efficient power plants, low-temperature district heating, more public transport, and the electrification of the transport sector. Recommendations such as these will support the development towards 100% RE in 2050, thus avoiding potential pitfalls associated with the short-term goals.

Acknowledgement

This project was partially financed by The City of Copenhagen and 4DH – an International Research Centre of 4th Generation District Heating (www.4dh.dk) supported by Innovation Fund Denmark. The Smart Energy System concept presented in this study has been continuously developed by the Sustainable Energy Planning Research Group at Aalborg University over the past 20 years under numerous projects, and is still being further developed (www.smartenergysystems.eu).

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Preface

The long-term goal for Denmark in 2050 is to have an energy supply based on 100% renewable energy. To achieve this goal, different parts of the country will have different roles. Here we identify the role of the Greater Copenhagen Area in such an energy system. The City of Copenhagen plays an important part, as it is the biggest municipality and the capital of Denmark. In this report, we outline:

1. Changes required towards a long-term Smart Energy System based on 100% renewable energy for Copenhagen in 2050. The scenario includes energy savings as well as energy supply for the electricity, heating, cooling and transport sectors.

2. The role of the Greater Copenhagen Area and how the city can contribute to the overall Danish transition towards 100% renewable energy.

3. A suggestion for a roadmap for this long-term vision.

The City of Copenhagen has a strategy to be CO_2-neutral in 2025 involving a series of concrete initiatives. Copenhagen was the first capital in the world to have such a goal. In this report, the long-term vision for 2050 is related to the short-term initiatives to evaluate whether these initiatives contribute to developing the electricity, heating and transport system in the direction that would make the long-term vision of 100% renewable energy possible.

The City of Copenhagen has received international recognition for its work within climate adaptation and mitigation. Copenhagen was elected as the *European Green Capital in 2014* by the European Commission for the initiatives and plans of becoming CO_2-neutral and actively improving the conditions for bicycles in the city [1]. In the 2014 edition of the Global Green Economy Index (GGEI), Copenhagen is the world's greenest city for the second year [2]. The city was also awarded the *City Climate Leadership Price* in 2013 for the planning and actions for reducing carbon emissions, including the 2025 Climate Plan [3]. *INDEX: Design to Improve Life* gave Copenhagen the design award for the city's planning of climate adaption in 2013 because of the solid framework established for sustainable design solutions in the future [4].

It is our hope that this report can contribute to a further development of the Copenhagen energy system towards 100% renewable energy by 2050 and enable Copenhagen to be a real life experiment for Smart Energy Systems (see Chapter 1).

This vision is the result of the collaboration between researchers from the Sustainable Energy Planning Research Group at Aalborg University, Department of Development and Planning, and employees from The City of Copenhagen, The Technical and Environmental Administration and The Financial Administration, in a period from August 2013 to until the summer of 2014.

Brian Vad Mathiesen and Rasmus Lund

January 2015

List of abbreviations

General:

BBR	Bygnings- og Boligregisteret (The Danish building register)
CEESA	Coherent Energy and Environmental System Analysis
CPH	Copenhagen
DKK	Danish Kroner (€100 is equivalent to 745 DKK)
O&M	Operation and Maintenance
R&D	Research and Development
RE(S)	Renewable Energy (System)

Technical terms:

APF	Advanced Pulverised Fuel
CCGT	Combined Cycle Gas Turbine
CCR	Carbon Capture and Recycle
CFB	Circulating Fluidised Bed
CHEC	Combustion and Harmful Emission Control
CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
DME	Dimethyl Ether
GIS	Geographical Information System
IC	Interconnection
JP	Jet Petrol
PP	Power Plant
PV	Photovoltaic
SNG	Synthetic Natural Gas
SOFC	Solid Oxide Fuel Cell

Units:

Bkm	Billion kilometres
MW	Mega Watt
MWe	Mega Watt electricity
MWth	Mega Watt thermal
PJ	Peta Joule
TWh	Tera Watt Hour

Institutions:

CTR	Centralkommunernes Transmissionsselskab (Metropolitan Copenhagen Heating Transmission Company)
DEA	Danish Energy Agency
DGC	Danish Gas Technology Centre
DTI	Danish Technological Institute
DTU	Technical University of Denmark
EU	European Union
HOFOR	Hovedstadsområdets Forsyningsselskab (Greater Copenhagen Utility)
SBi	Statens Byggeforskningsinstitut (Danish Building Research Institute)
VEKS	Vestegnens Kraftvarmeselskab (Western Copenhagen Heating Transmission Company)

1 Executive Summary

The governmental target in Denmark is to have a 100% renewable energy supply at the country level in 2050. This ambitious goal demands long-term planning and close cooperation between the municipalities, energy companies, public institutions, and the government. The pathway to this is structured with a number of sub-targets along the way, see Figure 1.

The development towards 100% renewable energy is a comprehensive transition of many parts of the energy system involving end energy demand, distribution, conversion, and resource exploitation. The City of Copenhagen has an important role in this transition in Denmark because of its position as the capital, inhabiting about 570,000 or one tenth of the total Danish population. In the Greater Copenhagen Area, the population is around 1.2 million1. The transition requires continuous adjustment and refining of the regulatory framework for the municipalities, energy companies, and other actors in the energy sectors to facilitate a sustainable and socioeconomically feasible transition. In other words, Strategic Energy Planning is required to conduct the changes necessary at a local level, in coordination with regional and national initiatives, while taking into account energy efficiency and renewable energy in the electricity, heating, cooling, industry and transport sectors.

Goals in broad political agreement for 2020:

- 12% reduction in the primary energy supply compared to 2006
- 35% renewable energy of the entire energy system (incl. transport)
- 50% wind power in the electricity supply
- 10% biofuels or renewable energy in the transport sector

The Government's goal in 2020:

- 40% CO_2 emission reductions compared to 2006

The Government's goal in 2030:

- No coal in the energy system
- No oil in the heat supply

The Government's goal in 2035:

- 100% renewable energy in the electricity and heating sector

The Government's goal in 2050:

- 100% renewable energy in Denmark (incl. transport and industry)

Figure 1: Important goals in the Danish future energy planning process.

[1] The City of Copenhagen refers to the administrative authority and area covered by the Municipality of Copenhagen. The Greater Copenhagen Area or Metropolitan Copenhagen includes the neighbouring municipalities (in total 18).

For a number of years, Copenhagen has worked on reducing greenhouse gas emissions and increasing the penetration of renewable energy. In 2009, the City Council agreed on a target to reduce greenhouse gas emissions by 20% by 2015 compared to 2005. This goal was reached by 2011. In 2009, it was agreed to make a vision to be CO2-neutral by 2025. The report "CPH 2025 Climate Plan" was published in August 2012 suggesting how to meet this target [5].

Moving from Carbon Neutrality to 100% Renewable Energy

Wind and solar resources are distributed differently around Denmark. For example, rural regions typically have much higher potentials than urban regions. This means that some municipalities will be able to install more wind power than required for their total energy consumption. In theory, this creates a carbon neutral municipality, since the consumption of energy is compensated for by the production of carbon neutral energy from the wind power. However, this wind power may not be utilised for demands that still use fossil fuel within the carbon neutral municipality, for example, in heavy-duty transport. Therefore, the Smart Energy System enables municipalities to move from being carbon neutral to 100% renewable, since it allows intermittent renewable sources to also replace final consumption locally, such as heating (via heat pumps) and transport (via electric cars and electrofuels).

This study focuses on Copenhagen's role in the overall transition of the Danish energy system. The CEESA 100% renewable energy scenario for Denmark suggested by a team of researchers from five Danish Universities in 2011 is used as the overall transition framework from today's energy system to 100% renewable energy. Critical issues in which action in Copenhagen is particularly important are indicated in this report. The primary energy supply for Denmark in the CEESA scenarios can be seen in Figure 2.

The CEESA scenario uses the Smart Energy Systems approach that integrates the heating, electricity and transport sectors, together with substantial energy savings, which allows a more efficient utilisation of renewable energy sources. This can be seen in Figure 2 where almost half of the total primary energy supply is from fluctuating renewable sources in 2050.

The origin of Smart Energy Systems and CEESA (www.SmartEnergySystem.eu)

The Smart Energy System concept and design for 100% renewable energy systems [6-8] is based on previous research, which has resulted in different scenario analyses of Denmark. In 2006 and 2009, this research documented that a transition to a 100% renewable energy supply by 2050 is technically possible and can be done in a socioeconomically beneficial way in the IDA Climate Plan 2050 [9]. On the basis of, among others, this work, the Danish government developed a vision and an official policy in 2011 of having a 100% renewable energy supply in Denmark by 2050 [10]. After 2009, the Smart Energy System concept was further developed in the CEESA project (Coherent Energy and Environmental System Analysis), where particular focus was put on transport and biomass resources (2011).

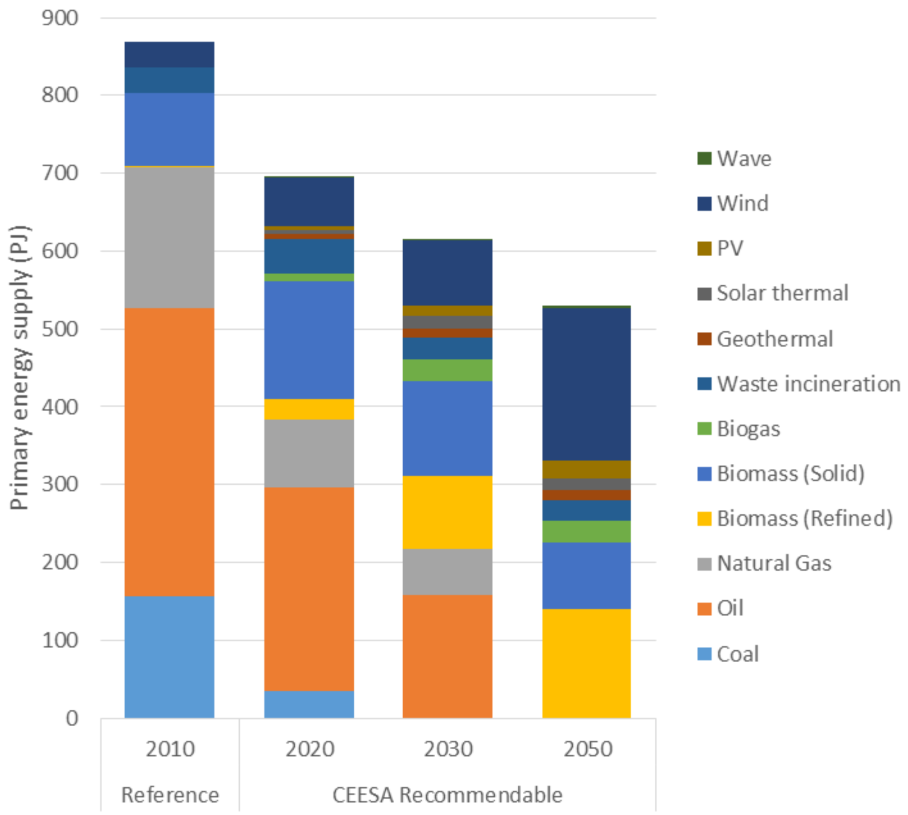


Figure 2: The primary energy supply for Denmark in 2010, in the CEESA Recommendable scenario.

1.1 Copenhagen in a National 100% Renewable Energy Context

Due to the characteristics and size of Copenhagen, The City of Copenhagen and other key stakeholders should pay special attention to the following elements to be able to cost-effectively convert to 100% renewable energy and to facilitate the overall nationwide transformation:

- Implementation of heat savings in buildings for energy demand reduction and investments in heat supply and distribution infrastructure. In addition to these steps, savings in household electricity and industry are important as well as fuel savings in industry.
- Implementation of renewable energy sources, such as wind power, photovoltaic, solar thermal and geothermal energy.
- Integration of the energy sectors by implementing smart energy technologies such as flexible CHP plants (Combined Heat and Power plants), large-scale heat pumps for district heating, and electrification of the transport sector.
- Changes to different transport modes, stabilisation of the transport demand, and implementation of electricity and sustainable alternatives to fossil fuels.

The energy supply in The Greater Copenhagen Area is characterized by the high population density, which generates a high energy demand, but also a good potential for the utilization of, e.g., district heating and effective public transport systems. In Figure 3, the division between the different energy end demands is illustrated for The City of Copenhagen for 2011.

Savings in Industry fuel demands as well as electricity consumption in households and industry are extremely important, and are a precondition of achieving a sustainable renewable energy system.

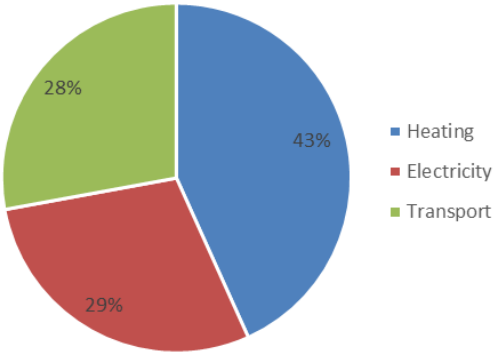


Figure 3: Shares of energy consumption in the three categories: Heating, electricity and transport for The City of Copenhagen in 2011. Main references: [11] and [12]. Calculations and references are elaborated in Appendix 1. Heat Savings in Buildings

Electricity savings in the demands we know today should be lowered by 30-50% in industry and households. In this report special attention has been put on the implementation of heat savings in buildings in The City of Copenhagen, i.e. energy demand reduction and investments in heat supply and distribution infrastructure.

The building stock in The City of Copenhagen is old and there is a large potential for energy efficiency improvements (See Figure 4). It has been shown that up to 53% of the heat in buildings can be saved on average in Denmark [13]. The feasible potential in The City of Copenhagen is 56% heat savings compared to today using this methodology. Implementing heat savings requires long-term planning and concrete strategies for how to implement the savings in cooperation with building owners, housing associations and other stakeholders. Reductions in the heat demand decrease both fuel consumption and investment costs of supply and distribution infrastructure.

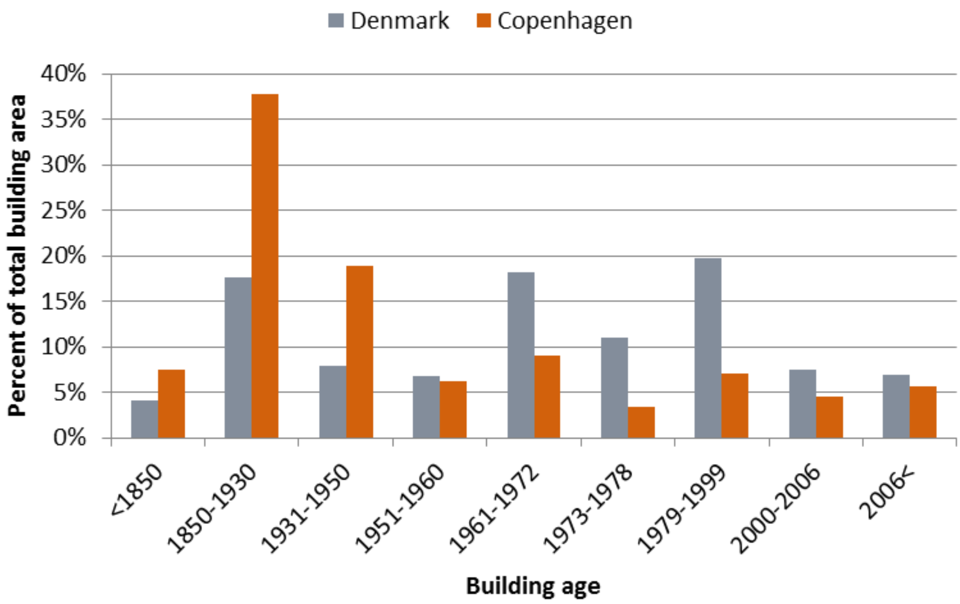


Figure 4: Shares of the building stock divided into intervals of the age of the building for Denmark and The City of Copenhagen, respectively (The percentage of building area relates to the floor area).

Although new buildings will and should have a significantly lower heat demand than the current level, studies show that it is socioeconomically feasible to connect new low energy buildings to low temperature district heating [13]. This is connected to the fact that individual heating systems, even with low demands, have higher unit costs and cannot compete with district heating costs. Even with net-zero emission buildings or plus energy buildings, unit costs are significant compared to the district heating option. The problem is that there will be a need for a heating/cooling system and that the reduction in the unit costs has a lower value limit compared to the capacity. In addition, there are behavioural aspects that favour district heating, as the users do not always use the energy as expected even in the case of well insulated houses with very low heat demands.

There is a marginal cost in the increased energy efficiency of new buildings, which should in principle not exceed the marginal cost of the supply from renewable based district heating systems. This balance between energy efficiency and heat supply for buildings is important to consider when planning a new housing area. In other words, there is a point at which the price of reducing the heat demand becomes more expensive than the price of implementing a sustainable heat supply.

1.1.1 Implementation of Renewable Energy Technology for heating and electricity supplies

Renewable energy production technologies and infrastructure form the basis for a renewable energy system. The implementation of renewable energy technologies is a joint responsibility between several actors, but municipalities have an important role in the planning of these activities.

The capacities of onshore and offshore wind power and solar PV provide almost 80% of the gross electricity consumption in Denmark in the CEESA 2050 scenario. To illustrate the current and the planned capacities, the relation between the capacities and the population of Denmark and The City of Copenhagen, respectively, are presented in Figure 5.

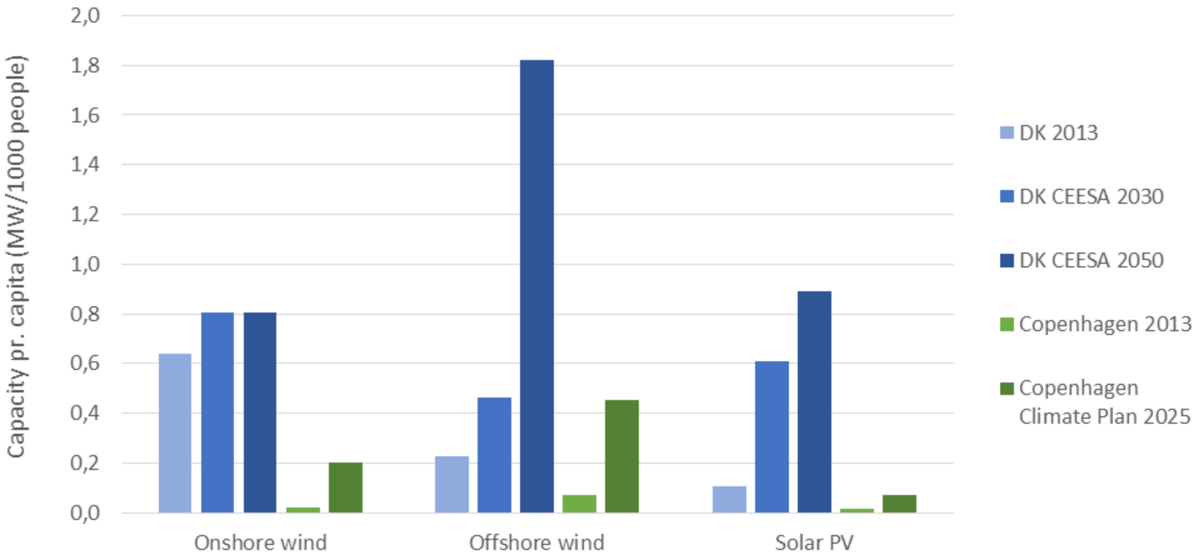


Figure 5: Capacity per capita of onshore wind, offshore wind and solar PV under five conditions. The DK and The City of Copenhagen 2013 values are historical data; the CEESA scenarios are the values from the CEESA scenario analysis, and the Copenhagen Climate Plan 2025 is the planned capacities for 2025 in the area of The City of Copenhagen.

The planned capacities in the CPH2025 plan are lower for onshore wind and solar PV than the average capacity per capita in Denmark today. The lower onshore wind capacity is due to the smaller area available for building wind turbines. The target for solar PV capacity is far lower than the current national average and here the area available for construction is not an issue as for onshore wind turbines. The lower target may be due to the lack of good support schemes at the time of developing the Copenhagen Climate Plan 2025. The target in CPH2025 for offshore wind power is a bit higher than the 2013 national average, but still very far from reaching the level recommended in CEESA in 2050. If Copenhagen was to meet these long-term targets in this 100% renewable energy system, Copenhagen would have to increase the capacities of wind power by a factor of four and solar PV by more than a factor of 10 until 2050 compared to the CPH2025 plan. This corresponds to approximately 500 MW of PV and approximately 1500 MW of wind power capacity (onshore or offshore) for The City of Copenhagen in 2050.

As The City of Copenhagen has different geographical and physical characteristics compared to other municipalities, it may shift towards more PV or consider how the city can contribute to the development by reducing the energy demands or implementing technologies to increase the flexibility in the energy systems.

Table 1: Capacities of onshore wind, offshore wind and solar PV under five conditions. The DK and The City of Copenhagen in 2013 values are historical data, the CEESA scenarios are the values from the CEESA scenario analysis, and the Copenhagen Climate Plan 2025 is the planned capacities for 2025 in the area of The City of Copenhagen.

(MW)	Status in Denmark 2013	Denmark in CEESA 2050	Status in The City of Copenhagen 2013	CPH Climate Plan 2025 targets 2025	The City of Copenhagen in CEESA 2050
Onshore wind	3,566	4,500	12	110*	450
Offshore wind	1,271	10,200	40	250*	1,020
Solar PV	593	5,000	7	40	500

*****_The total capacity of 360 MW wind power, mentioned in the CPH 2025 Climate Plan, is divided into onshore and offshore according to the ratio between on- and offshore wind power capacities in the CEESA 2050 scenario._

Today approximately 95% of The City of Copenhagen is covered by district heating networks as well as approximately 55% in the Greater Copenhagen Area. This will be an important piece of infrastructure in the future Smart Energy System. In the case that the district heating network was not developed to this extent, the recommendation would be to expand it. New heat sources such as solar thermal, geothermal, heat pumps and excess heat from bio-refineries should also be integrated into the Copenhagen energy system through the district heating supply system. A district heating system is a must in a renewable energy system scenario, because it enables the integration of low value heat sources, the cost-effective heat supply of houses, as well the cost-effective integration of fluctuating renewable energy sources such as PV and wind power. Even in the case of one-family houses, it is beneficial to have district heating both in today's perspective and in the future. Depending on the amount of waste heat from industry and bio-refineries that will be available in the future, large-scale MW-sized heat pumps, as well as large solar thermal and geothermal capacities can be implemented in the Copenhagen district heating system depending on their potential. At the moment, a major transition is taking place from a fossil-fuel based heat production in combined heat and power, to mainly biomass-based combined heat and power. In the outskirts of Copenhagen, the district heating supply should also be expanded to replace mainly natural gas boilers in detached houses. When heat savings are made in inner Copenhagen this enables marginally cheaper conversion from natural gas boilers in the outskirts of the city. More than 1,000 people every month choose The City of Copenhagen as their home. This means that new buildings have to be built, such as one-family detached houses, multifamily houses, offices, etc. Even though the new building stock would follow high insulation standards that will lower the heat consumption (as required in mandatory building class requirements), these buildings should be supplied by district heating (based on analyses of one-family houses and assuming no onsite energy production from PV etc.) [13].

Smart Energy System (www.SmartEnergySystem.eu)

The Smart Energy System concept outlines how national energy systems can be transformed from fossil fuels to 100% renewable energy. The two key forms of energy production are bioenergy and intermittent renewable energy such as wind and solar power. Bioenergy is very suitable as a replacement for fossil fuels since it has many similar characteristics, but in a 100% renewable energy system, bioenergy is a scarce resource. Intermittent renewable energy sources are more plentiful, but they pose a challenge due to the fluctuations in their production, which need to be accommodated. Therefore, accommodating large amounts of intermittent renewable energy and limiting the bioenergy resource to a sustainable level are two key features of the Smart Energy System concept. To achieve these, it is essential that synergies between the electricity, heat, and transport sectors are utilised more effectively in the future, especially thermal storage, heat pumps, electric vehicles, electrofuels, and fuel storage. This will improve the overall efficiency of the system and enable more intermittent renewable energy to be utilised. The result is a 100% renewable energy system and zero net carbon dioxide emissions. Furthermore, the cost of the Smart Energy System will be the same as a fossil fuel scenario, but more importantly, the Smart Energy System will be based on domestic infrastructure instead of imported fuels, thus creating more local jobs.

Figure 6 illustrates, based on CEESA, how the capacity for district heating production could develop in the district heating supply system of The Greater Copenhagen Area. The production capacity for solar thermal heat should be increased together with industrial waste heat, as well as waste heat from gasification and the synthesis of fuels for transport. The production capacity of district heating produced by CHP plants will decrease over time as the electricity-to-heat ratio of new CHP plants should be higher than today and therefore they will have a lower heat production capacity.

4th Generation District Heating (www.4DH.dk and www.heatroadmap.eu)

District heating transfers heat from a central source into the buildings of a town or city. In Denmark, most of the heat is supplied by large-scale combined heat and power (CHP) plants, but in the future, there will be many new forms of heat suppliers available. This includes wind power which can produce heat using large-scale heat pumps, solar thermal, deep geothermal, and surplus heat from industry. It is possible to extract more heat from these resources if their delivery temperature is lower; thus, reducing the temperature in the district heating network will allow more renewable heat to be utilised. Furthermore, if the temperature in the pipes is lower, then the amount of heat lost in the pipe is also reduced, and more of the heat produced reaches the end consumer. In the future, district heating distribution temperatures should be reduced from today's level of 80-100^{O}C to approximately 50-60 ^{O}C. This transition is the focus of the 4DH research project, which analyses three key aspects of low-temperature district heating: the evolvement of grids and components, the role of low-temperature district heating in the energy system, and the planning and coordination of its implementation [99-102].

The production of heat from geothermal sources should increase, while the share of waste incineration should gradually decrease to a lower level. This is due to an increased focus on recycling and resource efficiency. The level assumed here corresponds to reaching the current Dutch recycling levels used as a proxy of how much resource efficiency can be increased resulting in reducing waste incineration capacity. If heat from waste incineration is maintained at the current level, this would not pose a problem in flexible district heating grids.

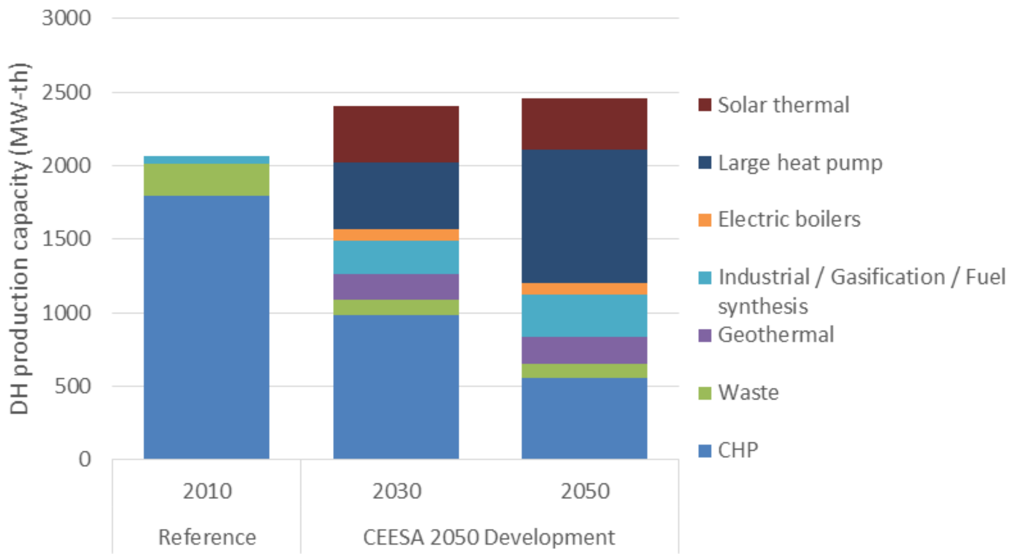


Figure 6: Heat production capacities in The Greater Copenhagen Areas assessed on the basis of the national average and assuming that the development in CEESA is reflected in The Greater Copenhagen Area. Fuel boilers are not included in this figure, but it is assumed that they are able to cover the expected peak demand.

A large share of these new heat sources will be low temperature energy sources; therefore, a strategy for converting the district heating systems to low supply temperatures should be developed. The low temperature district heating will also have lower distribution losses and higher supply efficiencies, such as in the case of large-scale heat pumps and CHP plants.

The capacity of large-scale heat pumps should be developed significantly during the early stages towards a 100% renewable system. Large-scale heat pumps can cost-effectively integrate wind power and PV power production. The implementation of heat pumps should be prioritized as the wind power capacity is already increasing in Denmark. In Copenhagen, such initiatives have already been taken to start this development.

1.1.2 Integration of Energy Sectors

The integration of the energy sectors and the development of a smart energy system is crucial to reaching a 100% renewable energy system in a sustainable and socioeconomically feasible way. In a system without any fossil fuel, it is important to consider the consumption of biomass; otherwise, adverse effects may occur and the overall sustainability may be jeopardised. It is hard to determine the amount of sustainable biomass consumption in the short and long term. One of the approaches could be to limit the biomass consumption in Denmark to a level that can be sustainably produced in Denmark. The amount of 240 PJ has previously been deemed a sustainable level in Denmark [14]. Even limited to this level of around 240 PJ, our biomass consumption would be higher per capita than the assessed global biomass potential per capita. Furthermore, it will require a substantial effort to reach a biomass consumption level of 240 PJ/year in Denmark. This requires an integrated energy systems approach including all energy-consuming sectors. If this approach is chosen, there is a potential to achieve 100% renewable energy in all sectors (electricity, heating, cooling and transport) with the same or lower overall costs for energy and transport than we have today.

Figure 7 demonstrates how the increased focus on system integration will affect the district heating system in Copenhagen. Three different district heating supplies are presented: Today's mix (reference), a 2025 mix for Copenhagen based on the implementation of the 2025 Climate Plan, and a CEESA 2050 mix outlining what is necessary in a 100% renewable energy context with a sustainable biomass consumption level.

Large Heat Pumps for District Heating in Denmark

Heat pumps in district heating in Denmark are today not a commonly used technology on a large scale. A number of DH plants in Denmark have invested in large electric heat pumps during the last five years, mainly using flue gas as the heat source [97,98]. But there are also examples where heat pumps are used for waste water, industrial waste heat, for increasing the efficiency of solar and thermal storage systems, or boosting the temperature between the supply and return pipes. In Denmark, there are not yet any large-scale examples of heat pumps using ambient heat sources, which increase the potential significantly, but in Drammen DH system in Norway, there is a case of a large-scale HP system that provides 14 MW of heat using sea water as its heat source – a technology that in principle could be implemented in Denmark as well. Currently, there are a number of demonstration projects in Denmark, where electric heat pumps are being installed to supply heat for DH from ambient heat sources, specifically ground water and lake water. For the planning of the system in Copenhagen, it is important to be aware that many different heat sources will need to be included in the system to reach the high levels suggested in this study.

Compared to the current system, the changes towards 2025 are small with regard to the type of capacity; however, the changes are significant with regard to the fuel mix. The CPH 2025 Climate Plan will ensure the use of renewable energy in the heating sector. With the goal of a 100% renewable energy and transport system in CEESA 2050, the focus on other sources needs to increase. Specifically the lack of large-scale heat pumps – even in the current system towards 2025 – is problematic. Already in 2020, the overall aim is to have 50% wind power in the Danish electricity mix, which means that changes must be made in the design of the energy system. Large-scale heat pumps enable the utilisation of wind power in the heating sector, and industrial waste heat should also be used. It can be recommended to start implementing large-scale heat pumps already now, and revising the vision towards 2025. Due to the demand for transport fuels in heavy-duty transport that cannot use electric propulsion systems, the excess heat from gasification and fuel synthesis plants is important to the integration of the transport sector with electricity and heating in the future 100% renewable energy system.

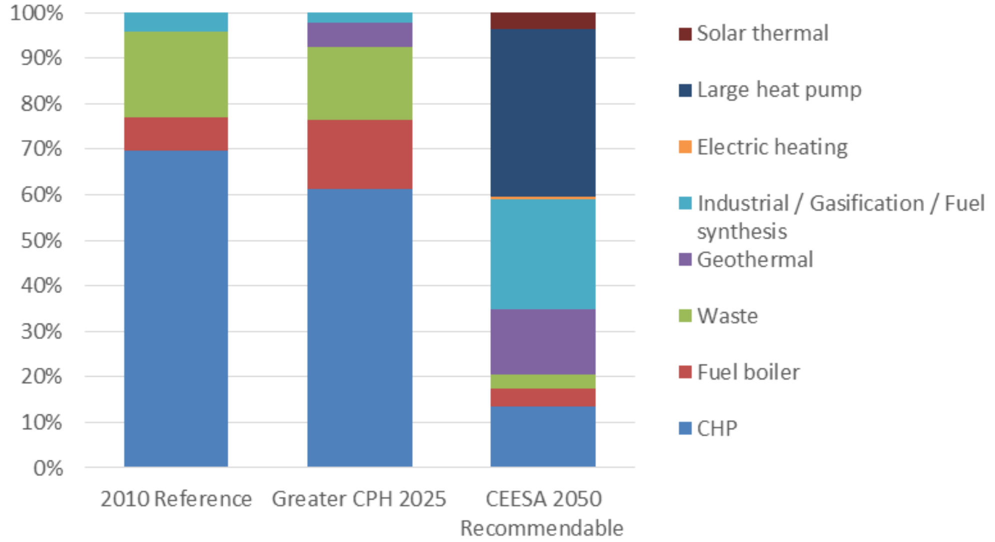


Figure 7: District heating production composition in central CHP areas in the 2010 Reference and in the CEESA 2050 Recommendable Scenario compared to a system model of the initiatives in the CPH 2025 Climate Plan.

In CEESA 2050, the heat production from CHP plants is significantly reduced as illustrated in Figure 7. The reduced operation of the CHP plants is caused by 1) the aim in the future system to reduce fuel consumption using fluctuating sources, which means that power plants and CHP plants have fewer operation hours, thus reducing the fuel consumption; 2) a replacement of heat production with other sources such as surplus heat from gasification and fuel synthesis plants, and 3) a change in the electricity-to-heat ratio of new CHP plants. This, in conjunction with other initiatives regarding energy savings, renewable electricity and efficient transport, can keep the biomass consumption at a sustainable level.

The CHP plants will play a new role in producing electricity when the fluctuating renewable sources do not cover the demand. To reduce the fuel use/production of the CHP plants as the wind power production is changing, the CHP plants will need to regulate their heat and electricity production in short periods of time. An analysis is carried out in this study to show which type of CHP plant is most suitable in this new role in the energy system, in terms of total biomass consumption and socioeconomic costs. Three CHP plant types have been assessed; a combined cycle gas turbine (CCGT), a steam turbine with a circulating fluidised bed boiler (CFB), and a steam turbine with an advanced pulverised fuel boiler (APF). The CFB boiler type is analysed with two different plant capacities – a high and a low.

The results clearly indicate that the CCGT plant is both more feasible and has lower cost for society. In an intermediate period, natural gas could be used instead of biomass. The CCGT plants use less biomass than the alternatives as they are more efficient and able to integrate higher levels of wind power efficiently. Applying small capacities of CFB plants will only make the system slightly more expensive and use slightly more biomass – provided that all other CHP and power plants are CCGT which is currently not the case. With large CFB capacities, the system will perform significantly worse on both parameters. Sensitivity analyses of the scenarios with varied interconnection capacities and electricity prices show that the CCGT plants are cheaper in all cases.

To contribute to the transition of the Danish energy system towards a 100% renewable system and to secure a sustainable use of biomass resources, Copenhagen should implement flexible CHP and power plants - potentially CCGT plants [15]. Other technologies such as biomass gasification, electrolysis and fuel synthesis should also be initiated and planned in order to increase the sector integration and to promote the Smart Energy System concept [7].

1.1.3 Transport in a renewable energy context in Copenhagen

The reduction of fossil fuels for transport is a major issue in the transition to 100% renewable energy. The transition of the transport energy demand to renewable energy entails radical changes of the current transport systems, which require long-term planning to establish high efficiency transport infrastructure. Fundamentally, transport demands should be reduced to limit the energy demand as well as environmental and social consequences. The road-based transport demand should be reduced and other means of transport should be prioritised in the sector. In public transport, rail, busses and bicycle infrastructure should be prioritized to provide easy mobility in the city. In general, the mobility in the city should be easier without personal vehicles.

Figure 8 shows the energy demands for transport today and in the CEESA 2050 scenario with 100% renewable energy for transport. The figure illustrates two different transport developments; high and medium increase in the transport demand for Denmark. The figure also shows the same developments for The City of Copenhagen. The high increase scenario includes a high increase in the road-based transport, but with a high degree of electrification. In the medium increase scenario, there is a much higher focus on modal shift; i.e., keeping the growth in the transport sector at a lower level and making sure that the growth is in the public transport. This can be seen in the figure as the airplane, truck and car transport decrease and the rail transport increases. The reduced energy demand here comes partly from the lower demand, but also from the increased efficiency of vehicles after the model shift.

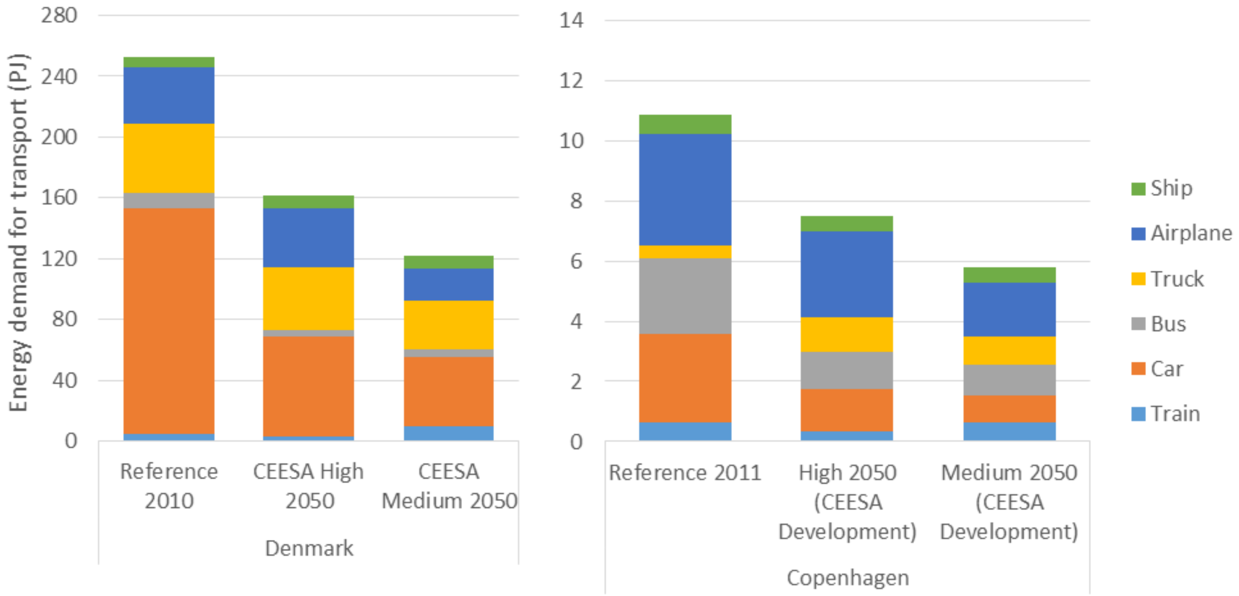


Figure 8: Energy consumption for transport in Denmark and The City of Copenhagen in 2011 and CEESA 2050 divided into means of transport.

In The City of Copenhagen, the transport demand will have to change from private vehicles to higher shares of public transport and non-motorised transport. Figure 9 shows how the market shares for modes of transport will change towards a 100% renewable system in 2050. The same tendencies also apply to Copenhagen. There is a need for large amounts of modal shifts from car to public transport or bike or walking and from public transport to bike or walking. This will require policy changes, in The City of Copenhagen, The Greater Copenhagen Area as well as nationally, to influence the incentive structures related to the choice of transport mode.

Although the transport demand will grow, the growth needs to be limited by urban planning measures and the modes of transport need to gradually change. In order to obtain such a scenario, the CEESA scenario assumes an increase in the share of biking and walking in the transport sector from 4.5% today to 6.3% in 2050. The public transport share needs to increase from 24% to about 39% and the vehicle transport – although being at the same level as today – needs to decline from 72% to 55% of the transport in 2050 (see Figure 9). It can be seen that Copenhagen has significantly more bike and public transport than the average of Denmark. As the biggest city in Denmark, Copenhagen should contribute to the national average by having more transport by bike and public transport in the future than the rest of the country, since in other municipalities it will be much harder to reach the same high level as in Copenhagen due to other infrastructure conditions.

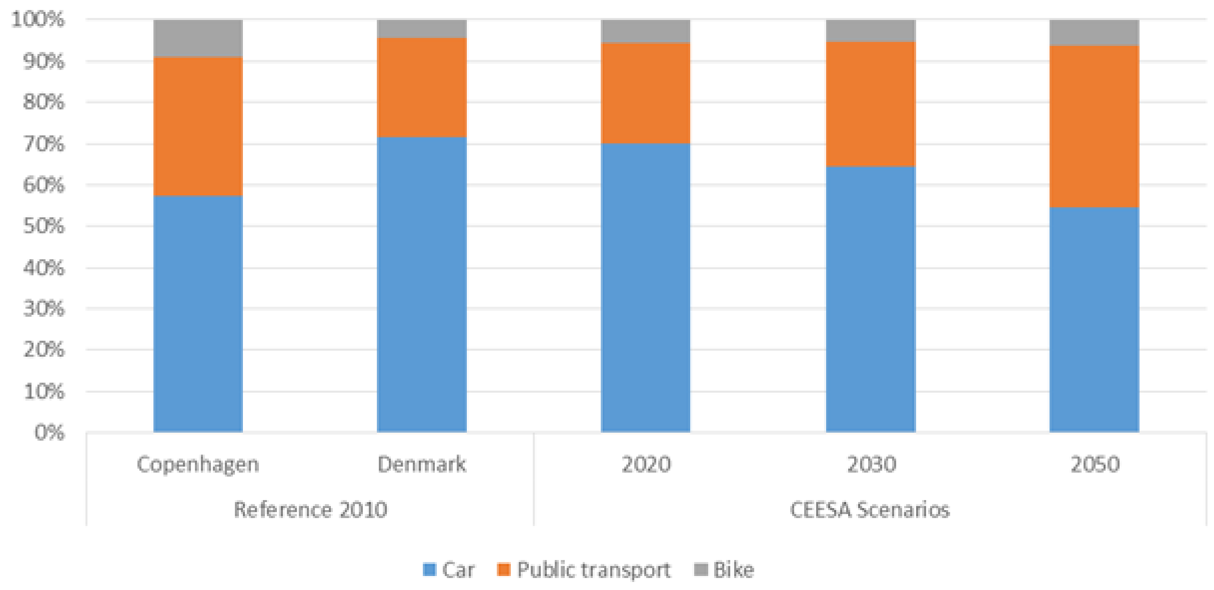


Figure 9: Shares of passenger transport in Copenhagen and Denmark in Reference 2010 and in the CEESA scenarios for 2020, 2030 and 2050 (Here Copenhagen includes the municipalities of Copenhagen, Frederiksberg, Gentofte, Gladsaxe, Herlev, Rødovre, Hvidovre, Tårnby and Dragør).

All modes of transport cannot be electrified, although this should be highly promoted. To cover the energy demand for trucks, ships and planes, electrofuels with a low biomass input should be considered to reduce the biomass consumption. A fuel production process that enables the hydrogenation of gasified biomass using hydrogen from water electrolysis will reduce the need for biomass input and thereby leave more biomass for other purposes. In CEESA, methanol and DME are produced using various electrofuel production processes. Electrofuels enable the use of energy from fluctuating resources, such as wind power and PV, for fuel production. This will improve the integration of the energy sectors and increase the utilisation of fluctuating renewable sources and the overall system efficiency.

1.2 Strategic Energy Planning in Copenhagen

The municipalities have an important role to play in renewable energy systems, because the systems will be much more decentralised with a focus on local resources and potentials. The municipality has the local energy planning authority and is able to support and implement projects that will contribute to the national targets. In the municipal energy planning, the national visions and targets have to be refined and converted into concrete actions. Here, the local resources and the specific potentials can be pointed out and integrated. This could be the conversion of heat and electricity production infrastructure, the connection of individual and natural gas heated areas to district heating, potentials of heat savings in buildings, the utilisation of waste heat from industry, and improvements of local and public transport systems.

While it can be argued that local energy planning to a certain extent follows national policy goals, local authorities also tend to emphasize those areas in which they possess some ability to act [16,17]. This means that local energy planning on the one hand has become more comprehensive, including more sectors and components of the energy system as well as taking more policy goals into account. On the other hand, especially municipal energy planning still seems to remain most effective within those fields in which local authorities and local energy companies have the executive powers; i.e., leading to the implementation of concrete projects. In other areas in which responsibilities are unclear or other actors than the local authorities and local energy companies are involved, the planning is not as effective in terms of leading to the implementation of concrete projects [18,19].

This indicates that there might be a potential to strengthen the coordination between the national energy strategies and the municipal energy planning to better reach the national targets. While coordination between the state and the municipalities is limited in the current system, in a strategic energy system, there should be a stronger integration of central and local energy planning. It is also suggested by [16] that the roles of the municipalities and the government in energy planning are being clarified and the municipalities are given the appropriate planning instruments to be able to effectively carry out the energy planning within all energy related sectors. On the basis of this, the following six recommendations can be given to The City of Copenhagen:

- To continuously do long-term analyses of different alternative scenarios of the energy system development
- To have an executive board in the municipality across municipal departments, thus promoting the cross-sectorial cooperation in the municipality
- To coordinate the energy planning initiatives with the other municipalities in the region
- To ensure the coordination between municipalities, district heating transmission companies and district heating supply companies
- To have a continuous focus on local involvement in the planning of energy infrastructure and possible ownership
- To continuously identify barriers to local implementation and communicate such barriers to the national level

The regional and national planning authorities also have important roles to play in strategic energy planning. These have to provide the right framework for the municipalities to effectively plan and implement strategies that support the national target of a renewable energy system. The following recommendations relate to the regional and national level:

- Region: To develop coherent energy plans in line with national goals addressing different resources and capacities of the municipalities
- National: To put forward guidelines for the role of the regions in the energy planning
- National: To introduce more specific requirements for the municipalities to do strategic energy planning
- National: To develop a national transport plan for how to reach 100% renewable energy supply for the transport in 2050.

1.3 Roadmap for The City of Copenhagen

The future development in Copenhagen should be seen in the context of the historical development. The development towards a more sustainable energy system in Denmark and Copenhagen has already been ongoing for many years supported by national, regional and local planning. Wind turbines have been installed at an increasing rate; district heating with combined heat and power production has replaced individual boilers; district heating is covering most of the city's heat demand; municipal waste is incinerated with energy recovery; building codes are requiring high-energy efficiency in new buildings, and existing buildings have improved significantly. In Copenhagen, high-frequency busses, metro and trains are covering most of the city area, car access to the city centre has been limited and the busses are prioritised in a few central streets.

The initiatives presented in the following sections should be implemented for Copenhagen to lead the way, as an active contributor to the national development towards a non-fossil Smart Energy System. The issues raised are divided into the short term, and medium or long-term planning.

1.3.1 Initiatives that can begin today

The investments in heat savings are important in the short term as heating requires large amounts of energy and investing in heat savings is good from a socio-economic perspective. These investments are also important because the dimensioning of the supply infrastructure depends on the current and future expected heat demands, meaning that the investment costs would be lower in case of lower heat demand. The **connection of new houses with district heating** is an important initiative because this will enable better system efficiency, higher utilisation of renewable energy sources, and lower socio-economic costs. These initiatives can be coupled with decreases in the district heating temperature to **low-temperature district heating** improving the overall efficiency. Tests should be initiated to gradually lower district heating temperatures in branches of the Copenhagen district heating networks. In should be noted that while the focus in this report has been on heat savings, **fuel savings in industry and electricity savings** in industry and households are extremely important as well.

Testing and demonstration of large-scale heat pumps for district heating is important and should start as soon as possible, because heat pumps contribute to the integration of the increasing wind power production. In Copenhagen, such initiatives have already been taken, and experiences with this project and projects abroad need to be used for a fast implementation of large-scale heat pumps. Biomass will be needed in the coming years in the Copenhagen energy mix, but there is a need for lowering the biomass demand through other sources such as **industrial waste heat, waste incineration, and geothermal sources**. Demonstration of large-scale **solar thermal resources** should be started with the aim of expanding this to a small percentage of the heat supply in Copenhagen. Substantial investigations of how to expand the use of local or sustainable biomass resources, e.g., through certification is needed. **Biomass certification** should be done in collaboration with national and EU authorities and should not be defined by industry.

Copenhagen should make a clear long-term plan for **photovoltaic, onshore wind power and offshore wind power**, and additionally make short-term implementation action plans.

Transport planning and increased investments in public transport infrastructure are crucial elements. The placement of services and uses of buildings in the city should be diversified through urban planning, to avoid unnecessary transport. **Less investment should be made in new roads** as the increase in the transport demand in the future should take place in other modes of transport. The more roads built, the harder it gets to have renewable energy in transport. More investments should be made in metros, light rail, bus and bike infrastructure, and further lock-in to road-based transport should be avoided. Although this is recommended for an efficient, low carbon transport infrastructure development for all of Denmark, this prioritisation is especially important in Copenhagen as the urban density here is high and covers a significant part of the population. Both passenger and freight transport should be considered in this respect.

In Copenhagen, **electric vehicles** are already starting to be implemented in the municipality's activities. The demonstration and promotion initiatives on charging infrastructure and parking spaces for electric vehicles should be continued and expanded. For personal vehicles, battery electric vehicles should be used. Other technologies such as fuel cell vehicles and gas vehicles should be avoided for personal transport. **Hybrid battery electric vehicles with simply range-extenders** such as international combustion engines should also be promoted to transfer as much as possible of the road-based transport to electricity.

For heavy transport – trucks, ships and planes – new technologies that can allow the use of wind power and other fluctuating resources in the transport sector should be prioritized. Copenhagen could contribute to such a development. Testing and demonstration of **biomass gasification and electrolyser technology** for the production of electrofuels such as methanol, DME and methane should be initiated to improve the development of the technology and lead to commercialization on the large scale.

1.3.2 Initiatives between 2020 and 2030

Flexible power plants should be implemented to support the increased integration of fluctuating renewable sources in the system. As old CHP plants are being decommissioned, new flexible CHP plants should replace these, preferably combined cycle gas turbines. Some types of thermal CHP plants allow by-pass, to enable heat-only production, but large-scale heat pumps for heat production are socio-economically more attractive and more fuel efficient. Therefore, this type of CHP plant is not recommended in a Smart Energy System context and in a context where biomass use should be limited. While thermal power plants have a much smaller role in a Smart Energy System, some may be viable in a transitional and limited period. This also means that to some extent, natural gas could be used in the shorter term, although gasified biomass should be used in the longer term. Using natural gas reduces the demand for biomass and improves the overall economy, while providing a short-term solution until large-scale heat pumps and gasification become commercially viable.

1.3.3 Initiatives between 2030 and 2050

A large-scale transformation in the transport sectors should take place in this period. Electric vehicles for light transport should already be widely used and more passenger and freight transport should take place by bike, light rail, metro and train at this time. For the remaining part of the transport that cannot be electrified, major changes need to take place in this period as the share is significant. **Large-scale gasification of biomass, electrolysis for the production of hydrogen for hydrogenation and fuel synthesis plants** should be implemented. These will serve to produce transport fuels, but also to integrate the wind power production increasing to about 80-90%. The new electrofuels such as methanol and DME may be supplied via the same distribution system as the petrol and diesel do today.

2 Introduction

The long-term goal in Danish energy policy is a national energy system based on 100% renewable energy in 2050. Currently, most energy systems are predominantly based on fossil fuels. In order to increase the security of supply, develop new technologies, and increasingly mitigate climate change, focus is on energy savings, renewable energy sources, and the handling of fluctuating renewable energy sources. The current energy system designs have flexibility within fossil fuels, which are used in power plants, boilers and vehicles in liquid, gaseous, and solid form. The current energy system design has built up infrastructure and storage facilities to cover the demands by means of transporting fossil fuels over large distances in ships and pipelines at the global level and providing national or regional energy infrastructure, such as gas and oil storage facilities and electricity production. Hence a global system is based on the easy storage and high energy density of fossil fuels that can flexibly meet the demands at the right time and place. While this is reality for the established fossil fuel-based energy system, the challenge is how similar flexibility and timely energy supply can be provided with increasing amounts of variable renewable energy.

2.1 Local Energy Systems in a National Perspective

Future renewable energy systems will have to be much more decentralised than traditional fossil fuel-based systems to use the available resources as efficiently as possible. Renewable energy will account for a much larger share of the local resources than the fossil fuel-based system. Solar thermal, heat savings, onshore wind turbines, geothermal energy, biogas production, and the utilisation of waste heat from industrial and other energy intensive processes are all examples of this. This means that the municipalities will have to play a larger role in the development towards the renewable energy system by identifying and utilising these local potentials. The transition towards 100% renewable energy requires local action.

All municipalities will have different potentials to develop and contribute to renewable energy systems. In municipalities of large cities, potentials can be related to the urban density like public transport, district heating and waste heat. In municipalities with less urban density, the potentials may be energy resources for biomass and wind utilisation. This also means that all municipalities should not do everything, but focus on their potentials and issues where it makes sense from a system perspective. The energy planning should also involve the cooperation with neighbouring municipalities to avoid sub-optimisation.

This project assesses the situation of Copenhagen and its potentials as a large urban municipality. It gives inputs to the future energy planning of the development towards 100% renewable energy in Copenhagen, from the perspective of a national energy system also developing towards more renewable energy. Here, some focus areas for Copenhagen are identified and analysed and future strategies are recommended for Copenhagen to contribute to an overall national 100% renewable energy system.

2.2 Methodology

As the energy system of Copenhagen should be seen in the context of the rest of Denmark being supplied by 100% renewable energy in 2050, the methodology is designed to give a number of recommendations for the future planning and development of the energy system in the Greater Copenhagen Area, while supporting the national development towards 100% renewable energy.

The analyses are based on the project Coherent Energy and Environmental System Analysis (CEESA). The CEESA project presents technical scenarios as well as implementation policies and a roadmap of Denmark's transition from a fossil-fuel dominated energy system to a supply system based completely on renewable energy with a dominating part of intermittent sources like wind and photovoltaic. Energy conservation and a certain technological development are prerequisites for this transition. The CEESA scenarios show how the transition can be performed before the year 2050, mainly by the use of known technologies combined with significant energy conservation. The project was partially financed by the Danish Council for Strategic Research and included more than 20 researchers from Aalborg University, University of Copenhagen, Technical University of Denmark, Technical University of Denmark Risø, University of Southern Denmark and Copenhagen Business School [14,20,21].

The analysis in this study is done in three steps which relate to the three chapters of the report 1, 1 and 1:

- *Step 1) To outline the potential national trends in the development towards a 100% renewable energy system with a focus on the issues relevant to the development in The City of Copenhagen and the Greater Copenhagen Area. This is done in line with the conclusions and findings in the CEESA project.*
- *Step 2) To profile the energy system of the Copenhagen to give an indication of the potentials in different sectors.*
- *Step 3) To put the Copenhagen energy system into the context of the presented trends in the potential national development suggested in the CEESA project. This is done to point out some specific areas that should be emphasised in the future planning and development of the regional energy systems.*

Due to its size, Copenhagen is important in some of the strategic choices that have to be made in the transformation towards a Danish 100% renewable energy system. A number of critical technology and infrastructure changes have been selected and analysed in further detail, and the results of these analyses are presented where it is relevant in the report. The specific assumptions and methods for these analyses are presented in the appendices. These are:

- An analysis of which types of power plants and combined heat and power plants are suitable in future 100% renewable energy systems
- An analysis of the heat saving potentials in The City of Copenhagen
- An analysis of potential transport pathways
- an analysis of the differences between the initiatives in the CPH 2025 Climate Plan and the CEESA results for 100% renewable energy in 2050

For the power plant analysis, the transport pathways analysis, and the CPH 2025 systems comparison to the recommendable CEESA 100% renewable energy scenario, the EnergyPLAN energy system analysis tool is used to identify the impacts of different changes in the system. The use of the EnergyPLAN model and the CEESA 2050 Recommendable scenario are presented in the following sections. The analysis of the heat saving potentials is conducted using geographical information systems (GIS) and data at the building level as well as data about heat saving potentials. The methodology regarding the use of GIS is also described below.

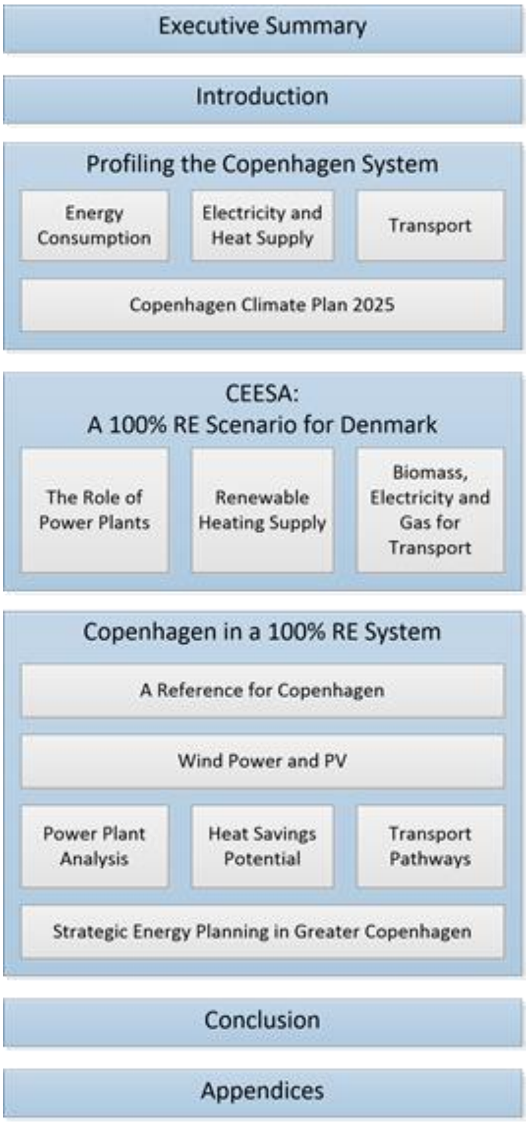


Figure 10: The report structure indicating chapters in blue and sections in grey boxes.

2.2.1 Energy Systems Analyses Using EnergyPLAN

In this study, EnergyPLAN is used for the energy systems analysis tasks, as in the CEESA project. EnergyPLAN is a computer model developed at Aalborg University for the simulation of the optimal operation of energy systems. The model is a deterministic input-output based model calculating the system operation of one full year with a time resolution of one hour. The model is designed for large-scale integration of renewable energy and for the integration of the electricity, district heating and gas systems, which makes the model able to simulate Smart Energy Systems. The full documentation of the EnergyPLAN model can be found in [22].

The model has been used for a large number of research projects related to energy systems modelling and the integration of renewable energy in local energy systems [23] and [24], and national energy systems [25], [26] and [27], as well as for the system integration of different technologies in renewable energy systems [28], [29] and [30].

Model Structure

The basic structure of the model is that demands and specifications of supply and conversion technologies are inputted and when the model is run, it seeks to cover the different demands using the available technologies in the most efficient way (see Figure 11). The criteria for what is most efficient are defined by an adjustable regulation strategy, which is presented in the following paragraph. This means that for every hour the model seeks to meet the demands in the most efficient way by first using the most efficient capacities and hereafter the less efficient capacities. In this way, the resources are used in the optimal way. If a calculation of the economic consequences of a modelled scenario is desired, economic costs for investments, fuels, and operation and maintenance can be inputted together with demands and technology specifications.

A number of different technologies are available in the model to increase the system flexibility and to integrate the electricity, district heating and gas systems, which can be seen in Figure 11. Some traditional examples are CHP units that coproduce heat and electricity, and heat pumps that use electricity to produce heat and thermal storage to balance the supply and demand for heating, but also new technologies as biomass gasifiers that convert biomass to a syngas with an excess heat production, electric vehicles with vehicle-to-grid options to balance electricity supply with demand, and chemical synthesis that combines a synthetic gas with hydrogen to produce a liquid fuel for transport.

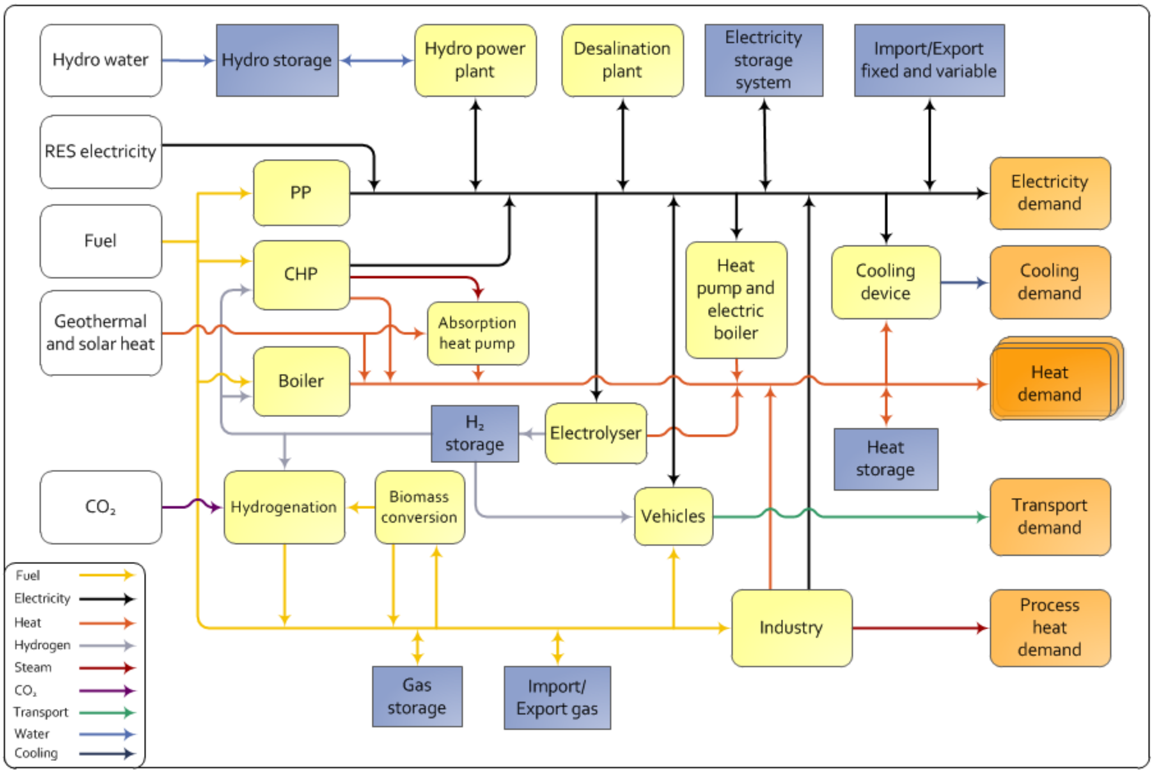


Figure 11: Flow diagram of the EnergyPLAN model version 11.0 [31]. White boxes indicate resources, yellow boxes conversion units and capacities, blue boxes storage and exchange options, and the orange boxes indicate demands.

The outputs of a model simulation contain the total fuel consumptions, CO_2 emissions, total annual costs, and a number of other annual values. It also contains monthly averages and hourly values for all supply and conversion technologies in the model.

The model works at an aggregated level meaning that all units of the same type in the modelled systems are seen as one large unit, and the efficiencies and types of fuel are weighted averages for the type of unit in the system. For example, all the centralised CHP plants in the model will have the same electric and heat efficiencies. The shares of different types of fuel consumption can be set to represent a specific distribution, for example if 50% of the fuel boilers use biomass and the other half uses natural gas, the fuel distribution for the fuel boiler unit is set at 50% biomass and 50% natural gas.

In the model, the DH (district heating) systems are divided into three different groups. All of the three groups have a demand that has to be supplied by units in the particular group. Group 1 is DH systems without electricity production, Group 2 is DH systems based on decentralised CHP units, and Group 3 is DH systems based on large centralised power plants. In the different groups, waste incineration, solar thermal, geothermal, industrial surplus heat, and other heat sources can be included as well.

The total annual costs in the model results are calculated as the sum of investments, fixed and variable operation, fuel and fuel handling, CO_2 costs, and electricity exchange costs. The investment costs are annualised according to the lifetime of the investment and a discount rate.

Model Regulation and Optimisation Strategies

A regulation strategy can be selected for the simulation of a scenario. The regulation strategy is set to optimise the simulation for different types of studies of energy systems depending on its purpose. There are two overall regulation strategies; Technical Optimisation and Market Economic Regulation, and each of the two has a few sub settings. For the Technical Optimisation strategy, it should be set how the model should prioritise the balancing of heat and electricity demands and how individual heat pumps should be operated. For the Market Economic Optimisation, it should be set how the model should regulate the charge of electric cars and vehicle-to-grid options. When using the Technical Optimisation strategy, the model prioritises fuel and energy efficient units, whereas the Market Economic Optimisation prioritises units with the lowest marginal production costs.

If the electricity production is higher than what can be consumed in one hour, excess electricity production will occur and the model has a number of options to handle this excess electricity. It can be handled internally by changing some production from CHP units to boilers or heat pumps, increasing CO_2 hydrogenation or curtailing the production. It is also an option to include interconnection capacities to neighbouring countries, which makes it possible to exchange electricity on an hourly basis. A time series of electricity market prices can be loaded into the model, which allows the model to import electricity when the market price is lower than the marginal production cost and to export when the market price is higher than the marginal production cost. The excess electricity is further discussed in the presentation of indicators for the power plant analysis in Appendix 3.

2.2.2 Application of The Heat Atlas to The City of Copenhagen

The heat atlas was first developed in relation to Heat Plan Denmark in 2008 [32] and has been in development since and most recently described in [33]. The main idea behind the heat atlas is to estimate the heat consumption in buildings based on information from the Register of Building and Dwellings in Denmark (BBR). BBR is updated on a regular basis by the municipalities, who maintain the information though the management of building projects where building owners has to provide information about their building. BBR is therefore a detailed dataset of all buildings in Denmark, out of which approximately 2.5 million buildings are heated. When using BBR one has to be aware that there are many registration errors due to the lack of updating and maintenance, especially in more rural areas. The heat atlas primarily uses three parameters from the BBR to estimate the heat demands: the age, type and size of each building.

The methodology to estimate the demands is based on a report from the Danish Building Research Institute (SBi) from 2010 [34]. The report is based on energy labelling from 2005 to 2010, which has been extrapolated to the whole Danish building stock within five categories: farm houses, single-family houses, detached houses, multi-storey houses, and trade and service buildings. Data regarding the energy quality of the building constructions was sorted by u-values to give an overview of the current level within each building category. The extrapolation was done based on BBR and the statistics bank from Danish Statistics. Each of the five categories was further divided into nine representative building periods to estimate the present heat consumption. The building periods represent the changing requirements following the building periods throughout the years. The heat consumption model was verified with the Energy Statistics from the Danish Energy Agency. In the report, the model is furthermore used to estimate the energy consumption when different improvements of the buildings are implemented. The model includes improvements of the building envelope (outer walls, ceiling, ground deck and windows) as well as ventilation, heat recycling and heat production from solar thermal collectors. In the report, these improvements are implemented in three scenarios: A, B and C reaching savings in heat demand of 52%, 65% and 73% respectively. The scenarios are based on reaching target U-values for each building improvement. All types of building improvements are implemented to certain degrees for each scenario and do not take the building periods into account, unless the target U-value is reached. This means that it is the same type of building improvements that are carried out in each scenario, but scenario C implements more than scenario A. The model also includes costs associated with the improvements, which are divided into two categories: direct and marginal costs. The direct costs are the investment of implementing the savings only with the purpose of energy renovating the building, while the marginal costs are the investments associated with improving the building when it is being renovated anyway. Simply put, the marginal cost is the cost of supplying a house with additional insulation or replacing existing windows with better windows [34].

The demands and scenarios from the SBi report form the basis of the heat atlas, which estimates demands and saving potentials for all buildings in Denmark in a GIS database at the building level. Additionally, the heat atlas includes information from the BBR on heat supply and building protection. The heat supply system information is not used in this report as Copenhagen is predominantly supplied by district heating. The protection information is used to choose the buildings in which it is possible to implement heat savings

2.2.3 Technological development and renewable energy scenarios in CEESA

The aim of the CEESA project was to design a relevant scenario for transforming the present energy system based mainly on fossil fuels into a 100% renewable energy system by year 2050. The results of the CEESA project are used as the basis of the analyses in this project. The design of such a scenario is highly dependent on the technologies which are assumed to be available within the chosen time horizon. To highlight this issue, the CEESA project has identified the following initial scenarios based on three different assumptions with regard to the available technologies:

CEESA-2050 Conservative: The conservative scenario is created using mostly known technologies and technologies which are available today. This scenario assumes that the current market can develop and improve existing technologies. In this scenario, the costs of undeveloped renewable energy technologies are high. Very little effort is made to push the technological development of new renewable energy technologies in Denmark or at a global level. However, the scenario does include certain energy efficiency improvements of existing technologies, such as improved electricity efficiencies of power plants, more efficient cars, trucks and planes, and better wind turbines. Moreover, the scenario assumes further technological developments of electric cars, hybrid vehicles, and bio-DME/methanol production technology (including biomass gasification technology).

CEESA-2050 Ideal: In the ideal scenario, technologies which are still in the development phase are included on a larger scale. The costs of undeveloped renewable energy technologies are low, due to significant efforts to develop, demonstrate and create markets for new technologies. For example, the ideal scenario assumes that fuel cells are available for power plants, and biomass conversion technologies (such as gasification) are available for most biomass types and on different scales. Co-electrolysis is also developed and the transport sector moves further towards electrification compared to the conservative scenario, e.g., by using only DME/methanol electrofuel in the parts of transport that cannot be covered with electric vehicles.

CEESA-2050 Recommendable: This scenario is a “realistic and recommendable” scenario based on a balanced assessment of realistic and achievable technology improvements. It is used to complete a number of more detailed analyses in the project, including the implementation strategy, as well as in a number of sensitivity analyses. Here, however, less co-electrolysis is used and a balance is implemented between bio-electrofuels (DME/methanol) and CO_2 electrofuels (DME/methanol) in the transport sector. This is the main CEESA scenario.

The Conservative and Ideal scenarios are used to illustrate that different technological developments will have different effects on the extent of the use of biomass resources, as well as the requirements for flexibility and Smart Energy System solutions. In the CEESA scenarios, the Smart Energy System integration is crucial. The scenarios rely on a holistic Smart Energy System including the use of: heat storages and district heating with CHP plants and large heat pumps, new electricity demands from large heat pumps and electric vehicles as storage options, electrolysers and liquid fuel for the transport sector, and enabling storage as liquids as well as gas storage.

All the above three technology scenarios are designed in a way in which renewable energy sources, such as wind power and PV, have been prioritized. Moreover, they are all based on decreases in the demand for electricity and heat as well as medium increases in transport demands. Consequently, none of the scenarios can be implemented without an active energy and transport policy. However, sensitivity analyses are conducted in terms of both a high energy demand scenario and the unsuccessful implementation of energy saving measures. These analyses point in the direction of higher costs, higher biomass consumption and/or an increased demand for wind turbines.

The reference scenario used in the current project is developed in connection to the CEESA project. The reference scenario of 2010 reflects the actual Danish energy system in 2010 based on statistical data from this year. The following years in the reference scenario, 2020, 2030 and 2050, have been defined to reflect a business-as-usual development only including the adopted policies from 2010. The purpose of this reference scenario is to show how the system will develop and look like if no new initiatives are implemented and if only traditional measures are applied. This is therefore not seen as a realistic development of the system, but rather as a base for assessing and understanding the changes that should take place in the development towards a 100% renewable energy system as suggested in the CEESA scenarios.

The scenario developed in CEESA is only a snapshot in time and will be subject to repeated improvements as further research is carried out. It is based on existing knowledge and potential developments into scenarios for the year 2050 based on many different aspects of the energy system including technology development, renewable resources, fuel prices, CO_2 prices, and investment costs.

The current primary energy supply in Denmark (fuel consumption and renewable energy production of electricity and heat for households, transport and industry) is approximately 850 PJ, taking into account the boundary conditions applied to transport in this study, in which all transport is accounted for, i.e., national/international demands and both for passengers and freight. If new initiatives are not taken, the energy consumption is expected to decrease marginally until 2020, but then increase gradually until 2050. The measures of energy savings, transport as well as renewable energy and system integration between the electricity, heat, transport and gas sectors can reduce the primary energy supply to approximately 670 PJ in CEESA 2020 and approximately 470 PJ in CEESA 2050. At the same time, the share of renewable energy from wind turbines, photovoltaic, solar thermal, and wave energy, as well as biomass will be increased. The share of renewable energy in the recommended energy system increases from about 20% in 2010 to 42% in 2020 and to about 65% in 2030. If the oil and gas consumption in refineries and for the extraction of oil in the North Sea is excluded, the share of renewable energy in the 2030 energy system is 73%. Coal is phased out before 2030. In 2050, the entire Danish energy system (incl. transport) is based on 100% renewable energy [14]. The primary energy supply is illustrated in Figure 12.

In addition to a transition from a fossil based energy system, the CEESA scenarios are able to show that 100% renewable energy is technically possible, since all scenarios are analysed on an hour-by-hour basis. Furthermore, the 100% renewable energy system has similar or lower costs than current fossil based energy systems and at the same time creates more jobs, causes fewer health related problems due to emissions, and reduces greenhouse gas emissions.

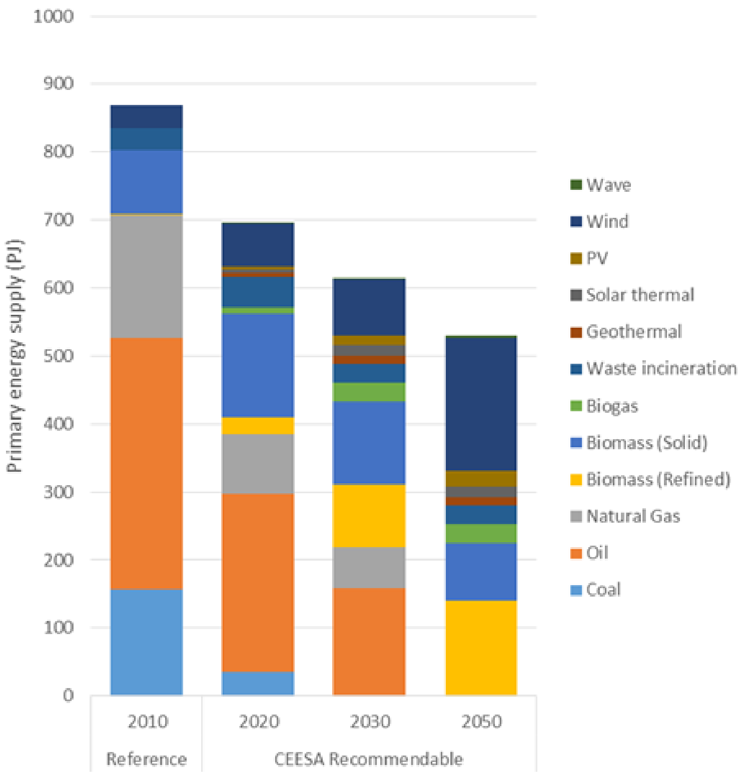


Figure 12: Primary energy supply of a Reference scenario for 2010 and the CEESA Recommendable 2020, 2030, 2050 scenarios divided into the different sources of energy.

3 Profiling the Copenhagen System

In this chapter, the current situation regarding energy consumption, heat and electricity production and energy demand for transport in The City of Copenhagen is outlined to indicate potential focus areas in the transition. Secondly, The City of Copenhagen's targets in the CPH 2025 Climate Plan are presented to indicate how the energy sector in the municipality is intended to develop towards 2025. This leads to a discussion and identification of focus areas relevant for the Greater Copenhagen Area in the development towards 100% renewable energy. The focus areas identified are further analysed and discussed in Chapter 1.

3.1 Current Status on Energy Supply and Demand

The energy supply in The City of Copenhagen is characterized by the high population density which generates a high energy demand, but also a good potential for the utilization of district heating and efficient public transport systems. The biggest share of the primary energy supply is used in CHP plants and the district heating consumption accounts for about 40% of the energy end consumption.

3.1.1 Energy Consumption

The energy consumption can be divided into three main categories: heating, electricity and transport. In Figure 13, the shares of these three categories are shown. With 43% the heating stands as the biggest category and it consists of about 95% district heating and the remaining 5% is individual heating. The use of electricity for heating is rather limited and is counted in the category of electricity consumption. The heat consumption and transport is elaborated further in the following sections. For electricity national averages are applied.

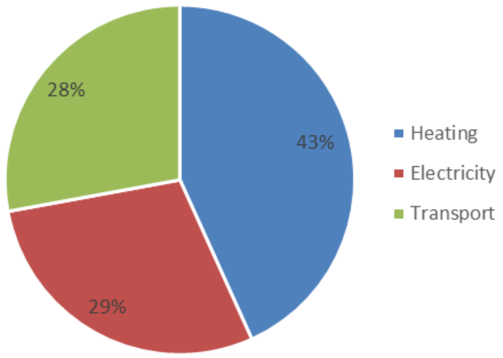


Figure 13: Shares of energy consumption in the three categories: Heating, electricity and transport for The City of Copenhagen. Main references: [11] and [12]. Calculations and references are elaborated in Appendix 1.

The district heating systems in The City of Copenhagen are highly developed covering 95% of the municipality area with district heating distribution (see Figure 14) [35]. The dense heat demand in the area gives high production efficiency compared to the individual heating. This also means that the potential for expanding the DH grid is rather small. On the other hand, some parts of the DH grid are supplied with DH in the form of steam which generates higher heat losses than with water-based DH systems. The steam supplied DH systems are gradually being converted to water-based DH as in the rest of the system and some of it is even converted to low temperature DH for lower heat losses and higher production efficiency.

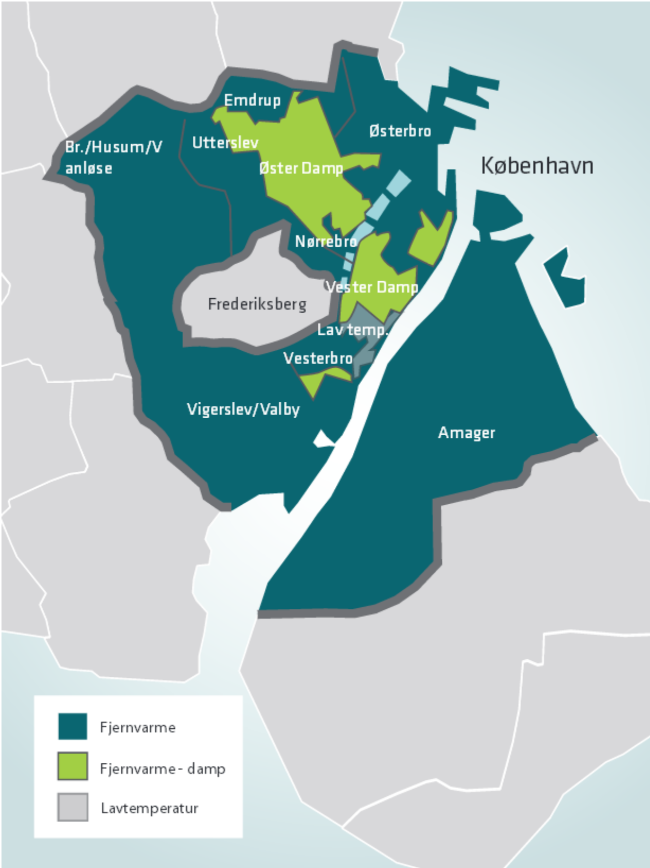


Figure 14: **Map of district heating areas in the City of Copenhagen (*Fjernvarme*: District heating, *Damp*: Steam, *Lavtemperatur*: Low temperature) [36].**

3.1.2 Electricity and Heat Production

In this section, the electricity and heat production for the Greater Copenhagen Area is presented in terms of production units and fuel consumption. The supply system for the whole Greater Copenhagen Area is included because there is a high degree of cooperation in the planning and operation of the energy supply across municipality boarders in this region. Moreover, the production of electricity and DH in the Greater Copenhagen Area is seen as a good representation of the supply in The City of Copenhagen. There are some district cooling supply systems in Copenhagen but these were not included.

The total heat production for the DH system of around 35 PJ is produced at four central CHP plants, three waste incineration plants (see Figure 15) and more than 50 peak load boiler plants. The production from the waste incinerators are here prioritised. In addition to the waste incineration plants, a demonstration geothermal plant and a waste water treatment plant supply waste heat to the DH system and the production from these is prioritized together with the waste incineration plants [37].

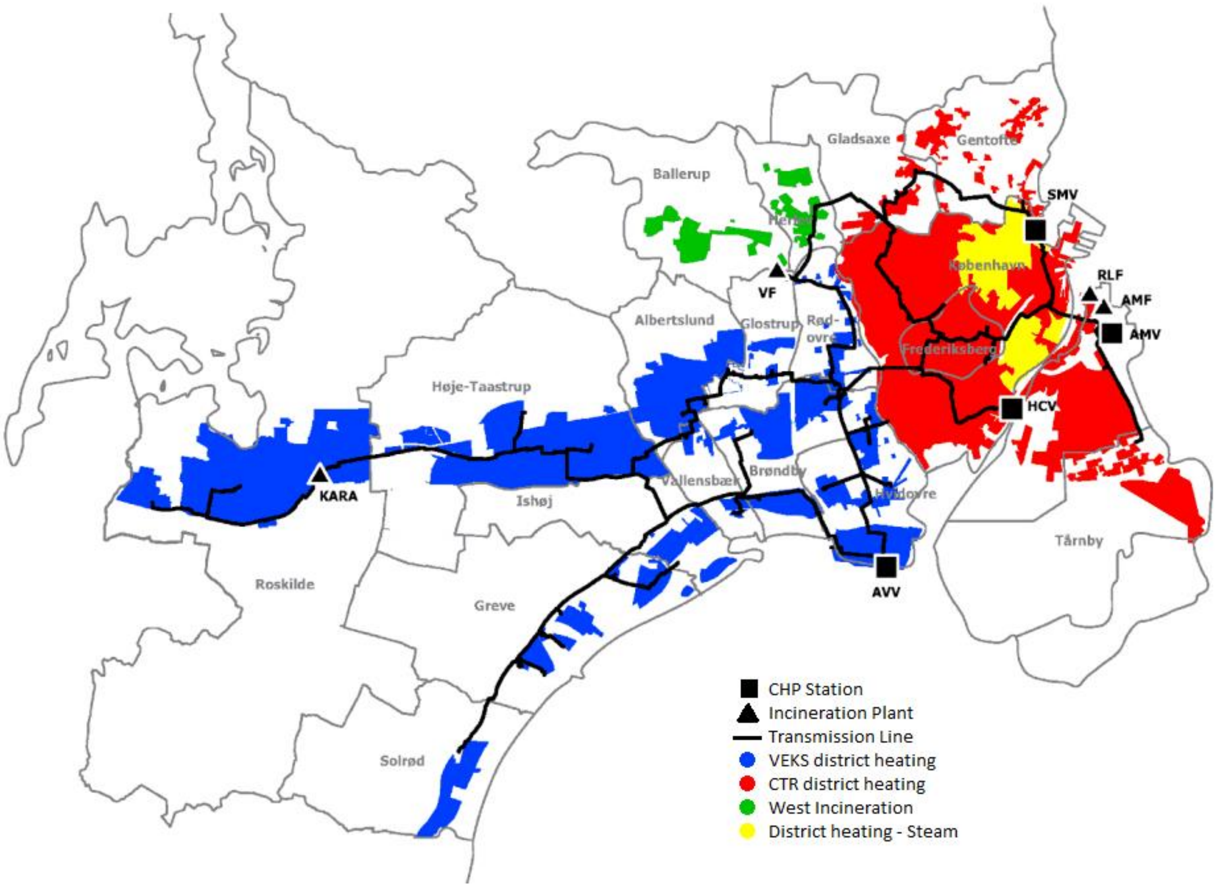


Figure 15: Map of DH areas in the Greater Copenhagen Area [38].

As can be seen in Table 2, the CHP plants use different fuels and most of them can use a combination of different fuels; biomass, coal and natural gas supplemented by fuel oil. The operation of the plants is optimized according to the production costs and environmental aspects, which means that the heat production is flexible to changes in fuel prices, electricity prices and fluctuations in heat demand, and a number of thermal storages were included [39].

Table 2: Fuel type and capacities at the main CHP plants and waste incineration plants in the Greater Copenhagen Area [40].

		Fuel	Capacity (heat) MJ/s	Capacity (electricity) MW
CHP Plants				
Amagerværket (AMV)	Unit 1	Biomass, coal, fuel oil	250	80
	Unit 2	Biomass, fuel oil	166	95
	Unit 3	Coal, fuel oil	331	263
Avedøreværket (AVV)	Unit 1	Coal, fuel oil	330	250
	Unit 2	Gas, biomass, fuel oil	570	570
H.C. Ørstedsværket (HCV)		Gas	815	185
Svanemølleværket (SMV)		Gas, fuel oil	355	81
Waste Incineration Plants				
Amagerforbrændingen (AMF)		Waste	120	25
Vestforbrænding (VF)		Waste	204	31
KARA/NOVEREN		Waste	69	12

In Figure 16, it can be seen that coal and wood pellets are the fuels mostly used in the heat and electricity production, both approximately 30%, and the fossil fuels (coal, oil and natural gas) count for 48% of the consumed fuels. In addition, 41% of the energy content in the waste is also based on fossil fuels [9], which in total make a fossil share of 56%. The 44% renewable share in the fuel consumption consists of wood pellets, straw, a small amount of biogas, and the biomass based fraction of the waste.

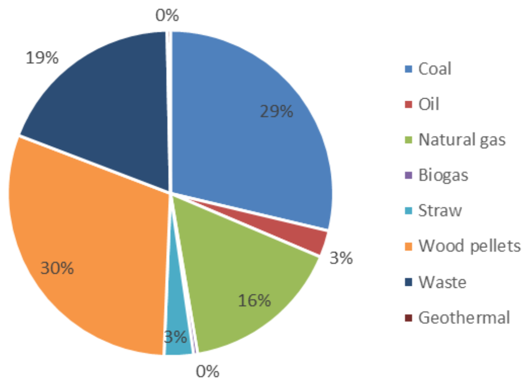


Figure 16: The shares of different fuels in the energy consumption at the plants for electricity and district heating production in The Greater Copenhagen Area.

The production from wind turbines can be measured in two different ways which give very different outputs. The first way is to count the turbines in the geographical area of the municipality – both onshore and offshore turbines. The other way, as suggested by [41], is to count the onshore turbines in the geographical area of the municipality and dividing the offshore turbines equally between the municipalities. In the case of the municipalities in the Greater Copenhagen Area, the total electricity production from wind in 2012 would be 567 TJ according to the first method, but 2,597 TJ if applying the second method. This makes the share of wind in the total electricity consumption 5% and 23%, respectively. In both cases, the share is lower than the national average which was 30% in 2012 [42].

3.1.3 Transport

The transport in The City of Copenhagen consists of a number of different means of transport, and different energy sources covering the transport demand are summarised here. Local transport is accounted to The City of Copenhagen, while regional and national transport is divided according to the population density in the particular related municipalities. All fuel consuming transport is included; cars, trucks, busses, trains, ships and aviation.

Figure 17 shows the energy consumption divided into type of energy supply. It can be seen that diesel and petrol account for more than half of the energy consumption, JP1 (Jet petroleum used in aviation) accounts for one third, and the rest (electricity, fuel oil and biofuel) makes only about 6%. The total energy consumption is 10,800 TJ, which is a small share of the total national consumption for transport of 210,000 TJ [43].

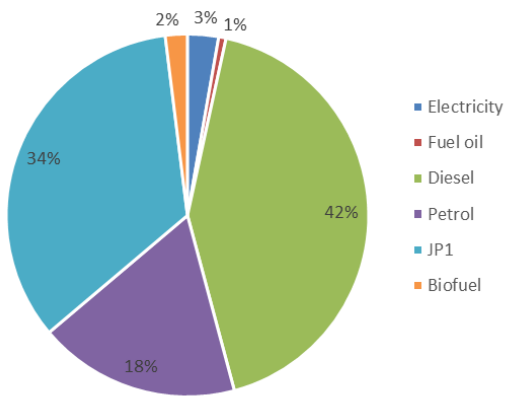


Figure 17: Total energy consumption for transport in The City of Copenhagen divided into type of energy supply.

This summary of the energy sources for the transport demand is based on an energy balance made by the consultancy company PlanEnergi for 2011 [11]. This is based on a number of sources about the transport in the city. Some of these are specific for The City of Copenhagen whereas others are national values for Denmark and scaled down by the population in Copenhagen. The data for each of the types of transport are elaborated in Appendix 1.

It can be seen from this that the energy supply for transport in The City of Copenhagen is mainly based on fossil fuels, except for the small amount of biofuel mixed into the regular transport fuel and the electricity produced from renewable energy. It should also be noted that the fuel consumption in The City Copenhagen is significantly lower than the national average per capita.

3.2 CPH 2025 Climate Plan

The CPH 2025 Climate Plan was presented in 2012 and introduced the target for The City of Copenhagen of becoming CO_2 neutral by 2025. This plan further presents a vision of becoming 100% renewable by 2050.

3.2.1 Background of the CPH 2025 Climate Plan

In 2009, The City of Copenhagen presented the plan called Københavns Klimaplan (Copenhagen Climate Plan) which set the goal of 20% reduction of CO_2 emissions in 2015 and presented a vision of making Copenhagen CO_2 neutral by 2025 [44]. With this plan, a process was initiated regarding the development towards a CO_2 neutral energy supply for heating, electricity and transport in the Greater Copenhagen Area.

Before Copenhagen Climate Plan was presented a dialogue took place with the involved energy companies in the Greater Copenhagen Area about the possibilities of going towards CO_2 neutrality. within the DH supply. The project Varmeplan Hovedstaden (Heat Plan Greater Copenhagen) was a central part of the development of Copenhagen Climate Plan that focused on the future heat supply in the Greater Copenhagen Area. The heat and electricity production at CHP plants accounts for the largest part of the CO_2 emission reductions in the planning for CO_2 neutrality. The project analysed different scenarios with a target of 70% renewable energy supply and one scenario with 100%. The results indicate that it is possible to reduce CO_2 emissions significantly and that it can be done in an economically feasible way [45]. As a follow-up, Heat Plan Greater Copenhagen 2 was presented with the purpose to create a common platform between the three supply companies for decisions regarding CO_2 neutral DH supply and involving the priority of projects and choice technologies [37]. With the municipal budget agreement in 2011, it was decided to refine the vision from 2009 of CO_2 neutrality in The City of Copenhagen by 2025 into a more specific plan. This plan is called CPH 2025 Climate Plan and was presented in 2012. CPH 2025 Climate Plan presents more specific goals and initiatives to make the municipality CO_2 neutral in 2025 [5]. The third stage in Heat Plan Greater Copenhagen 3 was initiated in November 2012 and finished in October 2014. The project had the purpose to analyse and coordinate large investments in the upcoming 10-15 years in the heat production and transmission systems. The project also aims to quantify the potential of interplay between the DH and electricity systems with large amounts of wind integration including a focus on the biomass consumption [46].

3.2.2 Initiatives for CO_2 Emission Reductions

The CPH 2025 Climate Plan presents a number of initiatives to reach the goal of CO_2 neutrality in 2025, structured in four categories; energy consumption, energy production, green mobility, and city administration initiatives. The initiatives in these categories make up for 94% of the required reductions and the remaining 6% is expected to come from new initiatives (see Figure 18). The total amount of CO_2 emissions from The City of Copenhagen that need to be removed is estimated at 1.2 m tons. The specific initiatives are summarised in Table 3. The CO_2 emissions from the four mentioned categories are not equal to the reduction targets of the same categories. It is assumed that the excess production of electricity from wind power and biomass power plants which is not consumed in the municipality will be exported, leading to the reduction of fossil fuel-based electricity production in other municipalities. 74% of the reduction of CO_2 emissions will come from the energy production which holds far the biggest share of the planned reductions. The consumption of fossil fuels for transport cannot realistically be substituted with renewable energy by 2025, but the emissions reduced through the overproduction of electricity counterbalance the emissions from transport in the municipality.

This methodology means that the reduction targets have to be adjusted if the wind power exported in the future does not replace coal power as it is assumed now. This would mean that the transport sector is not offset by lower emissions in the power plants elsewhere than in Copenhagen.

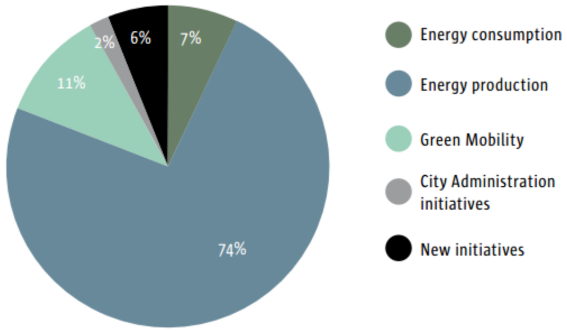


Figure 18: Distribution of CO_2 reductions in The CPH 2025 Climate Plan to reach the goal of CO_2 neutrality in 2025 resulting from initiatives contained in the four themes [5].

This could well be the case, as in many other parts of Denmark, coal CHP and power plants are being replaced by biomass. The initiatives in Table 3 are a summary of the full list of initiatives in the CPH 2025 Climate Plan [5]. These initiatives are used in the following section for identifying relevant focus areas for Copenhagen and in the definition of a Copenhagen reference system in Chapter 1.

Table 3: Summary of initiatives in the CPH 2025 Climate Plan for reductions of CO_2 emissions. Summarized from [5]

Category	Initiative
Energy Consumption	Energy renovation and refurbishment of existing buildings to reduce heat demand Promotion of low energy standards in new buildings Improving flexibility of demand to accommodate fluctuations in production from renewable energy sources
Energy Production	Development of new sources for district heating supply Construction of wind turbines, on and near shore including locations in other municipalities Conversion from coal and natural gas to biomass fired power plants Sorting out fossil based material from waste Bio-gasification of organic waste fractions
Green Mobility	Improving conditions for bikes and public transport Assessment of potentials for renewable fuels Intelligent operation of public transport
City Administration Initiatives	Reduction of energy consumption in municipality owned buildings Construction of solar PV on municipality buildings Municipality owned cars run on electricity, hydrogen or biofuel
New Initiatives	Undefined new projects that will reduce CO_2 emissions are expected to be initiated.

3.3 Key Focus Areas for Copenhagen Towards 100% Renewable Energy

The purpose of this section is to present identified key focus areas for The City of Copenhagen and the Greater Copenhagen Area in the development towards a 100% renewable energy system potentially in 2050. These are identified by comparing the tendencies with the current status on the energy supply in the city and the plans for future development. The key focus areas are presented in the following sections.

3.3.1 The Type of Power Plant in Renewable Energy Systems

The type of power plant in a system with 100% renewable energy supply and a high share of fluctuating resources was pointed out in the CEESA project as the key area in the electricity and heat balancing. In this project, combined cycle gas turbines are suggested as the best solution for CHP plants to keep the biomass consumption low and to regulate quickly for fluctuations in, e.g., wind power. In the CPH 2025 plan, it is suggested to implement biomass fired boilers for steam turbines, which is a technology with different characteristics. Therefore, the choice of power plants for central CHP areas is identified as a key focus area for the future development of the energy sector in Copenhagen.

3.3.2 Heat Demand Reductions in the Building Stock

According to a number of studies, heat demands in existing buildings should be reduced to approximately half of what it is today. Heat savings are not equally feasible in all buildings, but in most buildings at least 50% heat savings is feasible when taking into account the costs for the renovation and energy supply. In the CPH 2025 Climate Plan, the targets for heat savings are substantially lower than the 50% suggested; thus, the potentials for heat savings and the associated costs are identified as another key focus area.

3.3.3 Transport Pathways towards Renewable Energy

Regarding transport, a lot of effort has been put into developing transport pathways in the CEESA project and different scenarios have been analysed comparing costs and biomass consumption. In the CPH 2025 Climate Plan, the main focus is not on renewable energy solutions for transport and only a few possible components have been mentioned. Since transport is a very large energy consuming sector and an important part of a renewable energy system, the pathways towards renewable energy in transport have also been identified as a key focus area.

4 CEESA: A 100% Renewable Scenario for Denmark – A National Perspective

The future energy system will be very different from the current energy system. Today, the design of the energy system is based on fossil fuels. This makes the supply side of the energy system very flexible and reliable since large amounts of energy can be stored in liquid, gas, and solid forms via fossil fuels. This means that energy can be provided 'on demand', as long as there is a suitable fossil fuel storage nearby, such as:

- A diesel tank in a car
- A gas tank for a boiler
- A coal storage for a power plant

Fossil fuels have provided society with large amounts of energy storage and it is available on demand whenever it is required. This means that the energy system has been designed around this key attribute. In the beginning, energy systems were relatively simple. As displayed in Figure 19, power plants supplied electricity, boilers provided heat, and vehicles provided transport, all with the aid of flexible and stored energy in the form of fossil fuels.

However, after the oil crisis in the 1970s, the energy system began to change. It became apparent during the oil crisis that without fossil fuels, the energy system could not meet the demands of society. As a result, Danish energy policy began to change dramatically for the following key reasons:

- Security of supply: to reduce Denmark's dependency on imported fossil fuels
    - Job creation: to replace fuel expenses by expenses for paying off investments and thus creating new employment and enabling technological development
    - Climate change: to reduce Denmark's impact on the global climate

Due to these initiatives, the primary energy supply in Denmark has been the same in Denmark from the early 1970s until today. This has been due to three major successes in the Danish energy system:

1. Significant heat savings achieved by insulating houses
2. Expanding the use of waste heat from electricity production by replacing centralised power plants with combined heat and power (CHP) plants, in combination with a significant increase in the amount of district heating
3. Large-scale expansion of wind power to replace electricity from power plants

As can be seen in Figure 20, this has meant that the local communities have been engaged in wind power development and the expansion of district heating. Wind power is connected to local ownership schemes as are district heating and small-scale CHP.

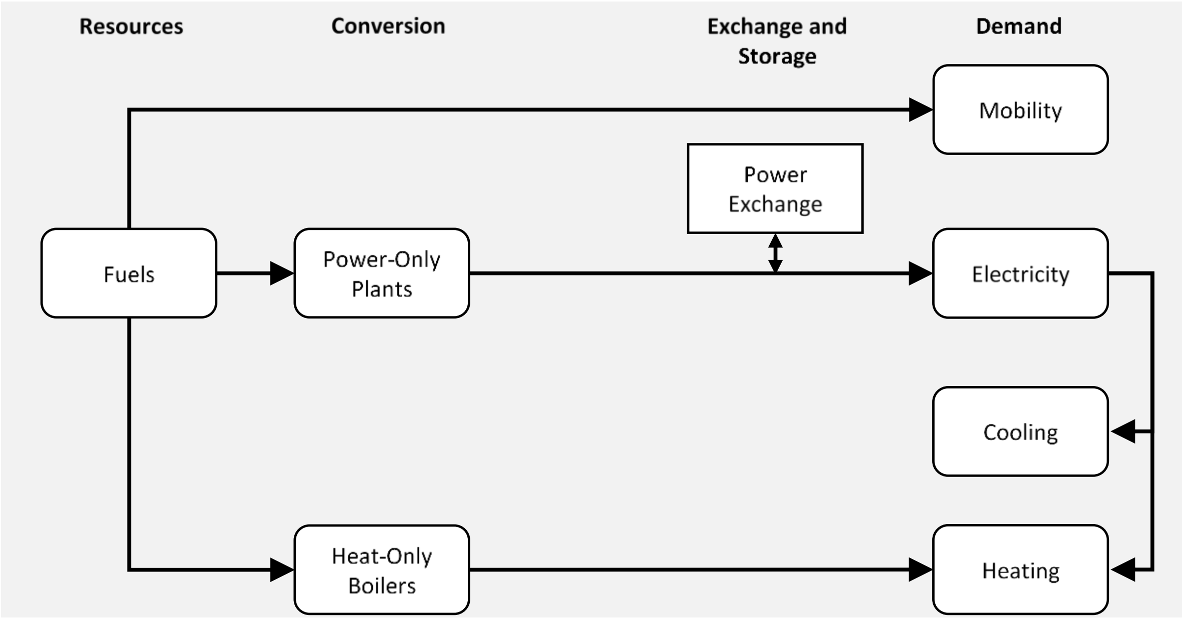


Figure 19: Interaction between sectors and technologies in the Danish energy system until the 1970s.

The energy end demand for heating has decreased, while the amount of square meters has risen and the use of CHP for heating and electricity has increased. At the same time, the amount of wind power has risen. Hereby, the total energy consumption in Denmark has been kept at a stable level and the energy supply has been diversified, primarily due to policies promoting the three issues mentioned above.

Although the primary energy supply has remained constant, the electricity demand has risen even though policies have promoted savings. Transport has not been neglected historically until 2008, although it has major influence on the security of supply and has significant environmental impacts [47,48].

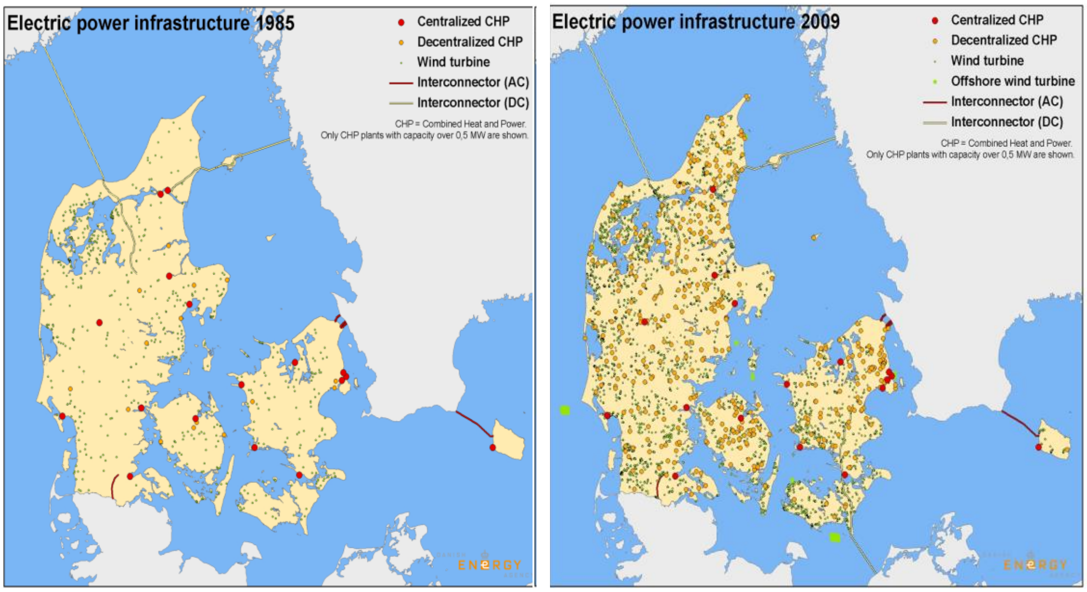


Figure 20: Development of the electric power system from 1985 until 2009 illustrated by the Danish Energy Agency.

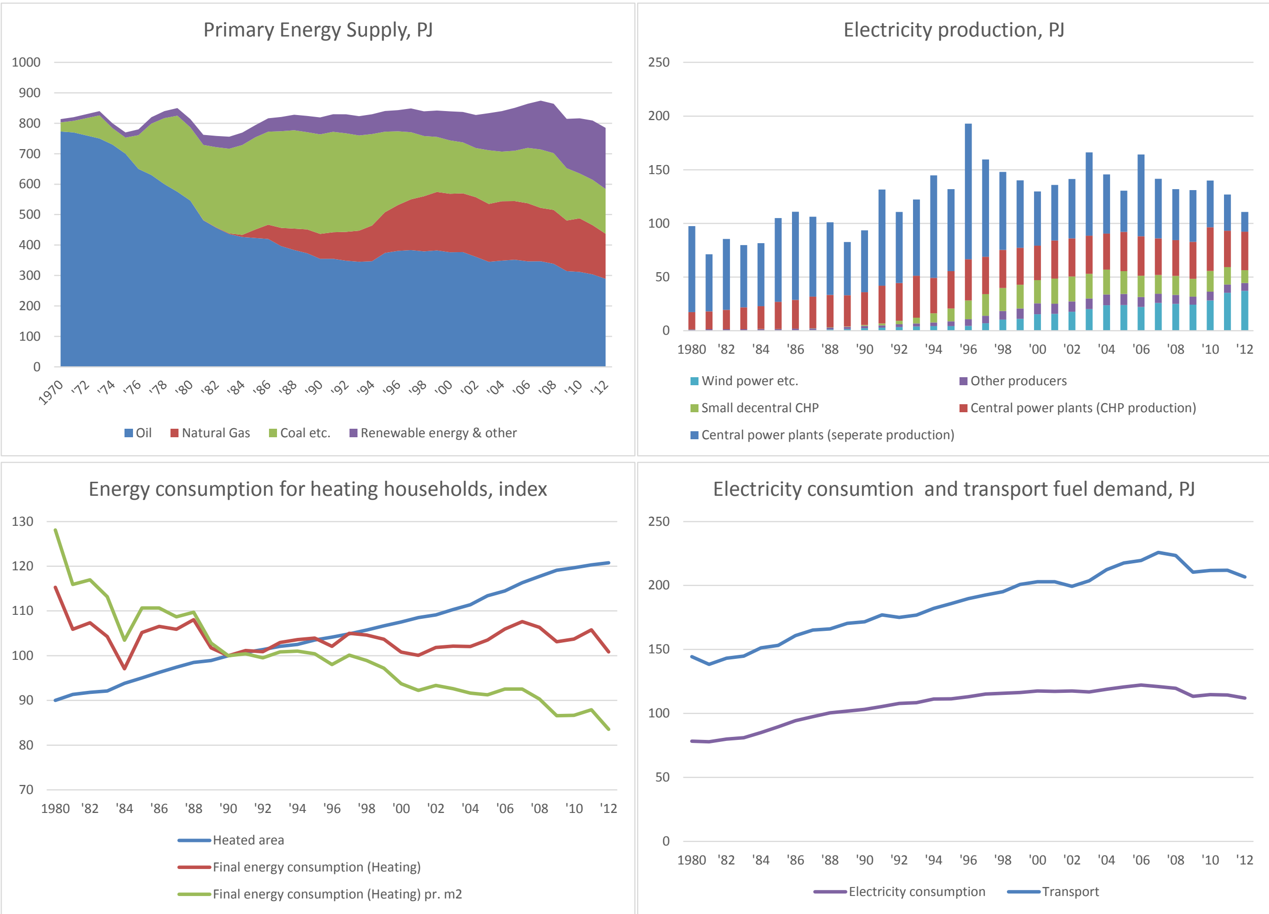


Figure 21: The primary energy supply (top left), types of electricity production units and total electricity production (top right), energy consumption for heating (bottom left) and electricity consumption and transport fuel demand (bottom right). Source: The Danish Energy Agency [49] (the primary energy demand includes years back to 1970. The period from 1970 until 1980 has been estimated from various sources).

These actions are now evident in the new structure of the Danish energy system, which is illustrated in Figure 22. The electricity and heat sectors have become heavily dependent on one another due to the introduction of CHP. At the same time, the electricity sector has begun to accommodate significant amounts of intermittent renewable energy, primarily using wind power, but also with some solar photovoltaic panels.

It is important to recognise that these changes have had a very positive impact on all aspects of the energy system. For example, **if oil was the only fuel utilised in Denmark today, as in the early 1970s, the annual socio-economic cost of the energy system in Denmark would be approximately 25 Billion DKK/year higher and the annual greenhouse gas emissions from Denmark would be approximately 20% higher than today**. This illustrates some of the impacts of an active energy policy over the past 40 years. However, the biggest challenges still lie ahead. Denmark has a target to become 100% renewable by the year 2050, which means that the changes required over the next 40 years are even greater than those achieved in the last 40 years.

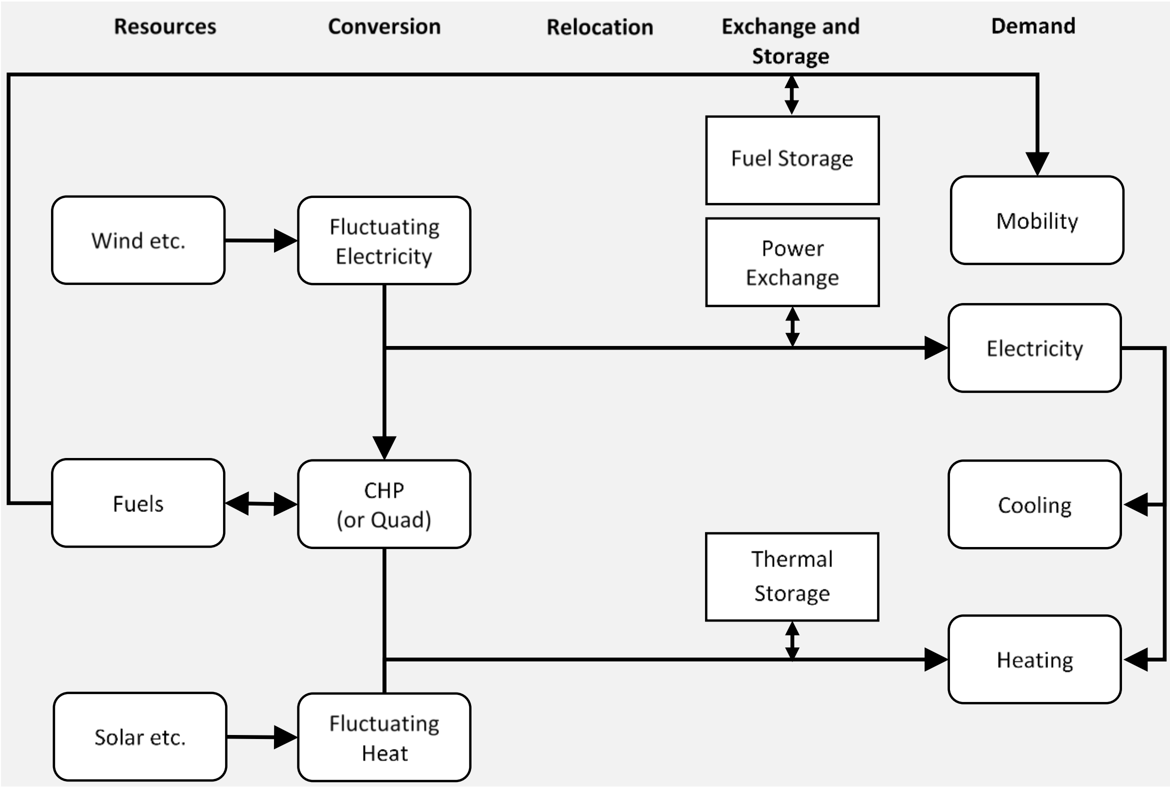


Figure 22: Interaction between sectors and technologies in the current energy system in Denmark.

This raises a very interesting and important question: what does a 100% renewable energy system in Denmark look like? This has been the focus of the CEESA research project, where the key result is the design and analyses of one potential scenario for 100% renewable energy in Denmark. As displayed in Figure 23, the structure of a 100% renewable energy system is much more complex than the existing energy system in Denmark. In the future, all sectors of the energy system will be interconnected with one another, in what is defined as a '**Smart Energy System'** [6-8,50]**.**

A Smart Energy System consists of new technologies and infrastructures which create new forms of flexibility, primarily in the 'conversion' stage of the energy system. This is achieved by transforming a simple linear approach in today's energy system (i.e., fuel to conversion to end-use) into a more interconnected approach. In simple terms, this means combining the electricity, heat, and transport sectors in such a way that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar energy. The Smart Energy System uses technologies such as:

- **Smart Electricity Grids** to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and photovoltaic energy.
- **Smart Thermal Grids** (District Heating and Cooling) to connect the electricity and heating sectors. This enables the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system.
- **Smart Gas Grids**, which are gas infrastructures that can intelligently integrate the actions of all users connected to it – suppliers, consumers and those that do both – in order to efficiently deliver sustainable,

economic and secure gas supplies and storage.

Based on these fundamental infrastructures, a Smart Energy System is defined as an approach in which smart Electricity, Thermal and Gas Grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system.

The transition towards such a system involves many complex changes, some of which are described briefly in the following.

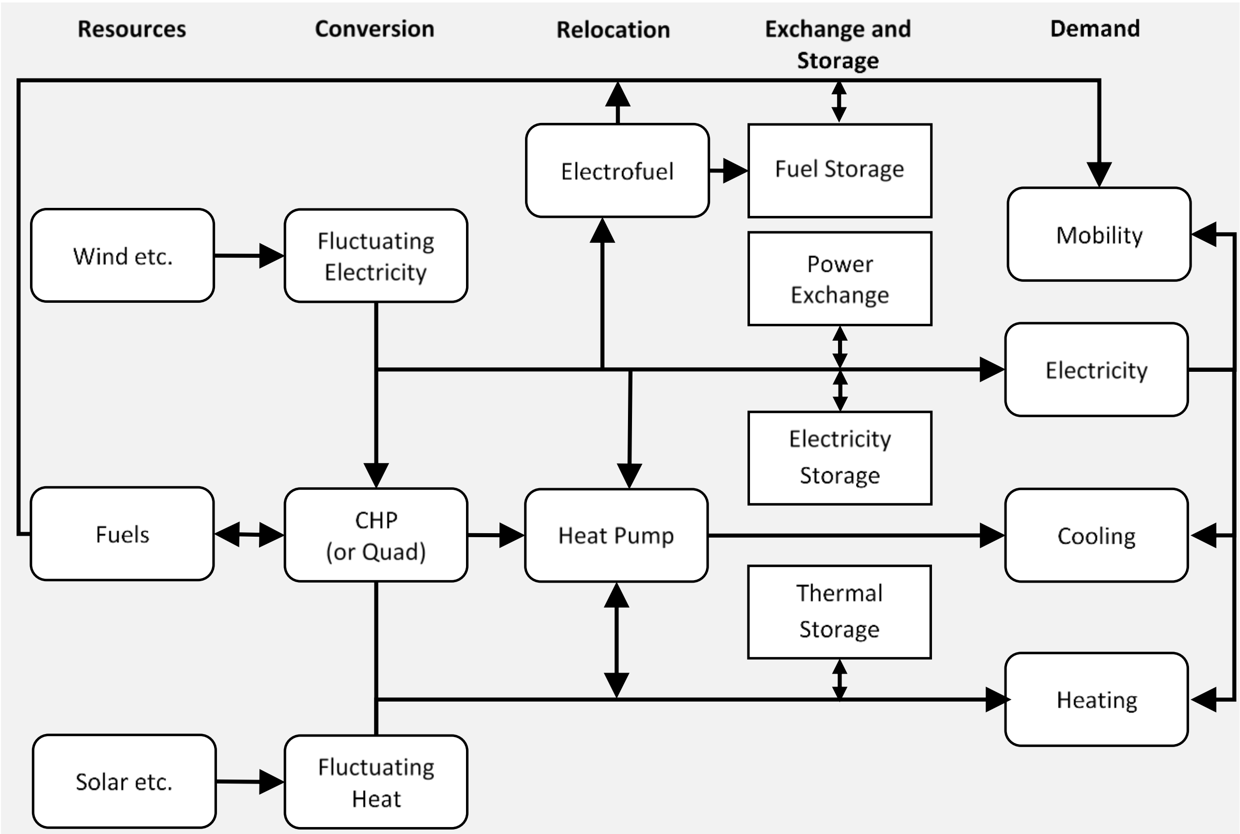


Figure 23: Interaction between sectors and technologies in a 100% renewable energy system in Denmark.

4.1 The Role of Power Plants in Future Energy Systems

Today electricity supply follows electricity demand. Consumers simply use the electricity they require and the electricity supply responds. As mentioned earlier, this is only possible due to the large amounts of energy stored in fossil fuels, since it enables the electricity supply to respond

..Electricity demands will have a new role in the electricity sector..

when necessary. This type of system is reflected in the business-as-usual Reference scenario developed in the CEESA project. In this scenario, the electricity sector continues to evolve under the same principals as today, where electricity production (Figure 24) responds to a fixed electricity demand and the heat supply is based mainly on CHP in combination with peak load boilers as well as individual boilers.

In contrast, parts of the electricity sector in the CEESA Recommendable 100% renewable energy scenario are based on the opposite principal: here the electricity demand responds to the electricity supply. In the CEESA scenario, intermittent renewable electricity accounts for approximately 80% of the total electricity production (Figure 25). This means that the majority of the electricity supply fluctuates.

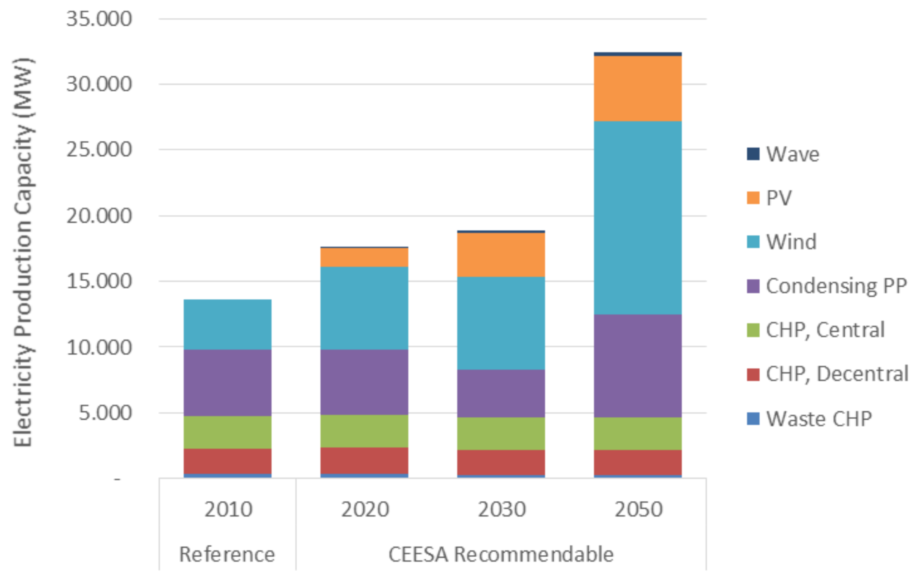


Figure 24: Electricity production capacity in Denmark between 2010 and 2050 for the CEESA Recommendable 100% renewable energy scenario.

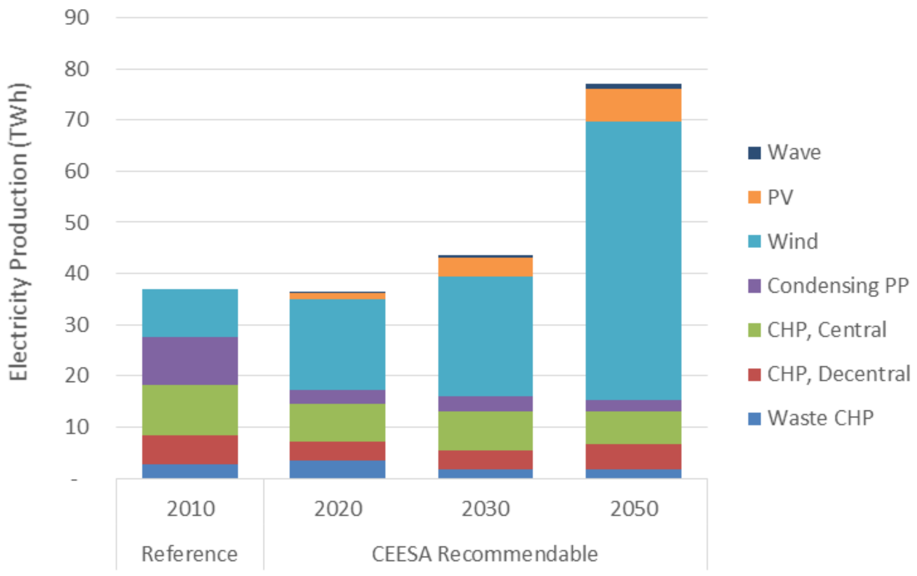


Figure 25: Electricity production in Denmark between 2010 and 2050 for the CEESA Recommendable 100% renewable energy scenario.

To accommodate this, the demand side of the electricity sector must become extremely flexible, which is possible due to the new electricity demands. Also the remaining power plants need to be able to operate as flexible as possible. These new demands include capacities of large-scale heat pumps in district heating networks and buildings. New demands are made flexible, e.g., electric vehicles and individual heat pumps as well as electrolysers for the production of electrofuels (Figure 26 and Figure 27). In this world, the roles of demand and supply are very different from today. The electricity demand as we know it today will be lower due to electricity savings; however, the new demand creates a total electricity demand which is twice the size of today. Electricity savings in the demands we know today should be lowered by 30-50% in industry and households ("Electricity demands" in Figure 26 and Figure 27).

To some extent, interconnectors to neighbouring countries can accommodate the integration of renewable energy sources, but there is a limit to the reasonable size of the interconnection capacity from an economic point of view. In CEESA, the economic impact of including interconnectors has been analysed and the results of this are illustrated in Appendix 1.

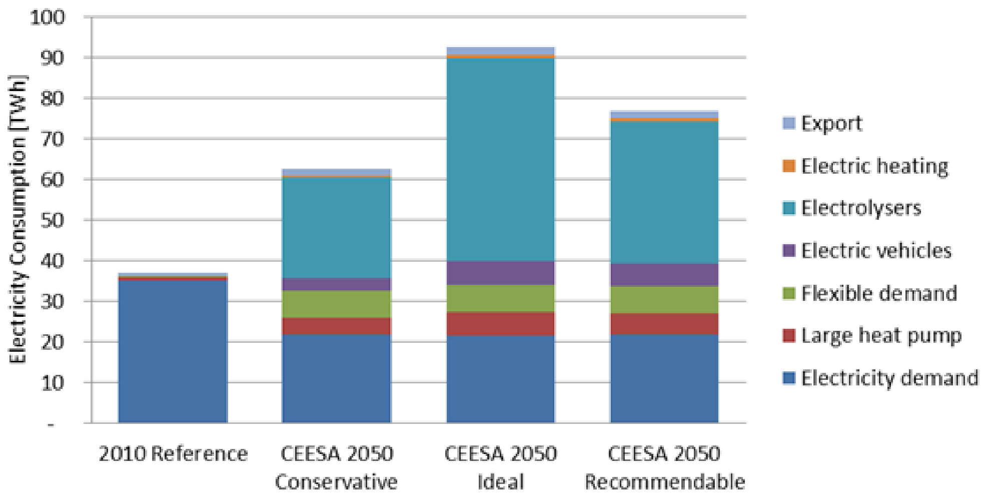


Figure 26: Electricity consumption in Denmark between 2010 and 2050 for the CEESA Recommendable 100% renewable energy scenario.

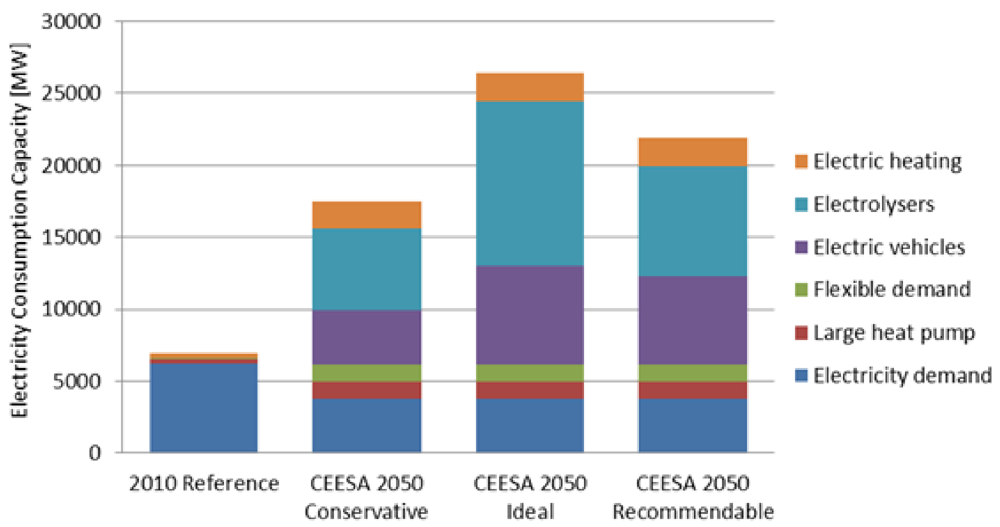


Figure 27: Electricity consumption capacity in Denmark between 2010 and 2050 for the CEESA Recommendable 100% renewable energy scenario.

..Power plants and CHP plants will provide less electricity and heat..

Although the demand for electricity will be 50% higher in the CEESA scenario compared to the reference scenario, the production of electricity and heat from power plants and CHP plants will decrease. As mentioned previously, wind, wave, and photovoltaic sources will provide approximately 80% of the electricity demand in the CEESA scenario. This means that the role of power plants will be changed significantly. Power plants will primarily be used to accommodate short-term imbalances between electricity supply and demand, which occur due to mismatches between the fluctuating renewable resources and the demand for electricity. The capacity of power plants required in the system will remain very similar to the capacity utilised today (Figure 24), since it will be necessary during times of extreme shortages of renewable electricity production. However, the electricity produced from the power plants will be reduced from today's level of 25 TWh to approximately 14 TWh [14].

Like in the case of electricity, the production of heat for district heating from the CHP plants will also be reduced, although district heating will still be extremely important. The integration of the district heating systems and the electricity sector with renewable energy by the use of large-scale heat pumps provides a cost-effective heating solution, while increasing the level of feasible wind power in the electricity system. In the CEESA Smart Energy System, there are also a number of additional new renewable heat sources. As displayed in Figure 28, renewable heat will primarily come from electricity via large-scale heat pumps, but solar thermal and geothermal heat will each account for a significant 10% of the district heating supply. The new excess heat supplies will come from the new energy conversion technologies that are necessary in the energy system. Biomass gasification plants and electrolysers could potentially provide heat to the district heating system, but the exact level of excess heat from these plants is still rather unclear. Therefore, only heat from biomass gasification has been utilised in the CEESA scenarios and it accounts for another 8% of the district heating supply.

Heat savings are important in CEESA, and the heat demand in all buildings is reduced by about 50% on average - both in areas with district heating and in areas with individual heating systems. The heat demand will remain a non-flexible demand; however, the thermal storages will enable flexibility for both the heat and electricity sector, where heat storages enable the use of waste heat, large-scale heat pumps (when there is a large renewable electricity production), and CHP plants (when there is a need for electricity production).

Wind power will reduce the number of operating hours feasible for CHP plants from an electricity perspective, which will also result in less heat production from the CHP plants. However, this can be compensated for by new renewable and surplus heat supplies in the energy system, which makes it possible for the system to operate with a relatively low electricity and heat production from the power plants.

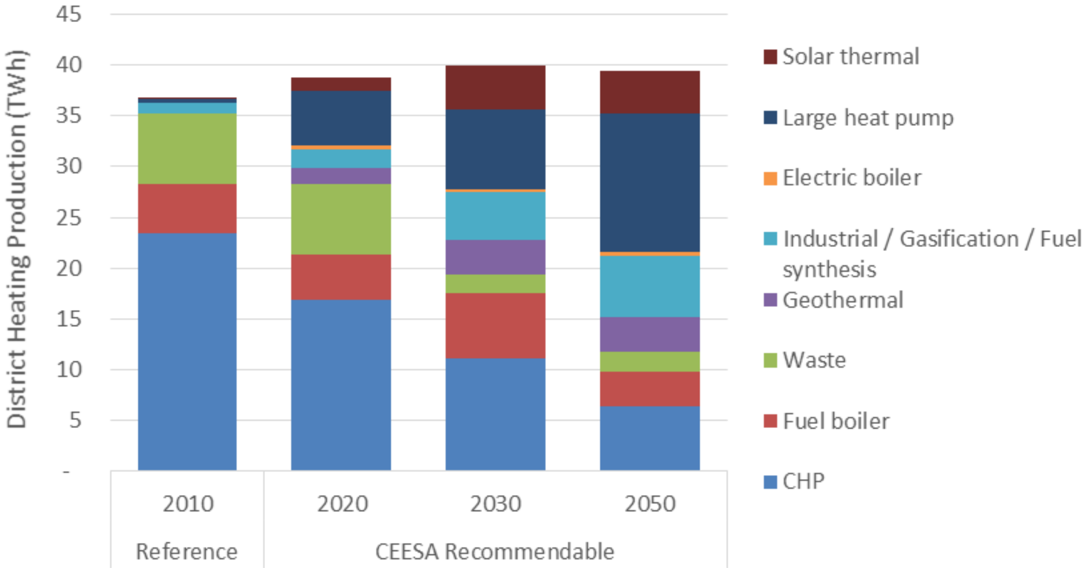


Figure 28: District heating production in Denmark between 2010 and 2050 for the CEESA Recommendable 100% renewable energy scenario.

In Figure 29, the DH production capacities to supply heat are displayed. When the figure is compared to Figure 28 it can be seen that the capacities of the fuel boilers are relatively high compared to the low production from the boilers. The boilers, including flue gas condensation, have a capacity large enough to cover the full demand in peak situations, but they are only used in a low number of hours and only to supplement the other sources of heat that are not dispatchable like solar or geothermal heat.

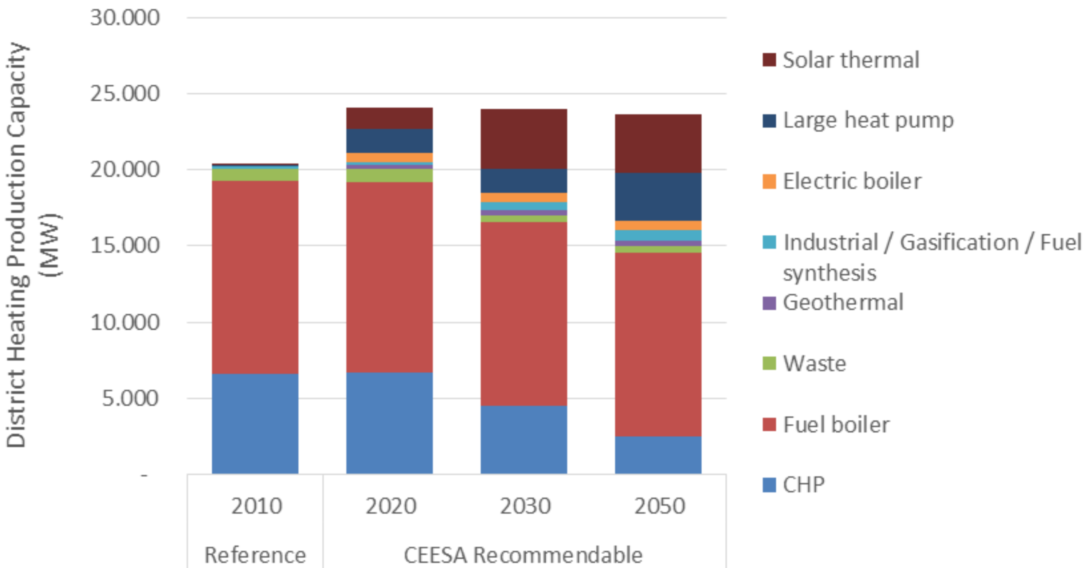


Figure 29: District heating production capacities in Denmark between 2010 and 2050 for the CEESA Recommendable 100% renewable energy scenario

Power plants will need to change in the future to fulfil this new role. In particular, the type of power plant in a 100% renewable energy system is very important. The analyses in the CEESA project show that the main purpose of all power plants in a future 100% renewable energy system will be to accommodate short-term imbalances; in other words, future power plants need to be very good at regulating over a short period of time. Power plants can typically be defined as centralised and decentralised, with centralised referring to the large power stations in the cities.

..Good regulation abilities of power plants and CHP plants are important in 100% renewable energy systems..

Today, there are approximately 450 small decentralised CHP plants in Denmark, which are primarily run on natural gas. These plants are usually reciprocating gas engines with fast start-up and regulation characteristics, which make these more flexible than most large plants. Even today, some of these decentralised plants are operating for a very low number of hours each year; for example, the gas engines in Skagen only operate for approximately 2000 hours each year [51]. This indicates that the decentralised power plants in use today should be preserved in a future 100% renewable energy system. Otherwise, the centralised CHP plants should be able to regulate even more.

In contrast, the centralised power plants of today are not ideal for a 100% renewable energy. Most of the large-scale centralised plants are based on steam turbine technology. These turbines are slower at regulating and they are expensive to shut down and restart. Also when they operate to accommodate the electricity supply, they is still have a heat production making them less fuel efficient. Therefore, they are not the most suitable type of power plant to follow intermittent renewable energy like wind power. An alternative to steam turbines is gas turbines. These units are able to change their production much faster than steam turbines, and can do this fuel efficiently.

Biomass can be used directly in a boiler to generate steam to drive a steam turbine. Biomass can also be used in a gas turbine, but as indicated in Figure 30, it must be gasified first. The use of biomass in a gas turbine generates more energy losses, due to the additional conversion necessary in the biomass gasifier. However, a large amount of these losses may be utilised in low temperature DH in future systems. New steam turbine plants may be able to let the steam bypass the turbine, meaning that the electricity production is reduced and only heat is produced from the plant, hence working as a biomass boiler. It is important that the plant includes a flue gas condensation unit to reach high efficiency as indicated in the figure. The flue gas condensation is not modelled as an individual unit, but is included in the thermal efficiency of CHP units. These plants may be able to operate the bypass rather fast to regulate for fluctuations in, for example, wind power production. The problem is that using a bypass function reduces the system efficiency of the biomass consumption, since electric energy is a higher level of energy than thermal energy; electricity can be directly converted to heat, but not the opposite way.

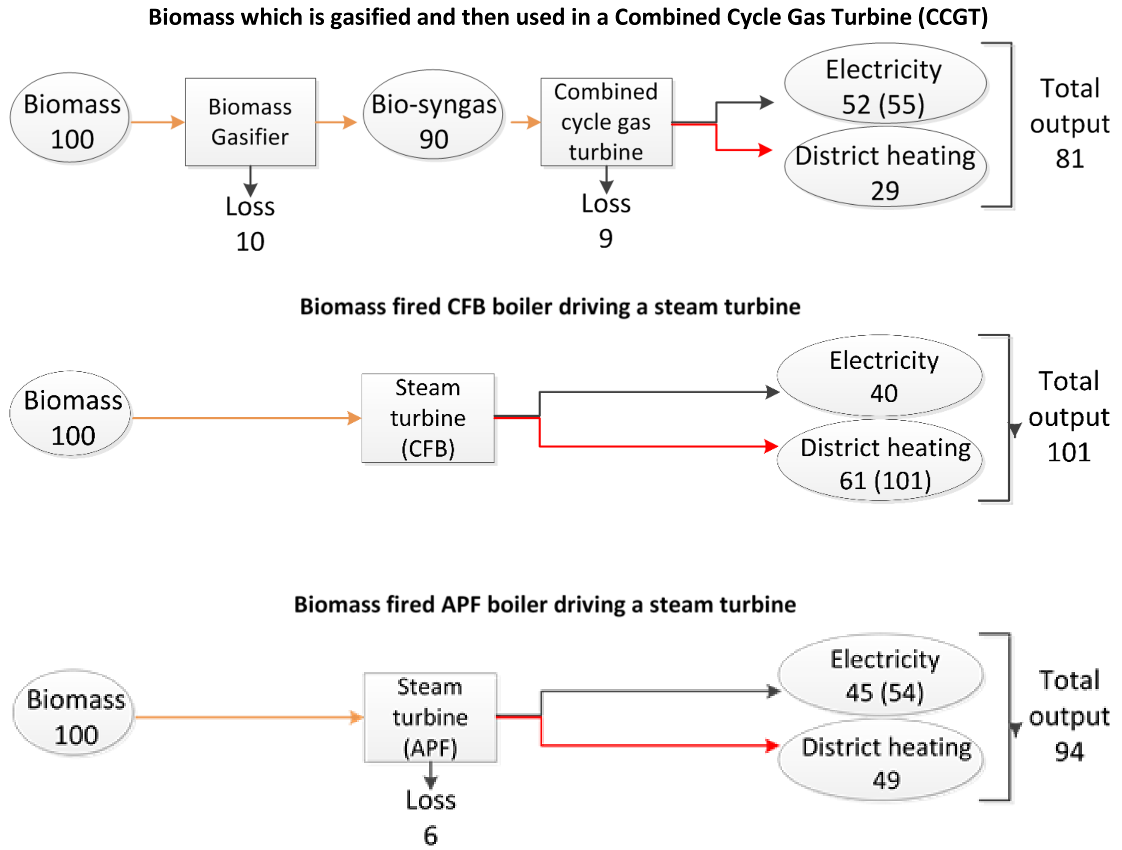


Figure 30: Using biomass in a steam and gas turbine with the potential characteristics of 2050. Values in brackets are assuming operation in bypass mode for the CFB boiler and steam turbine or condensing mode power production for the combined cycle gas turbine.

In Figure 30, three different options for a large power plant using biomass are illustrated and compared on their basic input-output characteristics. At the plant level, steam turbines are a more efficient way of using biomass due to lower losses. However, these plant types should be considered from a system perspective and not only at the plant level. In a system with a high share of fluctuating renewable sources, the flexibility of the power plants is very important to the total efficiency of the system. The CCGT system gives flexibility to the system in several ways. The gas turbine itself can regulate its load up and down faster than the other unit types. When the steam cycle is operated (combined cycle), the unit generates very high electric efficiency which can be used in the case of low production from fluctuating sources. The biomass gasification plant (which produces for the gas turbine) should be connected to the gas grid; this connects a larger number of producers and consumers of gas, a gas storage system and the easy transport of the fuel, which all make the system better in terms of reacting to fluctuations in the production of renewable electricity.

An analysis of the plant types is presented in Chapter 5.3. Here the conclusion is that the higher electric efficiency and production flexibility of the combined cycle gas turbines make up for the lower heat efficiency and improve the total system fuel efficiency.

4.1.1 Importance to the Energy System in the Greater Copenhagen Area

The three points outlined in this section; change of the roles of supply and demand, less electricity and heat production from power plants, and increased need for flexible power production, make a central part of a 100% renewable energy system in Denmark. Each of these will enable the different energy sectors to integrate more effectively and allow the systems to utilise high amounts of intermittent renewable energy sources. The transition to a more flexible and energy efficient power production should be developed in the whole country for both decentralised and centralised plants, since the same power system covers the whole country, in contrast to DH systems for example. The centralised plants in the large cities play an important role because they account for a large share of the production capacity. Therefore, decisions relating to these plants have a large impact on the flexibility of the total system. A large share of the centralised power plants in Denmark is located in the Greater Copenhagen Area, which means that the development here is important in terms of shaping the future energy system in Denmark.

Planning and operation of CHP plants today is to a large extent determined by the heat demands and cost of supplying heat, also in the Greater Copenhagen Area. If this perspective continues to influence the planning, this will be a challenge to the implementation of Smart Energy Systems, which focuses on the overall feasibility of the energy system, rather than planning a cheap heat supply alone. This problem may not be solved by the local authorities alone, but attention should be paid to the fact that heat supply planning should not be done independently from energy system planning.

4.2 Heat Supply in Future Energy Systems

As mentioned, the heat supply from CHP plants and waste incineration plants will decrease, but as the total district heating demand will not be reduced, other sources will have to be introduced. Renewable heat, such as heat pumps, solar thermal, and geothermal, along with a range of surplus heat supplies, such as fuel synthesis plants and biomass gasifiers, will be able to provide heat to district heating networks in the future. This means that many new forms of heat will be delivered to the district heating network. The temperature level of the existing DH systems today is in many cases too high for a feasible utilisation of these new heat sources. Brand and Svendsen [52] suggest supply temperatures of 50-55°C and only in peak heat demand hours, accounting for 2% of the year, the supply temperature should be up to 67°C. This and the development of DH systems are outlined in Figure 31. Here it can also be seen how the energy efficiency of the system increases together with the amount of new heat sources in the system.

..District heating networks will need to reduce their operating temperature, accommodate more renewable energy, and provide heat to low energy buildings..

The temperature levels in the DH systems should be low enough in the distribution grids to reduce the heat losses from the distribution pipes and to accommodate local heat sources. The future role of the transmission pipes in district heating networks needs to be discussed in this context. One solution could be to keep a high supply temperature in the transmission grid to boost the temperature level in the distribution grids at peak hours, with a supply from CHP or other high temperature sources. Another solution could be to have a low temperature in the transmission grid and hereby allow heat sources connected to distribution grids to easily feed into the transmission grid by transferring heat from one distribution system to another. It may also be a combination of the two approaches following the heating season. No specific research has been carried out yet on this issue regarding the role of transmission DH grids in renewable energy systems, but it is seen as an important parameter that the transmission system contributes to system flexibility and the accommodation of low temperature heat sources.

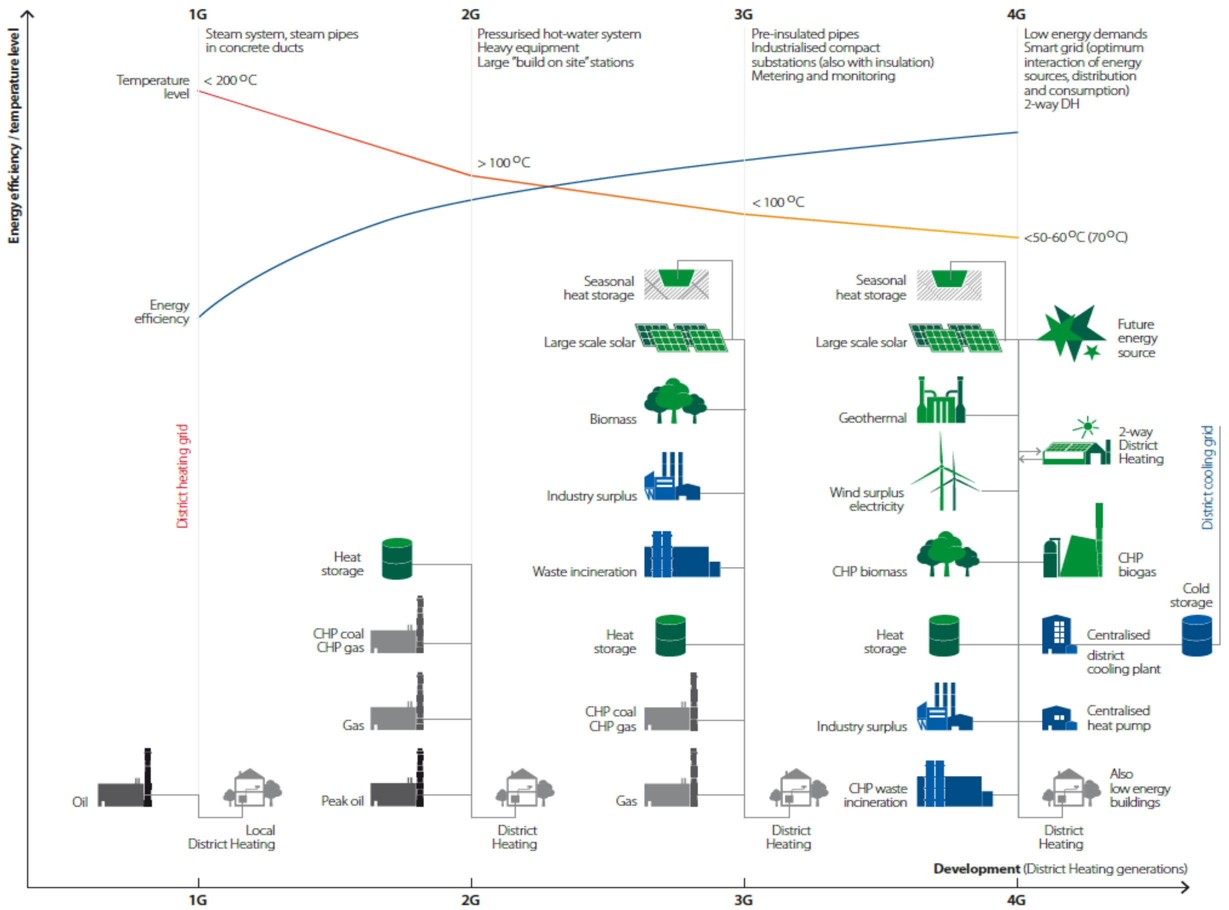


Figure 31: Development of district heating in the past (1st and 2nd Generation), current district heating technology (3rd Generation), and the future of district heating (4th Generation) [53].

At the same time as this development, the heat demand on the consumer side will increase and decrease in different ways between now and 2050. It will increase in absolute terms as the district heating network expands [54], but it will decrease for the individual consumer as more heat savings are added to the buildings. Therefore, the heat density in district heating areas will be reduced, but the length of district heating networks will increase in Denmark and in the Greater Copenhagen Area. To enable this transition, new district heating components, installation techniques, and planning tools will need to be developed, which is the focus in the 4DH (4th Generation District Heating) research centre [55].

..Production from waste incineration will decrease, while industrial and other surplus heat sources will increase..

The heat production from the waste incineration CHP of today will be reduced as more combustible waste fractions are sorted out of the municipal waste for reuse or recycling. In a 100% renewable energy system, the fractions of fossil based materials like plastics will also be replaced or sorted out. The remaining waste fractions for incineration will be available in lower quantities and are expected to have a lower calorific value; thus, a lower energy output from incineration is expected. The surplus heat from industries may be lower than today because of increased energy efficiency measures, but large amounts of heat that could be recovered for DH are still wasted today because of DH temperature levels and the lack of suitable regulations for waste heat recovery.

More surplus heat should be recovered from industries in future energy systems but potential new sources should also be utilised. Some are already used in a few places today, e.g., geothermal and large electric heat pumps, which both have much larger potential. Also sources that are not relevant in the actual energy system may come to play important roles in the future heat supply, e.g., biomass gasification units or electrolysers. These technologies play central roles in the CEESA scenario and they may have surplus heat that can be recovered in DH systems. In the CEESA scenarios, only some surplus heat from gasification is included for DH supply and none from electrolysis, because of the uncertainties about the technologies in future large-scale systems.

..There is a balance between heat supply and heat savings in both existing buildings and in new buildings..

To reach a 100% renewable energy system, substantial heat savings in the building stock will be necessary. The consumption of heating in buildings accounts for about one third of the energy consumption in Denmark and reductions in the heating demand in buildings in a future energy system will both imply reduced fuel and energy consumption, but also a reduced need for conversion capacities to supply the heating. But to which extent will it be feasible to refurbish houses and invest in energy savings? And to which geographical extent will it be feasible to develop the district heating systems in the future energy system?

There is a balance in the feasibility between heat savings and the supply of heating. There are costs connected to both heat supply and heat savings, but from a societal perspective, focus should be to find the long-term optimum between investments in heat supply and heat savings. In some cases, mainly new buildings, it will be relevant to consider low energy or passive houses with a very small heat demand. In other cases, mainly older existing buildings, the costs of heat savings per energy unit will be higher than the cost of supplying the remaining heat demand at some point. In most existing buildings, a substantial amount of heat savings will be feasible though.

District heating systems will need to be extended to convert some of the present natural gas areas or areas with individual boilers to district heating, which will improve the overall energy efficiency. The development of DH systems requires substantial investments in infrastructure and, in some cases, it will be more socio-economically feasible to invest in a new individual heat supply solution such as heat pumps and solar thermal combined with heat savings. This will depend on the efficiency of the DH system, the amount of waste heat sources in the local area, and the heat demand density of the area.

4.2.1 Importance to the Energy System in the Greater Copenhagen Area

The points outlined in this section; i.e., requirement of reduction of temperature level in DH systems, change in heat sources for DH supply, and the balance between heat supply and heat savings, are important because the infrastructure should be dimensioned for the future demand situation and for the integration of new renewable heat sources into the supply. Large investments in technologies that do not suit a future 100% renewable energy system may result in an inefficient system where low marginal prices keep renewable and more efficient alternatives out of competition. This points to the importance of energy savings in buildings and assessments of the potentials and the feasibility of investing in heat savings, to avoid an over-dimensioned supply system. The Greater Copenhagen Area includes Denmark's largest DH system and it is also the most densely populated area of Denmark. This means that the planning of the development of the DH systems in Copenhagen is very important. Here initiatives for heat demand reductions should be planned together with initiatives for the supply systems, including low temperature DH.

Heat savings in particular – and thereby lower demand - are also important because the low-cost base load heat sources can be supplied to other areas through the DH transmission system in the Greater Copenhagen Area and thus enable cheaper replacement of for example natural gas boilers. Heat savings in the City of Copenhagen may therefore lower heating costs in other municipalities. This should be considered in connection to a strategic energy plan.

4.3 Biomass, Electricity and Gas for Transport in Renewable Energy Systems

Previously, there was a lot of focus on the type of power plants that should be used for burning biomass in the future. The results from the analysis in this study indicate that gasified biomass in gas turbines requires less biomass than the burning of biomass in steam turbines. The significance of this result is enhanced when considering the potential biomass resource that is expected to be available in the future. This was another key focus in the CEESA project.

..There is a limited biomass resource in Denmark and the rest of the world..

The results from CEESA suggest that there will be approximately 240 PJ of biomass available in Denmark in 2050. This will come from a variety of sources such as straw, animal manure, and forests. If more biomass is required, then it is very likely that agricultural land will need to be converted to energy crops; thus, biomass production will begin to impact food supply. This should be avoided if it is technically possible and economically viable to do so. In 2050, the transport sector would require approximately 280 PJ of oil in a business-as-usual scenario [14]. Therefore, it will not be possible to simply convert combustion in the energy system from fossil fuels to biomass in the future, while still consuming a sustainable level of biomass. Hence, saving biomass by using gas turbines instead of steam turbines is crucial when considering the importance of saving biomass in the future.

It is reasonable to question if the lack of biomass in Denmark could be overcome by importing biomass from other countries. However, forecasts at present indicate that Denmark has more biomass than the average biomass potential worldwide, see Figure 32 where the three first sections are estimates of global biomass potential per capita and the last section is an estimation of the Danish biomass potential. The latter corresponds to the figure used in CEESA and the medium level in the figure is assumed in the analyses. This is equivalent to 240 PJ in total for Denmark. If an energy strategy is developed based on the import of biomass, then Denmark will be an over-consumer in terms of reaching a global level of sustainable consumption. It is therefore possible to import biomass, but the consequence is that the rest of the world is then unlikely to be able to convert to a sustainable level of consumption. Furthermore, the CEESA scenario includes technologies which will enable a 100% renewable energy system in Denmark, without depending on biomass imports. [56]

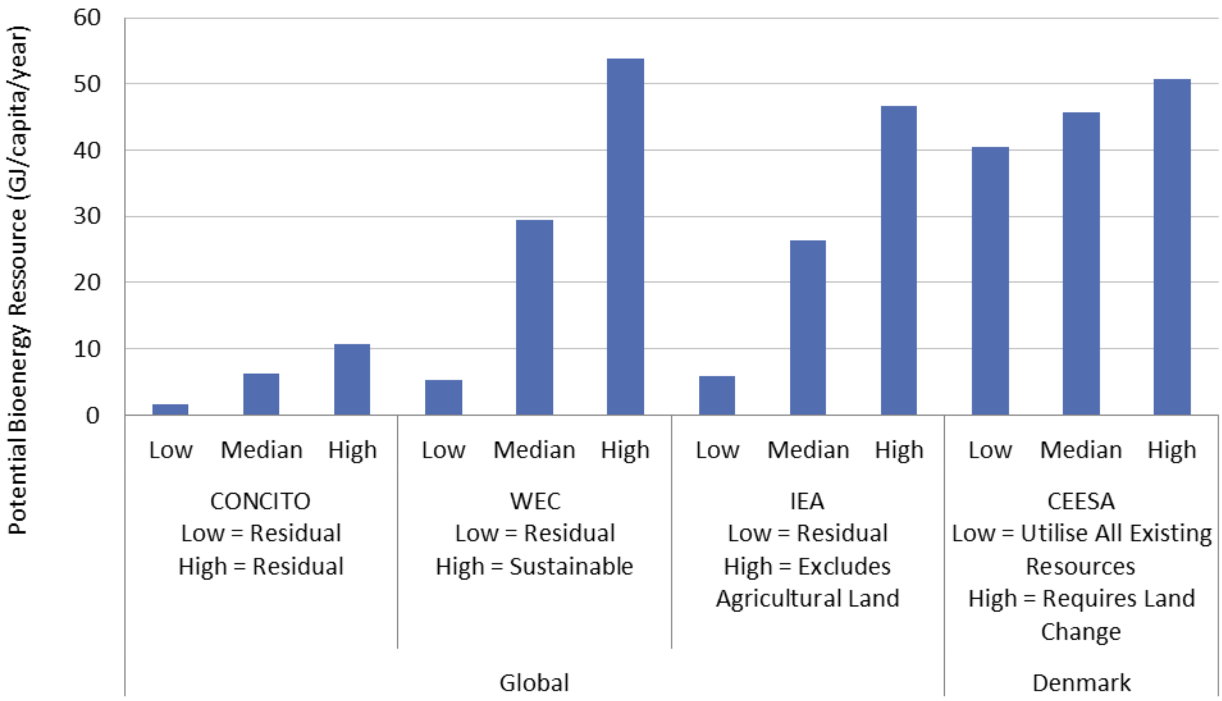


Figure 32: Comparison between the global and Danish [14] bioenergy resources available for energy production. The global estimates are from CONCITO [57], the World Energy Council [58], and the International Energy Agency [59].

..Transport will need to be electrified as much as possible..

The transport sector has less renewable energy today than both the electricity and heating sectors. Transport requires fuel with very specific criteria, which means that it is difficult to replace oil at present. Typically, the two renewable resources which are promoted for the transport sector are electricity and biomass. As already discussed, biomass is likely to be a very scarce resource in the future with only approximately 240 PJ available in Denmark [14]. In contrast, there is a relatively large renewable electricity potential in Denmark of approximately 1,400 PJ (390 TWh) [60], excluding wave and tidal power. Therefore, there is much more renewable electricity than biomass.

In addition, biomass is still subject to numerous uncertainties including the effect on food production, its prioritisation in the energy system, and the impact of biomass combustion on the environment. Some of these issues are evident when comparing the average direct land-use requirements for wind power and biofuels. It is evident in Figure 33 that wind power requires an average of 600 times less gross-land to produce the same amount of energy (1 PJ) compared to biofuels [14]. This means that wind power will not use as much land as biofuels and it will not compete with food production to the extent that biofuels do. Also, since there is no combustion in relation to wind power, there are no greenhouse gas (GHG) emissions connected with wind power production. This means that electricity should be prioritised over biofuels for transport where it is technically and economically viable to do so.

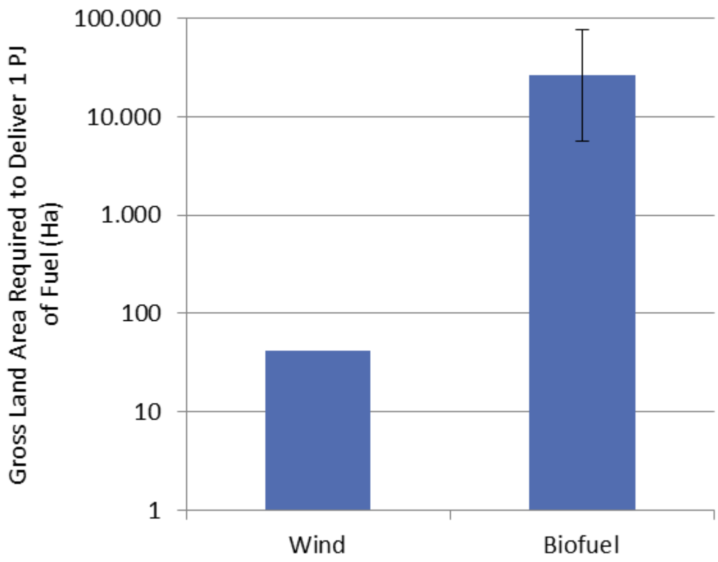


Figure 33: Gross land area required to produce 1 PJ of wind generated electricity [61] and biofuel. The error bars for biofuel illustrate the variation between the different forms of bioenergy considered [14].

At present, the most common way to use electricity in transport is via an electric car. Private cars are relatively light and the average journey is relatively short compared to other modes of transport. An electric car can now travel approximately 150 km on a single charge, with significant improvements expected in the near future [56]. Electricity can also be utilised for freight transport by converting to rail instead of trucks for transporting goods. Plans are in place to extend the electrification of Denmark's rail. By utilising this infrastructure more, it is possible to reduce the demand for trucks. This will not only require the development of the electric rail technology, but it will also require more advanced logistics in the transport of goods, so that they can be distributed at the beginning and end of their journey.

..Heavy duty and long-distance transport will require energy-dense electrofuels..

The energy density of batteries (Wh/kg) is not high enough today for heavy-duty transport such as trucks and busses, as well as long distance transport such as ships and aeroplanes. These modes of transport require some form of energy-dense liquid or gaseous fuel. Biofuels are once again a natural consideration here since they have a relatively high energy density, as outlined in Figure 34. The problem with biomass is its limited availability, as previously discussed.

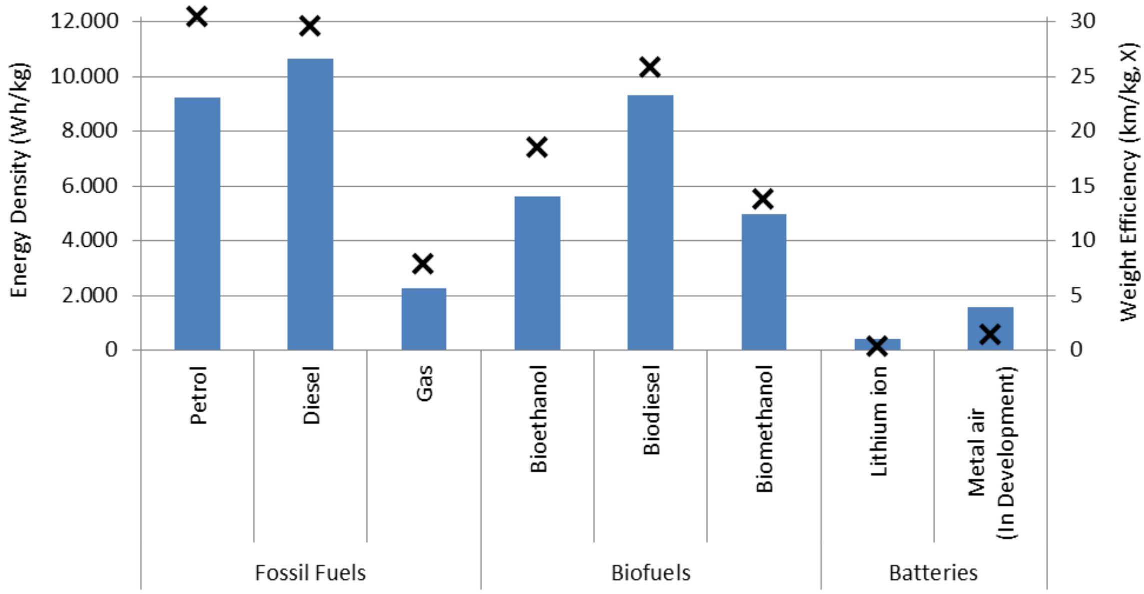


Figure 34: Energy density and weight efficiency for a selection of fossil fuels, biofuels, and batteries [62,63]. It is assumed that the efficiency of petrol and bioethanol cars is 1.9 MJ/km; for diesel, biodiesel, and bio-methanol it is assumed to be 1.6 MJ/km, while for electric vehicles it is 0.5 MJ/km.

In an ideal scenario, the energy density of batteries will develop very quickly and be similar to the level of oil and biofuels. At present, this does not seem likely. An alternative approach which enables the utilisation of electricity in these modes of transport, but does not utilise unsustainable levels of biomass, is necessary. In CEESA, the solution proposed is electrofuel, which has been defined as the separate production of hydrogen (H_2) and carbon dioxide (CO_2), which are subsequently combined to produce a liquid or gaseous fuel. This is a multi-step process in which:

1. **Carbon dioxide** must be obtained from sources such as a power plant, an industrial process, carbon trees, or from biomass.
2. **Hydrogen** must be produced by electrolysis, so that renewable electricity is the main energy consumed.
3. Carbon and hydrogen are combined together in a process known as **chemical synthesis**. This is a well-established process in the fossil fuel sector. The two gases are combined with different catalysts, depending on the final fuel that is required.

This solution enables the use of electricity in energy dense fuels, while the amount of biomass required is reduced significantly compared to biofuels. Numerous different options have been developed based on this principle in the CEESA project [14,21,64,65]. Two examples are presented here in Figure 35 and Figure 36.

In Figure 35, carbon is obtained from biomass which is gasified, while hydrogen is obtained from electrolysis which is powered by electricity. The aim is to use as much intermittent renewable electricity as possible, but there may be hours when power plants are required here also. The gasified biomass and hydrogen are mixed in the chemical synthesis plant to produce methanol, which can then be used in cars and trucks. Although the energy flows here are based on methanol, they are very similar to the energy flows expected if dimethyl ether (DME) was produced. Hence, this pathway can be considered representative of both.

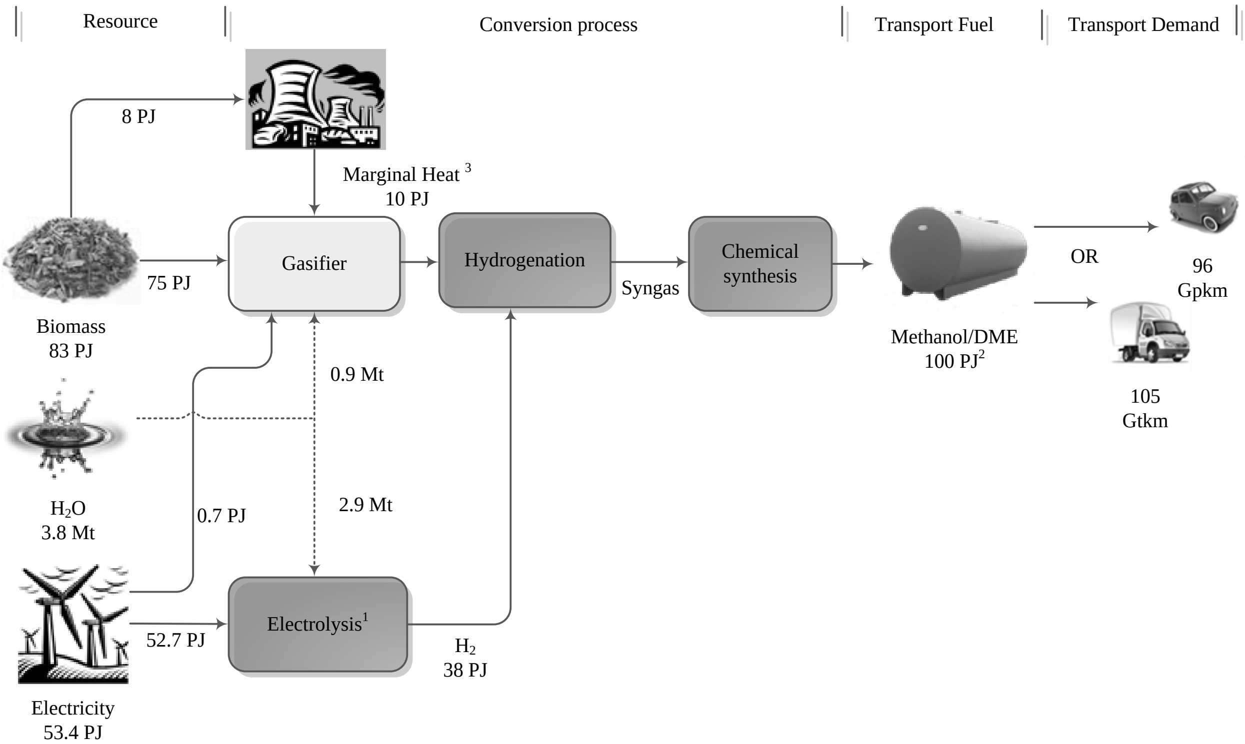


Figure 35: Steam gasification of biomass which is subsequently hydrogenated. [1]The electrolyser efficiency is assumed to be 73% for the steam electrolysis [9,66]. [2]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage. [3]Marginal efficiency is assumed to be 125% and the steam share 13% relative to the biomass input.

There is still some uncertainty about which fuel will be chosen in the future. For example, methane is another option instead of methanol or DME. In Figure 36, the energy flows for one potential methane pathway are displayed. Here carbon is obtained from the exhaust of a power plant and hydrogen is once again produced by electrolysis. This time methane is produced from the chemical synthesis process. Since this is a gaseous fuel instead of liquid, the type of infrastructure necessary is very different here. Apart from this, the technologies utilised in both the methanol/DME and the methane pathways are very similar. Carbon capture and electrolysis are common to both; thus, there should be a focus on further developing these technologies. This type of fuel production will be essential for utilising renewable electricity in transport and also minimising the amount of biomass utilised in Denmark. A less obvious benefit is the fact that these pathways connect renewable electricity production to a very large amount of energy storage, which is fuel storage.

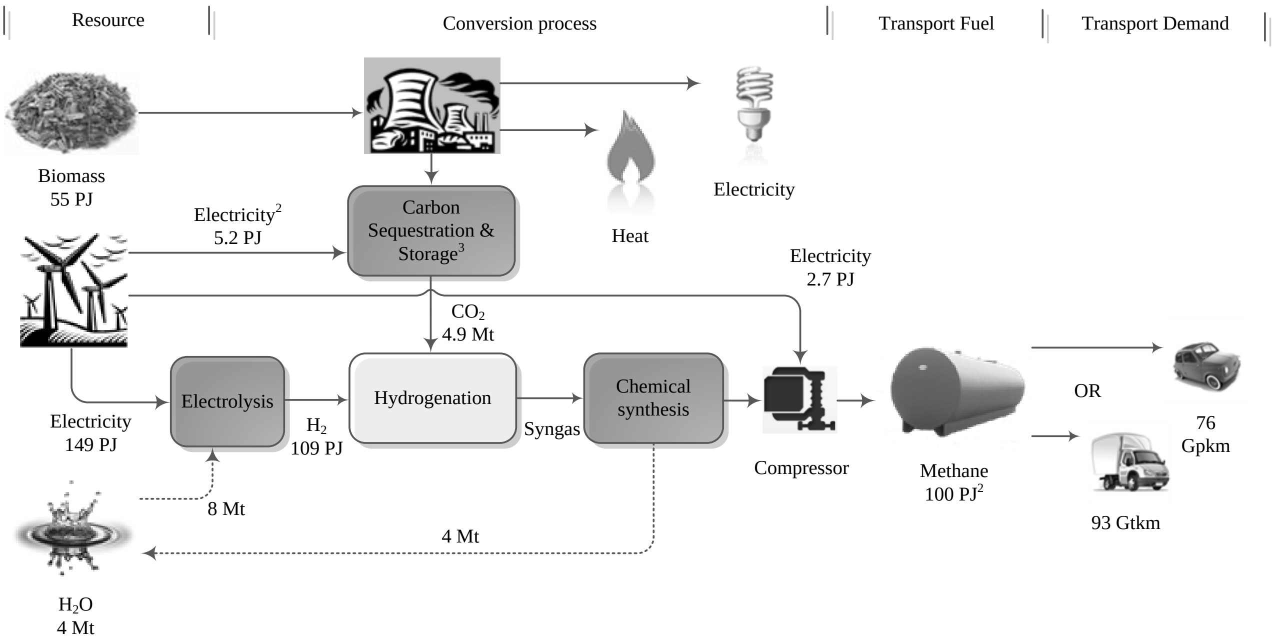


Figure 36: Hydrogenation of carbon dioxide sequestered using CCR to methane. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29MWh/tCO₂ for capturing carbon dioxide from coal power plants [67]. [3]Carbon capture & recycling (CCR) is used in CEESA since it is currently a cheaper alternative to carbon trees [68,69]. If carbon trees were used here, they would require approximately 5% more electricity [68]. [4]Assuming electrolyser efficiency of 73% for the steam electrolysis [70]. [5]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.

..Fuel storage will significantly enhance the flexibility of the energy system..

Electrofuel connects intermittent renewable electricity production with the extremely large amounts of fuel storage capacities at present in Denmark. To put this in context, there is currently around 50 TWh of oil storage and 11 TWh of gas storage in Denmark. In comparison, there is only 65 GWh of thermal storage in Denmark (see Figure 37), while in the context of electricity storage, the four pumped hydroelectric energy storage plants in Britain have a combined storage capacity of 30 GWh [71]. Therefore, by connecting renewable electricity production to fuel storage via electrofuels, the flexibility on the demand side of the electricity system is now enough to enable about 80% of the electricity production to be provided by wind, wave, and photovoltaic sources.

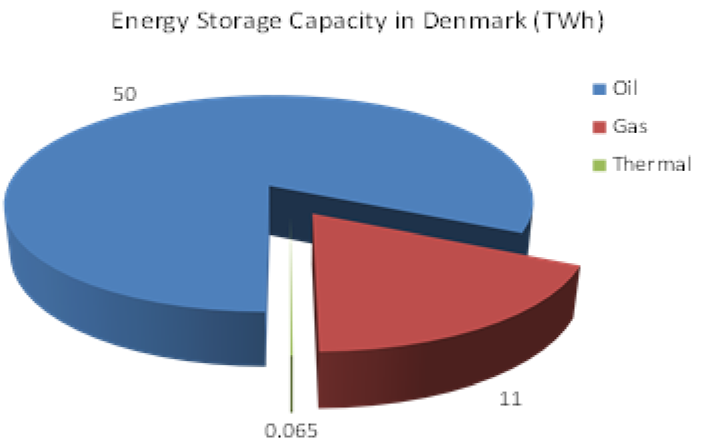


Figure 37: Different types and quantities of energy storage currently available in Denmark. Oil: [72], Gas: [73], Thermal: [74]

The three main points that can be drawn from this section are:

- Biomass is a limited resource that will be required for many purposes in a 100% renewable energy system.
- As much transport as possible should be electrified and the remaining transport demand requires a high energy density electrofuel.
- The use of biomass for purposes where it is not strictly needed should be strongly limited.

4.3.1 Importance to the Energy System in the Greater Copenhagen Area

Heavy transport and aviation are difficult to supply without biomass. Also the peak and back-up supplies of electricity and heat will need some biomass, but it should be limited. For light transport, electric vehicles have shown to be the most efficient solution compared to others such as hydrogen cars. Hydrogen cars represent another option of fuelling light transport without biomass, so this conclusion may change in the future if new technology shows different results. According to the assessments in connection to the CEESA project, gas should generally not be used for transport purposes because this is an inefficient use of the biomass resource. However, when gasified biomass is upgraded using electricity and converted to a liquid electrofuel it becomes feasible to apply to heavy transport.

In the Greater Copenhagen area, the population density is high which makes it feasible to focus on the electrification of public transport and the promotion of electric vehicles. There is a need to develop new infrastructure to induce the transition of the transport sector towards renewable energy supply. Here the focus should be on forms of transport with or without a minimum consumption of biomass.

5 The Role of Copenhagen in a 100% Renewable Energy System

About 10% of the Danish population lives in The City of Copenhagen and the energy systems in the Greater Copenhagen Area are closely connected to the neighbouring regions. The DH system of the Greater Copenhagen Area accounts for about 25% of the total DH production in Denmark, and for this large amounts of fuel are imported from other regions and countries. The size of the municipality and the extent of the DH systems make it possible to test and demonstrate technology and solutions in a scale that might not be possible elsewhere. Successful implementation and experience with new solutions in Copenhagen will support a spread of these solutions to other regions. This means that Copenhagen potentially can play a key role in the development towards a 100% renewable energy Denmark.

This chapter is divided into five sections, each highlighting some issues or challenges for Copenhagen in the development towards a sustainable renewable energy system. The first section presents a reference scenario for the Greater Copenhagen Area to illustrate the impacts of the CPH2025 Climate Plan from an energy system perspective and some of the challenges in this connection. The second section contains an analysis of which type of power plant should be chosen for a renewable energy system, since large power plants are located in Copenhagen and are an important part of the local energy system. The third section presents an analysis of the heat savings potential in Copenhagen. The fourth section discusses possible pathways for the energy supply for transport and some implications of these, and the fifth and last section relates the concepts of Strategic Energy Planning to the case of Copenhagen and suggests possible improvements in this connection.

5.1 A Reference Scenario for The Greater Copenhagen Area in 2025

In the CPH 2025 Climate Plan, the main focus is to develop the energy system of Copenhagen into a CO_2 neutral system by 2025, but this does not necessarily imply that the system will be suitable for supporting a large-scale 100% renewable national energy system. To evaluate how the initiatives in the CPH 2025 Climate plan are in line with the required national development towards a 100% renewable energy system in 2050 according to the CEESA project, a reference scenario for the capital region has been set up with the implementation of the specific initiatives in the CPH 2025 Climate Plan.

It is important to remember that in a 100% renewable national energy system, not all regional energy systems should necessarily resemble the CEESA 2050 Recommendable scenario as shown in the following figures. Different parts of the country and different regions have different potentials and resources which should be reflected in the energy production and capacities. Especially for the electricity production and capacities, differences can be expected; e.g., wind power production may be higher in western Jutland than the average and the condensing power production capacity may be higher in the larger cities. The heat production figures are differentiated according to the type of DH network; hence the central CHP areas are grouped together including the Greater Copenhagen area.

In Figure 38 and Figure 39, the composition of the electricity production and the electricity production capacity are compared between the three scenarios: The two national scenarios Reference 2025 and CEESA 2050 Recommendable and the local scenario Greater CPH 2025 described above. The Greater CPH 2025 scenario is put between the two other scenarios to indicate the chronological order of the scenarios. It should be noted that the time intervals between the scenarios are not the same.

It can be seen that the expected share of wind power production and capacity in the electricity supply is lower than in the other two scenarios. The production in CPH 2025 is only 21%, while the national production is expected to be about 50% in 2020. Also the thermal electricity production share is larger in the Greater CPH 2025 scenario than in the 2010 Reference, and it will decrease significantly in the CEESA 2050 Recommendable scenario. The share of solar PV capacity is increased compared to the CEESA scenario. There is about 2% solar PV in Greater CPH 2025, but 17% in CEESA 2050 Recommendable; thus, large expansions will still be needed in order to reach the national average in 2050.

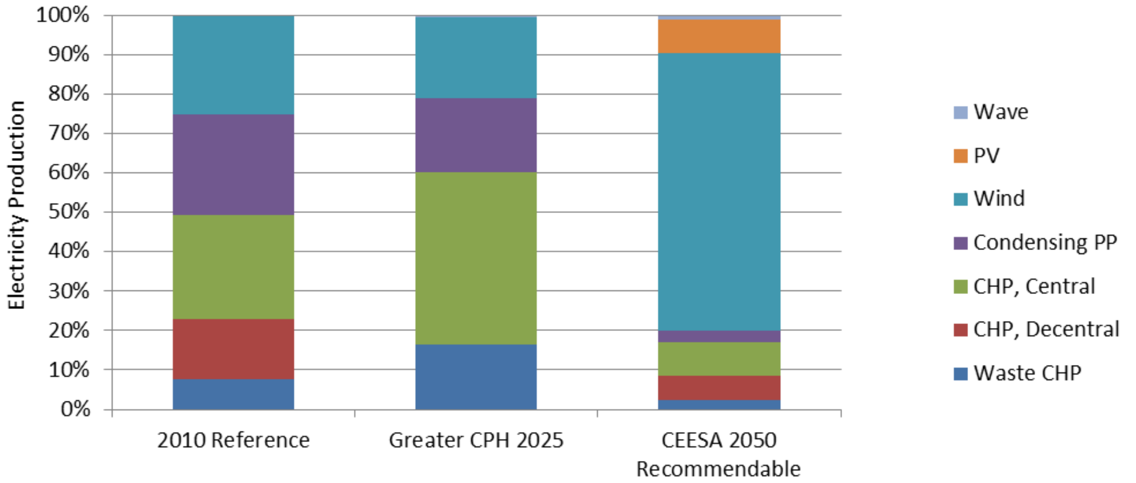


Figure 38: Sources of electricity production in the three scenarios; 2010 Reference, Greater CPH 2025 and CEESA 2050 Recommendable.

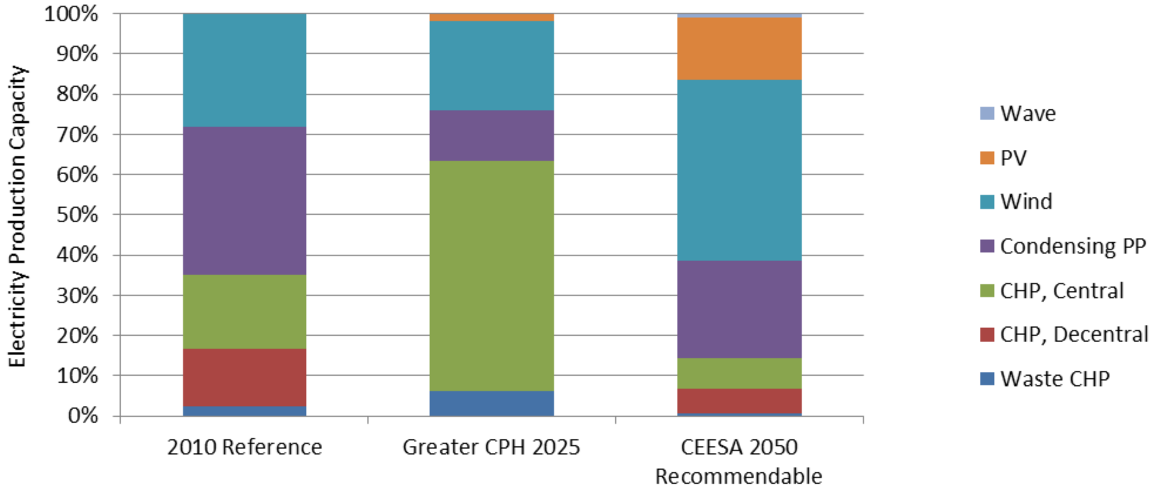


Figure 39: Electricity production capacity in the three scenarios; 2010 Reference, Greater CPH 2025 and CEESA 2050 Recommendable.

The Greater Copenhagen Area accounts for about 25% of the energy consumption and population in Denmark. Relating the tendencies in CEESA to the Greater Copenhagen Area system on specific capacities, this would mean that around 3,700MW of wind power capacity and 1,300MW of solar PV capacity should be installed. The CHP capacity should be 1,100MW, the waste CHP capacity should be less than 100MW, and the condensing power capacity about 2,000MW.

The shares of different sources of heat production and heat production capacities in central CHP areas are presented in Figure 40 and Figure 41. It can be seen that the heat production in the 2010 Reference is almost solely based on thermal fuel based units, but is dramatically changed in CEESA 2050 Recommendable to many sources and types of production units. In the Greater CPH 2025 scenario, the geothermal capacity and production are increased, but to reach the composition of CEESA 2050 Recommendable, a large amount still needs to be implemented. Especially the absence of heat pumps in the expected systems is clear, because heat pumps make the largest contribution in the CEESA scenario. As new production units and heat sources are introduced in the systems, the share of the heat production based on CHP will gradually be reduced because the new sources are substituting more operating hours on the CHP units.

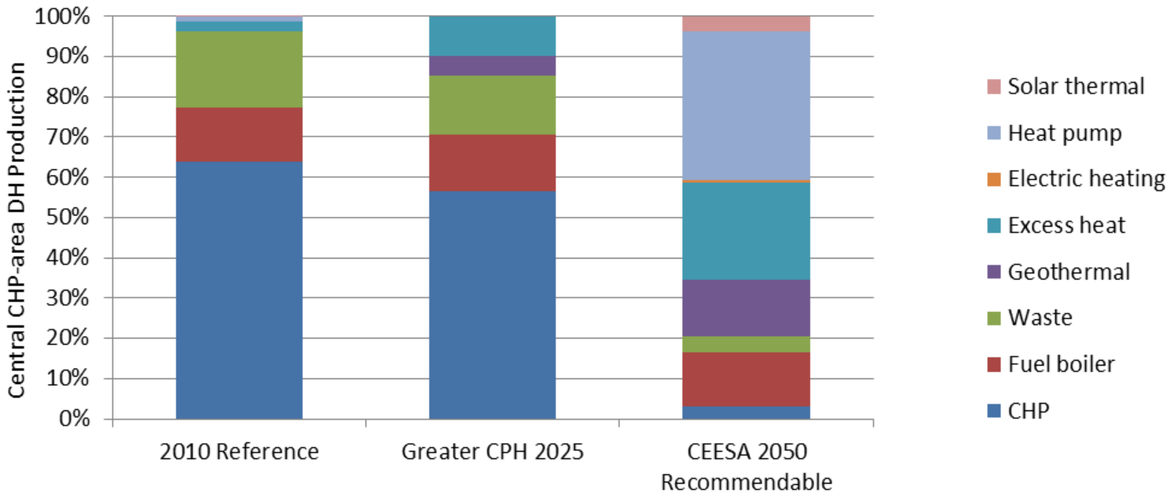


Figure 40: District heating production in central CHP areas in the three scenarios; 2010 Reference, Greater CPH 2025 and CEESA 2050 Recommendable.

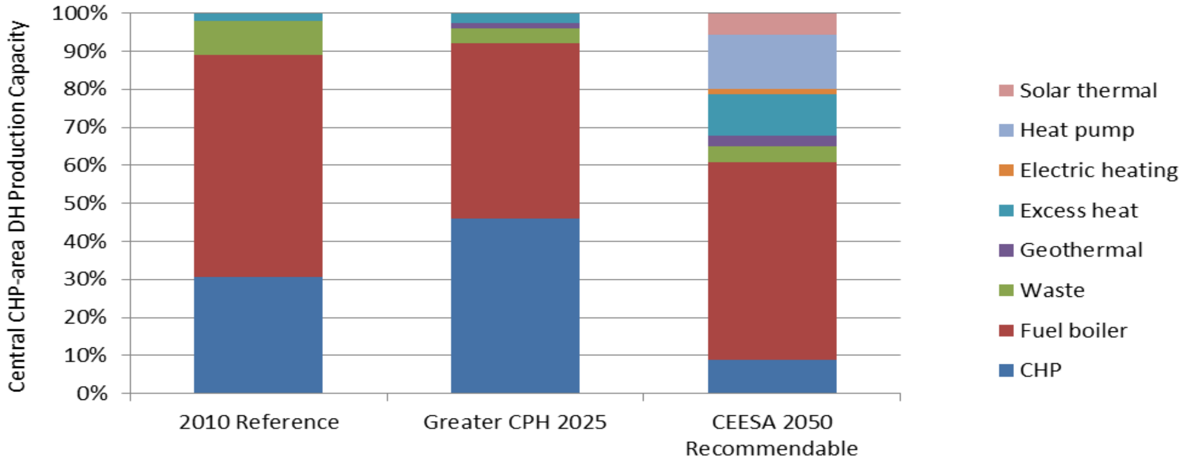


Figure 41: District heating production capacity in central CHP areas in the three scenarios; 2010 Reference, Greater CPH 2025 and CEESA 2050 Recommendable.

For the DH production capacity, the tendencies from CEESA can be transferred to the Greater Copenhagen Area. The DH production in the Greater Copenhagen Area accounts for about

45%. When the CEESA capacities in central CHP areas are transferred to the Greater Copenhagen Area in this ratio, the CHP capacity should be 600MW, fuel boilers 3,400MW, and waste CHP 250MW. The capacity of large heat pumps should be about 900MW, geothermal 200MW, and solar thermal about 600MW.

5.2 Level of ambition for renewable energy production capacities

The basis for a renewable energy system is to have renewable energy production technologies and infrastructure. The implementation of renewable energy technologies is a joint responsibility between several actors, but municipalities play an important role in the planning of these activities. The 100% renewable energy supply is an ambitious goal and it requires the contribution of all municipalities to its realisation.

The capacities of onshore and offshore wind power and solar PV provide almost 80% of the gross electricity consumption in Denmark in the CEESA 2050 scenario. It is crucial that sufficient production capacities are installed. To illustrate the current and the planned capacities, the relation between the capacities and the population of Denmark and The City of Copenhagen, respectively, are presented in Figure 42.

The planned capacities in the CPH2025 plan are lower for onshore wind and solar PV than the average capacity of today in Denmark. The lower onshore wind capacity is due to the lower available area for building wind turbines. The target for solar PV capacity is far lower than the current national average. Here the available area for construction is not an issue, but the lack of good support schemes at the time of the plan may be. The target in CPH2025 for offshore wind power is a bit higher than the 2013 national average, but it is still very far from reaching the recommended level of CEESA in 2050.

The capacities are presented in Table 4. As can be seen, in order to meet the ambitious level of the national target for 2050, The City of Copenhagen should increase the capacities of wind power by a factor of 4 until 2050 to approximately 1500 MW and solar PV by more than a factor of 10 to approximately 500 MW.

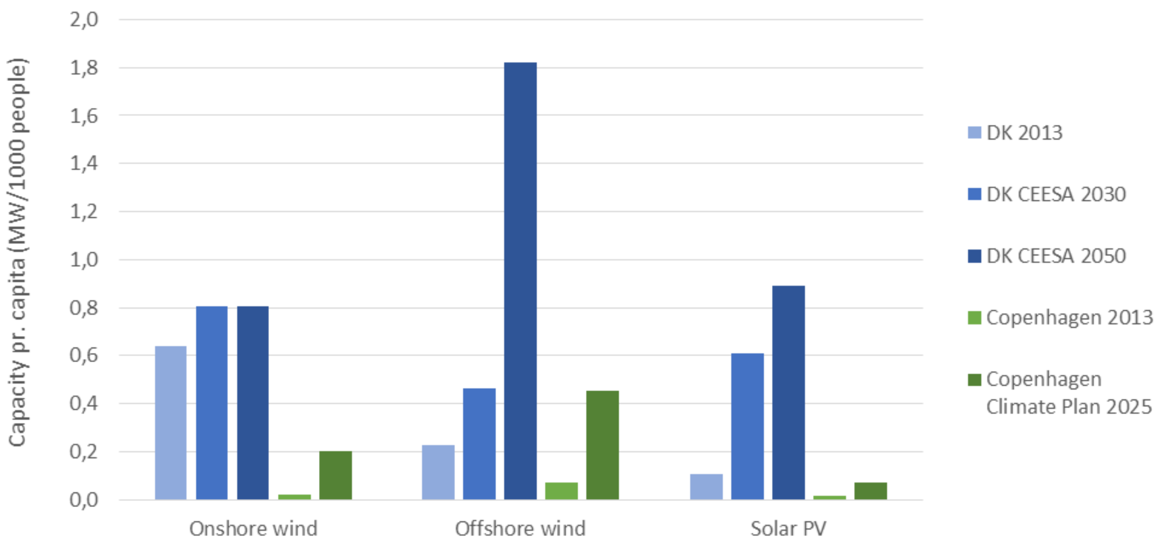


Figure 42: Capacity per capita of onshore wind, offshore wind and solar PV under five conditions. The DK and The City of Copenhagen 2013 values are historical data, the CEESA scenarios are the values from the CEESA scenarios, and the Copenhagen Climate Plan 2025 is the planned capacities for 2025 in The City of Copenhagen.

The City of Copenhagen may not necessarily need to completely fulfil these targets, since municipalities have different local geographical, economic, and resource conditions. All municipalities have to contribute to the overall development, and if Copenhagen is not able to implement the suggested shares of production capacities, it should contribute significantly to the development in other ways, for example by reducing the energy demands or implementing technologies to increase flexibility in the energy systems.

Table 4: Capacities of onshore wind, offshore wind and solar PV under five conditions. The DK and The City of Copenhagen in 2013 values are historical data, the CEESA scenarios are the values from the CEESA scenario analysis, and the Copenhagen Climate Plan 2025 is the planned capacities for 2025 in the area of The City of Copenhagen.

(MW)	Status in Denmark 2013	Denmark in CEESA 2050	Status in The City of Copenhagen 2013	CPH Climate Plan 2025 targets 2025	The City of Copenhagen in CEESA 2050
Onshore wind	3,566	4,500	12	110*	450
Offshore wind	1,271	10,200	40	250*	1,020
Solar PV	593	5,000	7	40	500

**The total capacity of 360 MW wind power, mentioned in the CPH 2025 Climate Plan, is divided into onshore and offshore according to the ratio between on- and offshore wind power capacities in the CEESA 2050 scenario.*

5.3 Power Plants in The Greater Copenhagen Area in a 100% renewable energy system

As presented in Section 1.1, there are a number of criteria for choosing power plants suitable for a 100% renewable energy system in Denmark. The main criteria for this choice of power plant are summarized in the following:

- The power plant should enable fast up- and downward ramping of the electricity production to accommodate the fluctuations in renewable sources.
- It should use the fuel in an efficient way, with high electrical efficiency, in order to limit the biomass consumption for electricity production as much as possible and leave biomass resources for other sectors with a higher need for biomass, mainly the transport sector.
- It should be able to use gasified biomass gas as fuel to increases the flexibility of other systems as well, thus improving the overall system efficiency.
- The power plant should be socioeconomically competitive to alternative options.

Taking the mentioned criteria into consideration, the combined cycle gas turbine is seen as the currently available best technology for dispatchable power production in renewable energy systems, which can regulate for wind power and other intermittent renewable electricity productions. This conclusion applies to all large power plants in Denmark. As a large share of these large power plants is located in the Greater Copenhagen Area, this is an important issue for the development of the energy system in the region and for how this regional development can support the national transition to 100% renewable energy.

In the CPH 2025 Climate Plan, it is suggested to build biomass CHP plants in the future. Therefore, the impacts of two different types of biomass CHP plants are compared to the combined cycle gas turbine type suggested in this study. There are two different versions of the CFB plant scenario because the capacity of the unit is important to the result of the analysis. The four analysed scenarios are sketched in

Table 5 and the thorough description is found on page 73 in Appendix 1.

The results of the analysis show that gas turbines using gasified biomass are more efficient than steam turbines when considering the joint energy system. Although the biomass-fired steam turbine is more efficient at a plant level, it is not as efficient from a renewable energy system perspective because of the lower ability to regulate the load for the fluctuations in the electricity production.

The impact of the steam turbines has been quantified (see Figure 43). The CEESA 2050 Recommendable scenario for Denmark would use 0.8 TWh/year more biomass and cost 0.6 BDKK/year more if the CFB boiler steam turbines with low capacity are used in the centralised power plants instead of gas turbines. If a high capacity is assumed, the biomass use would increase by 13.3 TWh/year and the cost would increase by 2.5 BDKK/year. In the case of an APF boiler CHP plant, the system would use 4.1TWh more biomass and cost 9.4 BDKK more per year.

Table 5: Basic structure of scenarios analysed in relation to the power plant analysis.

Scenario	Combined cycle gas turbine	Steam turbine (CFB) Low	Steam turbine (CFB) High	Steam turbine (APF)
Fuel type	Gas (gasified wood chips)	Wood chips	Wood chips	Wood pellets
CHP electric capacity (MW)	2,500	850	2,000	2,500
Condensing operation	Yes	No, Gas turbines applied	No, Gas turbines applied	Yes

This difference between boiler types is very important when the lifetime of a power plant is taken into account. Steam turbines have a lifetime of at least 25 years. If a new steam turbine is constructed in Copenhagen today, it will define the development of the heat and power supply in the Greater Copenhagen Area in a crucial period of time towards 2050 when Denmark is planning to be 100% renewable. Therefore, the focus today should be on the development of biomass gasification and the construction of centralised gas turbines. If a new centralised power plant is required, then natural gas could be utilised in a gas turbine while the biomass gasification technology is being developed for this purpose.

It can be seen from the results above that the difference between the combined cycle gas turbine scenario and the CFB low capacity scenario is not very large. It should be noticed that the capacity of 850MW is for the whole country, which means that the share that can be allocated to the Greater Copenhagen Area will be approximately 210 MW. If the high capacity of 2,000 MW is utilised, the results get significantly worse. For the Greater Copenhagen Area this would mean an allocated share of approximately 500MW. Applying small capacities of CFB plants will only make the system slightly more expensive and use slightly more biomass – providing that all other CHP and power plants are CCGT which is currently not the case. With large CFB capacities the system will perform significantly worse on both parameters.

The increased biomass consumption that would result from implementing other power plant types than the recommended CCGT plant types will be a problem to the sustainability of the energy system. Biomass can easily be imported from other parts of Europe or other continents, but if many other countries start utilising biomass resources for energy purposes as well, the pressure on the global resources will increase.

Therefore, it is recommended that the total consumption of biomass does not exceed the national potential of residual biomass, which here is assumed to be 240 PJ (66.6 TWh). If all CHP plants in Denmark convert from coal to biomass, this limit might be met before 2025, but if the transition from coal-based electricity and heating is done in a more intelligent way, this might not be the case. It is not certain that increased biomass consumption in Denmark alone will be a problem, but it is a problem if large investments in infrastructure lock the system to a large consumption of biomass that may not be produced on a sustainable basis.

A full description of the assumptions, methodology and results of the analysis is found in Appendix 1 and in [15].

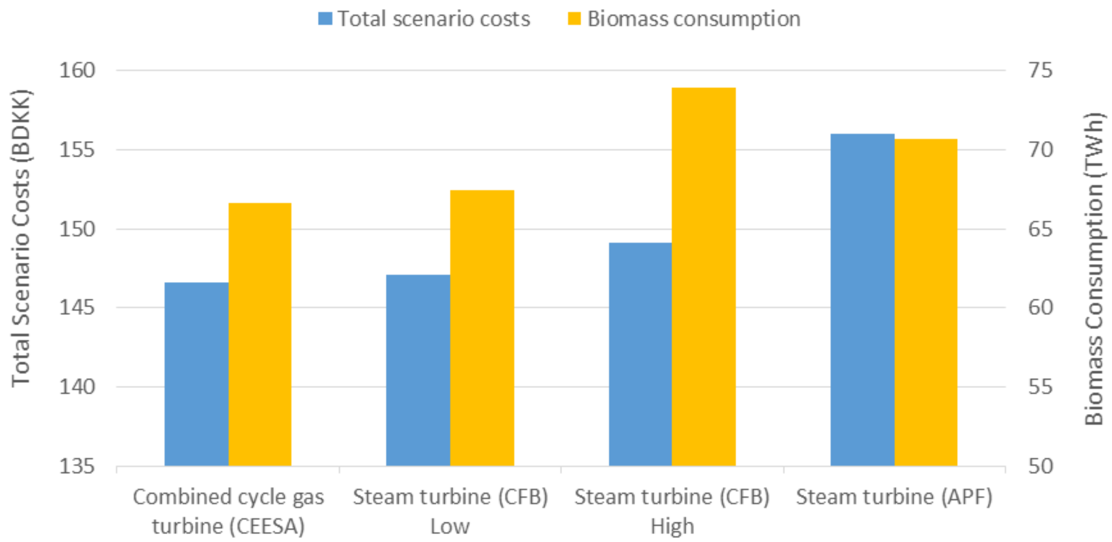


Figure 43: Total scenario costs and biomass consumption for the four analysed scenarios.

5.4 Heat saving potential in The City of Copenhagen

The heat saving potential is found based on the heat atlas developed by Aalborg University, which is described in Section 2.2.2.

5.4.1 The building stock

The building stock in The City of Copenhagen differs from the Danish building stock in general. This is illustrated in Figure 44 and

Figure 45 showing building age and type, respectively.

In regard to age, the buildings in The City of Copenhagen are mainly built before 1960, whereas in Denmark in general a large share is built between 1960 and 2000. The types of buildings are also different, where the majority of buildings in The City of Copenhagen is multi-storey buildings (building type 140 in Figure 45) and offices (type 320) and the rest of the country has a larger share of single-family houses (type 120), terraced houses (type 130) and industries (types 210 and 220). These differences in the building stock affect the heat demand. Older buildings will often have a larger heat saving potential than newer, while the demand will be lower in multi-storey buildings than in single-family houses. The next section explains the overall difference in heat saving potentials between The City of Copenhagen and Denmark as well as the methodology behind the heat atlas which is used to estimate the saving potentials.

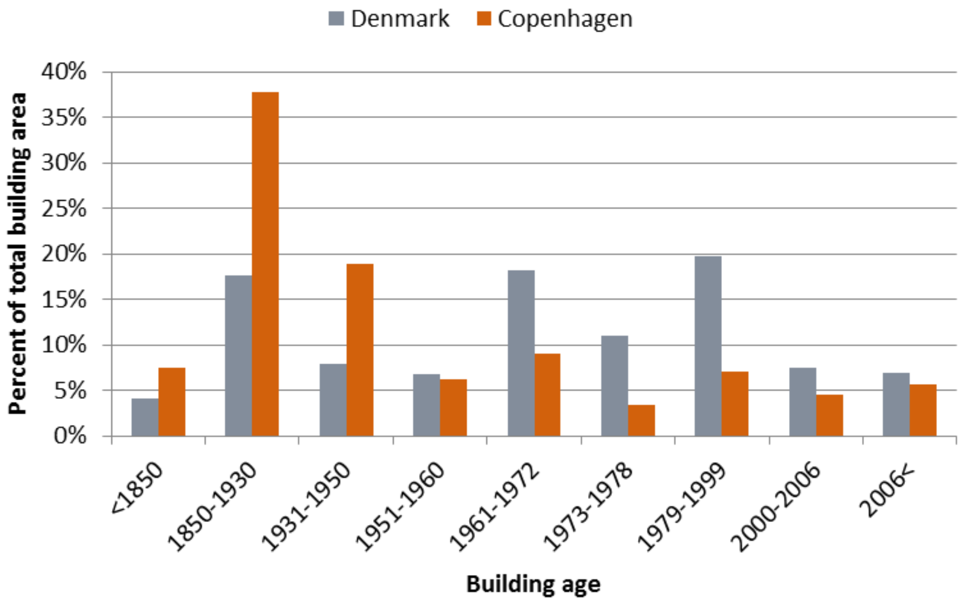


Figure 44: Comparison of building age between Denmark and The City of Copenhagen.

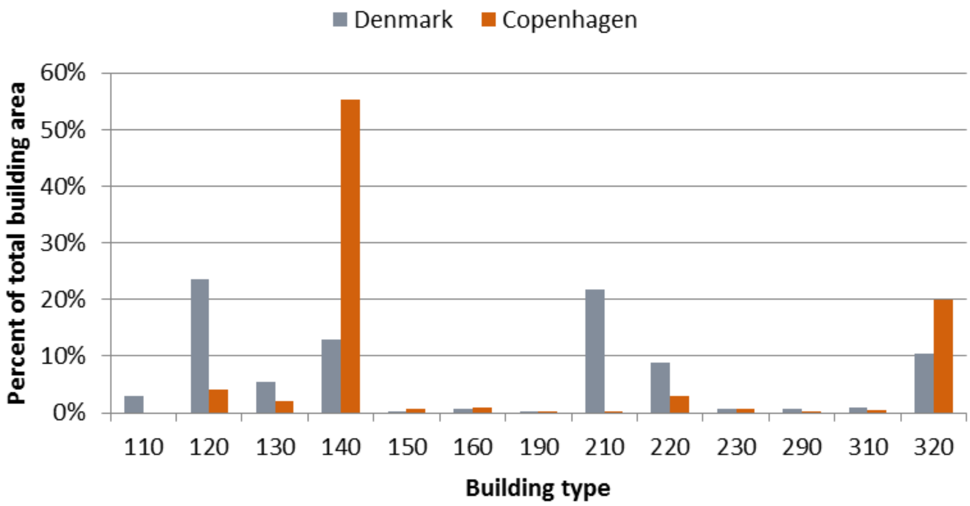


Figure 45: Comparison of building types between Denmark and The City of Copenhagen.

5.4.2 The potential heat savings

In this report, an extract from the heat atlas was made for The City of Copenhagen and compared to the rest of Denmark. In Figure 46, the overall saving potentials for scenarios A, B and C are presented for both Denmark and The City of Copenhagen. The scenarios are based on the aim of reaching target U-values for each building improvement. All types of building improvements are implemented to certain degrees for each scenario and do not take the building periods into account, unless the target U-value is reached. This means that the same type of building improvements are carried out in each scenario, but scenario C implements more than scenario A.

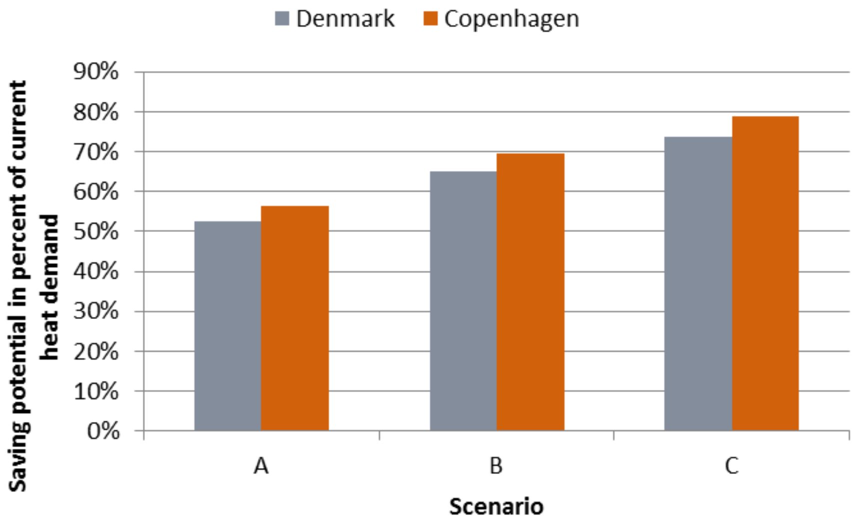


Figure 46: Comparison of heat demand saving scenarios between Denmark and Copenhagen.

It is clear that the saving potential in Copenhagen is higher than in Denmark as a whole, which is due to the difference in the building stock. Scenario A has a potential of saving 56% in The City of Copenhagen and 53% in Denmark as a whole, and scenario C has a potential of saving 79% in Copenhagen and 74% in Denmark.

The heat atlas used in this report is based on an extract from the BBR from April 1st 2013 with data updated on December 5th 2012. Buildings constructed after this period are not included in the analysis.

In some buildings, it is not possible to make energy renovations due to building protection, high existing standard, or the lack of information in the BBR. Therefore, the initial step in the analysis is to choose the share of the buildings where heat savings are an option. Choosing all buildings from the heat atlas where heat savings are possible gives a list of 48,591 buildings with a total heat demand of 4.8 TWh/year in The City of Copenhagen.

5.4.2.1 Investment costs related to implementing heat savings

Implementing scenarios A and C for all the chosen buildings gives the investment costs shown in Figure 47. If Scenario A is implemented in all buildings, heat savings would be 2.7 TWh/year, while implementing Scenario C would result in savings of 3.8 TWh/year. There are two types of costs for each scenario, the direct costs and marginal costs. As mentioned before, the direct costs are the costs for implementing heat savings with the sole purpose of energy renovating buildings, while the marginal cost is the cost associated with implementing energy renovations when the building is renovated anyway.

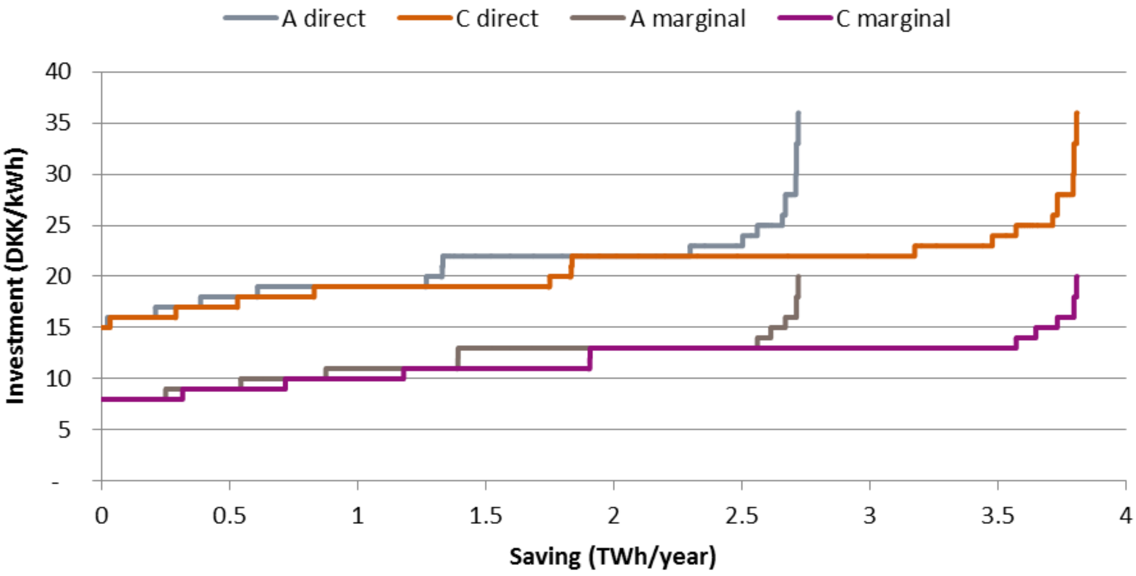


Figure 47: Investment cost of full implementation of scenarios A and C in The City of Copenhagen.

It is clear that the marginal costs correspond to about half of the direct costs. Additionally, it is clear that there is a difference in costs where the cheapest buildings have a marginal saving cost below 10 DKK/kWh and the more expensive buildings above 15 DKK/kWh. This means that a 56% reduction can be achieved through all four strategies. The accumulated costs of this are shown in Figure 48.

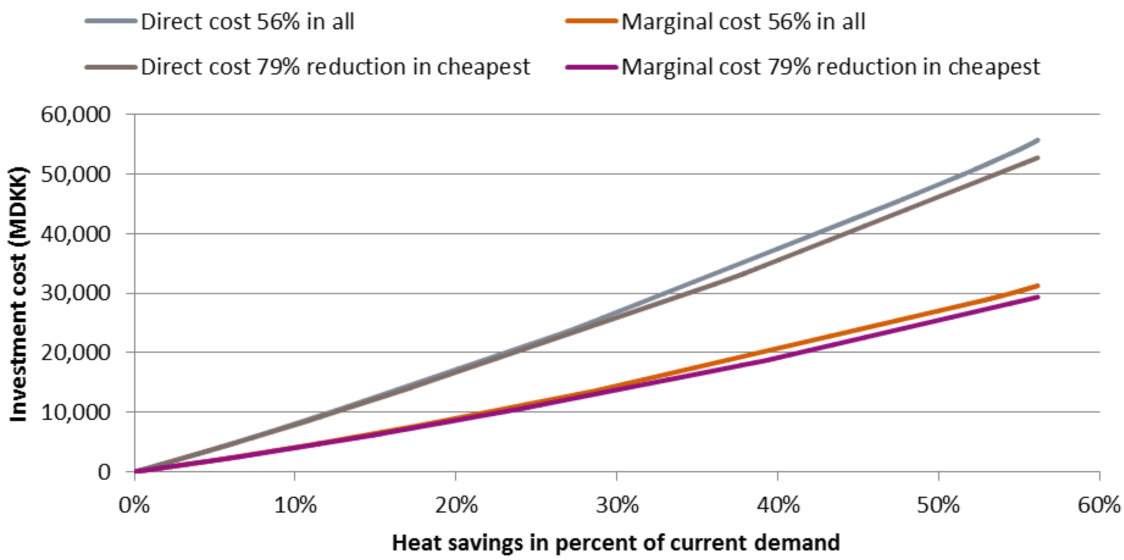


Figure 48: Accumulated investment costs where "56% in all" represents scenario A and "79% in cheapest" represents scenario C.

It is important to notice that there are two overall strategies which both achieve the same level of annual heat savings. The first is to improve all buildings to the same level, while the second is to only improve some of the buildings but to a higher level. The reason for choosing the latter is that some buildings are more expensive to renovate than others as shown in Figure 47. Figure 48 illustrates that the cheapest option is to partly implement Scenario C to achieve 56% savings and use marginal costs. It is, however, close to the cost of implementing Scenario A in all buildings to achieve 56% savings. As a large share of the buildings in the municipality has similar costs, choosing between strategies does not influence the total investment much. The more important point is that the use of marginal cost greatly reduces investment costs. This means that for the individual building, the strategy should be to implement energy renovations when the building is to be renovated anyway. Even though the investment costs are almost the same for both scenarios, choosing either of them will make a difference in terms of where the heat saving is placed geographically. In the following section, geographic representations of the heat savings are presented in the form of maps.

5.4.2.2 Heat saving potentials

A geographic representation of the heat saving potential is shown in Figure 49 for Scenario A.

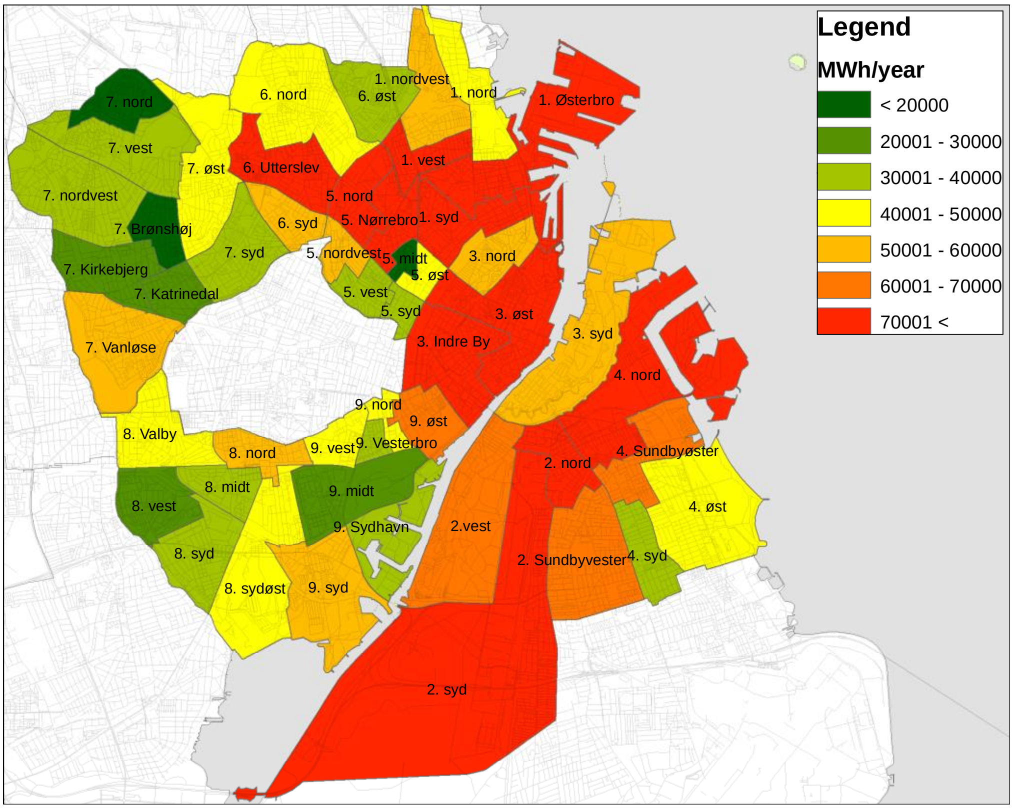


Figure 49: Heat saving potential for each district when implementing scenario A in all buildings.

The heat saving potential is highest in the inner city areas, which is due to a combination of the age of the building stock and the building density within these areas. Comparing scenario A and scenario C shows that in the latter, a larger part of the heat savings is allocated to the buildings with the lowest implementation cost. This is mainly because the buildings with the lowest heat saving cost are not geographically evenly distributed; thus, in some areas there are more of these buildings. Also, it does not seem like there is a pattern in regard to where the cheapest buildings are placed; it is both in central city areas as well as areas further away from the city centre.

5.4.2.3 *The heat demand before and after implementation of heat savings*

Implementing Scenario C with 79% in the cheapest buildings, thus reaching 56% accumulated, would be the cheapest solution. However, it must be underlined that the difference between this and implementing Scenario A in all buildings is not significant. The maps include the demands of buildings where no heat savings are implemented.

In Figure 50, the present demand is shown as annual heat demand in the buildings within each area. The present figures show that the demand is largest in the city centre, but also that many other areas have large annual demands. In Figure 51, the heat demand after implementing heat savings is illustrated. This shows that most areas have changed to lower categories, giving a map with mainly green areas.

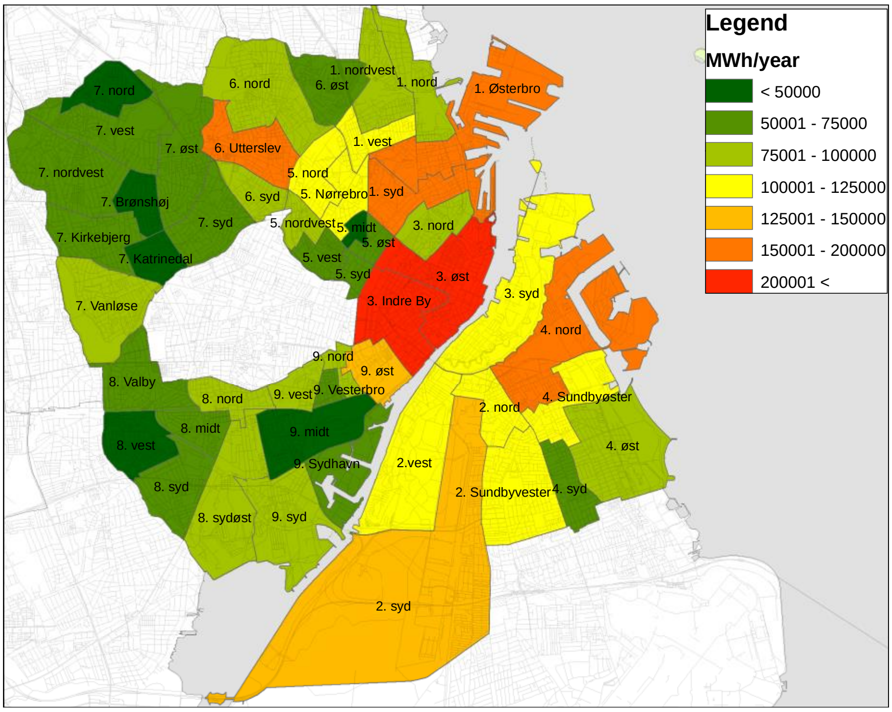


Figure 50: Heat demand before implementing heat savings in The City of Copenhagen.

The result is basically as it could be expected, since the scenario reduces the heat demands significantly compared to the present level. From a heat supply side, it is also useful to see what the heat density of each area is before and after implementing the heat savings, as this will influence the technical design of the future supply system. Therefore, the heat demand given in kWh/m^2 is shown in Figure 52 and Figure 53.

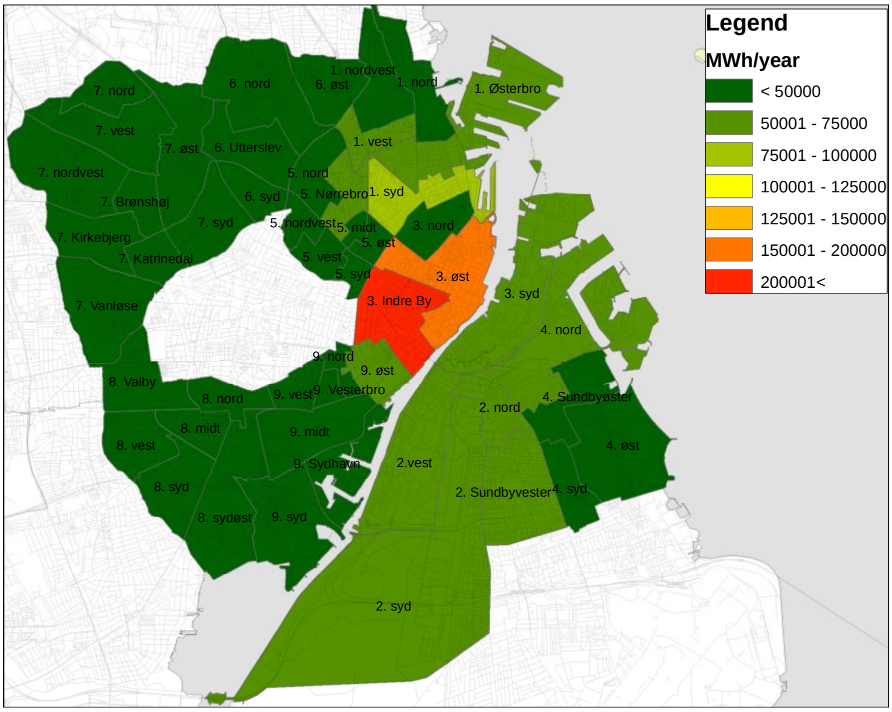


Figure 51: Heat demand after implementing heat savings in The City of Copenhagen.

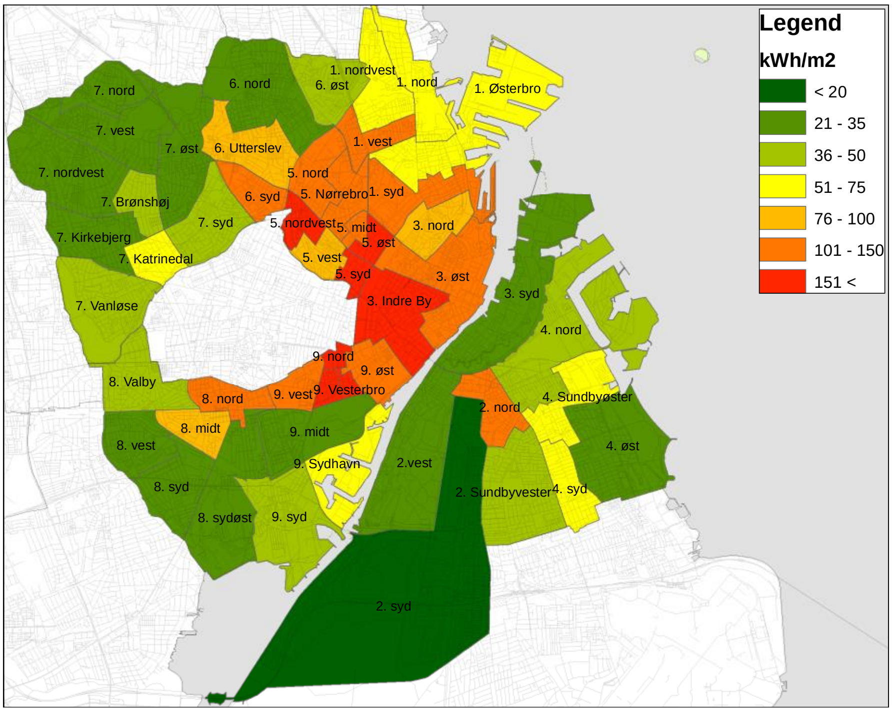


Figure 52: kWh/m² before implementing heat savings.

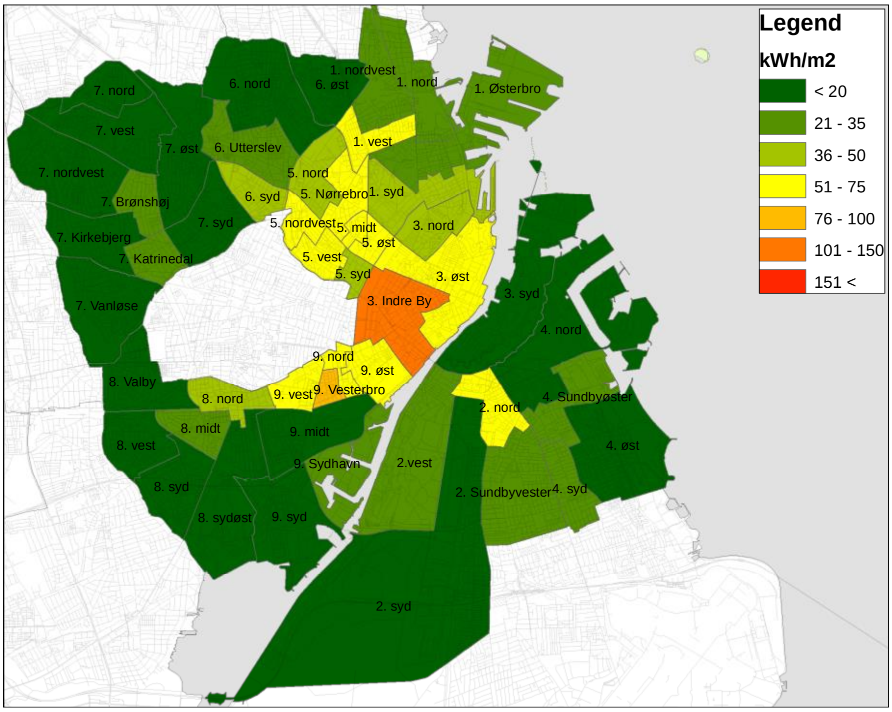


Figure 53: kWh/m² after implementing heat savings in The City of Copenhagen.

As in the previous maps, more areas turn green when implementing savings, suggesting that the heat demand density is lowered. With the current heat demand, most areas have a heat demand density of 35 kWh/m^2 and in many of the inner city areas it is higher than 75 kWh/m^2. After implementing the heat savings, almost all areas have a density below 75 kWh/m^2. This also means that it will be a good idea to coordinate energy renovation in buildings with the renovation or replacement of district heating pipes, as the existing pipes can be replaced with pipes of smaller dimension if none of the buildings require high forward temperatures.

5.4.3 Inner Nørrebro

Since the heat atlas relates to the building level, it is possible to locate the heat demands and saving potentials at a more detailed level than shown above. As the heat atlas is based on average consumptions for each building category, it needs to be aggregated into larger areas. In the case of Inner Nørrebro, the information from the atlas is aggregated within blocks. As written earlier, a good indication of the heat saving potential is the age of buildings; therefore, the average construction year within each block is illustrated in Figure 54.

As can be seen, a large majority of blocks have buildings that are built before 1950. This already indicates that most areas of Inner Nørrebro would possibly benefit from energy renovations. Figure 55 shows the heat saving potential within each block, based on the implementation of scenario A with 56% heat savings in all buildings.

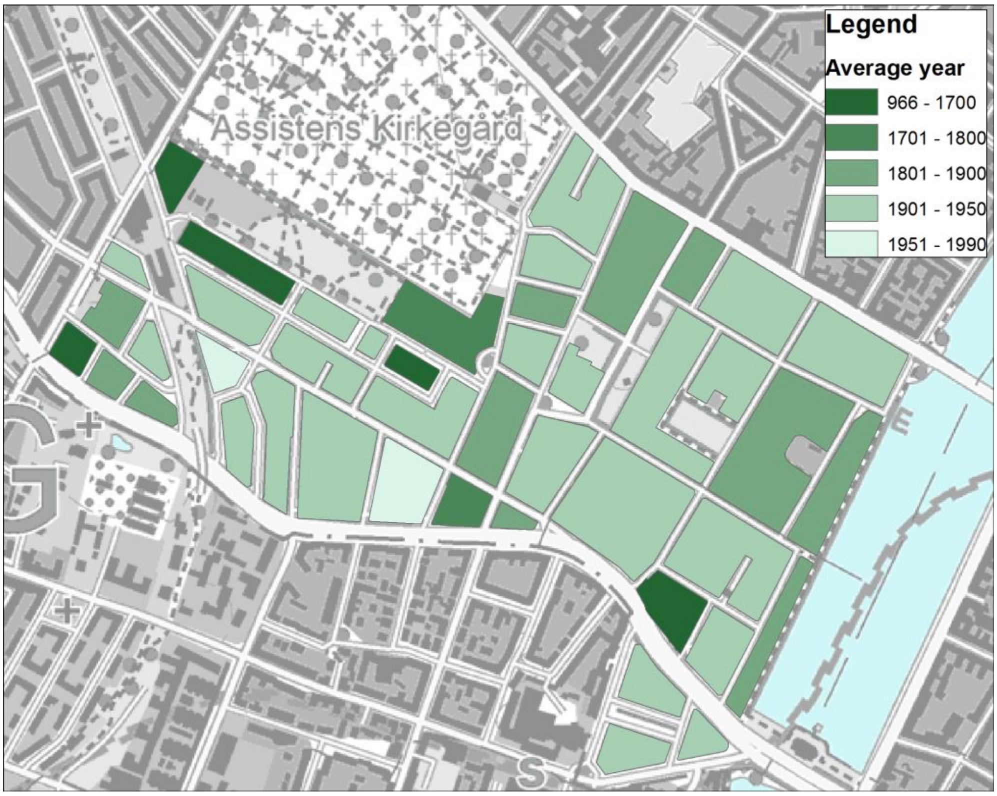


Figure 54: Average construction year within blocks in Inner Nørrebro.

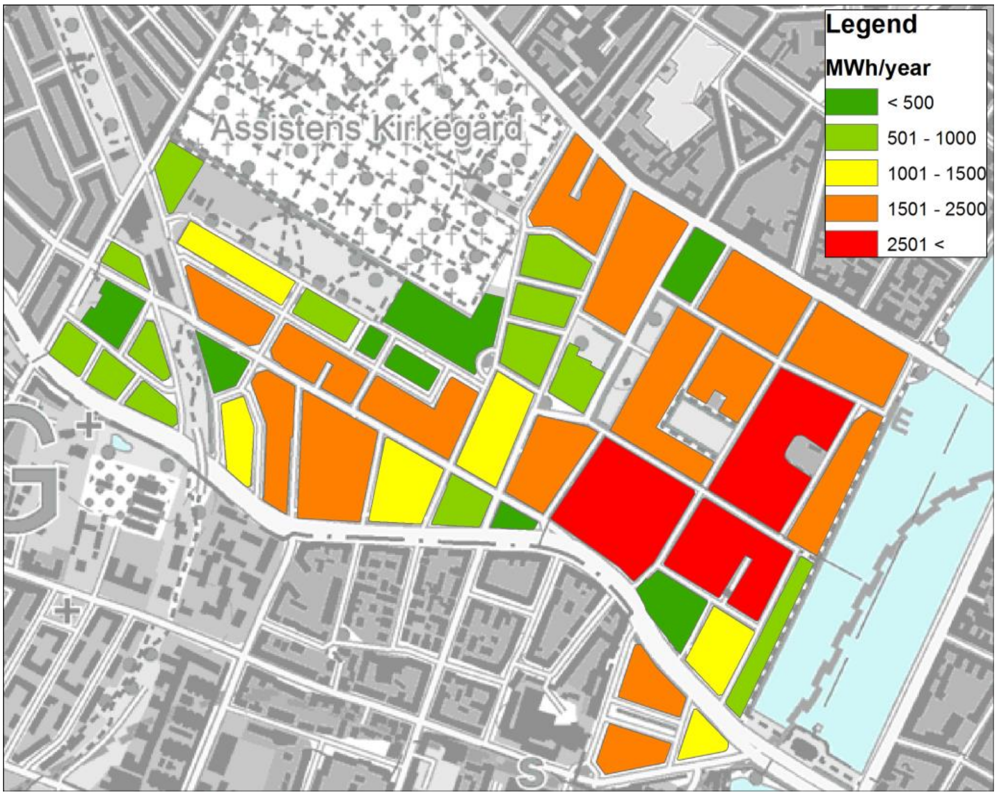


Figure 55: Heat saving potential within blocks based on implementing scenario A in all buildings in Inner Nørrebro.

As expected, the saving potential varies within each block from savings of less than 500 MWh/year to savings above 2,500 MWh/year, as in the case of three areas. This is not necessarily an indication of where to start energy renovating buildings as building blocks vary in size, which naturally gives higher potentials in larger areas. However, the map does indicate that the potentials are largest in the eastern side of the area where the saving potential in almost all blocks is above 1,500 MWh/year. The economic costs associated with implementing heat savings also vary. Figure 56 shows the costs sorted by size, from lowest to highest.

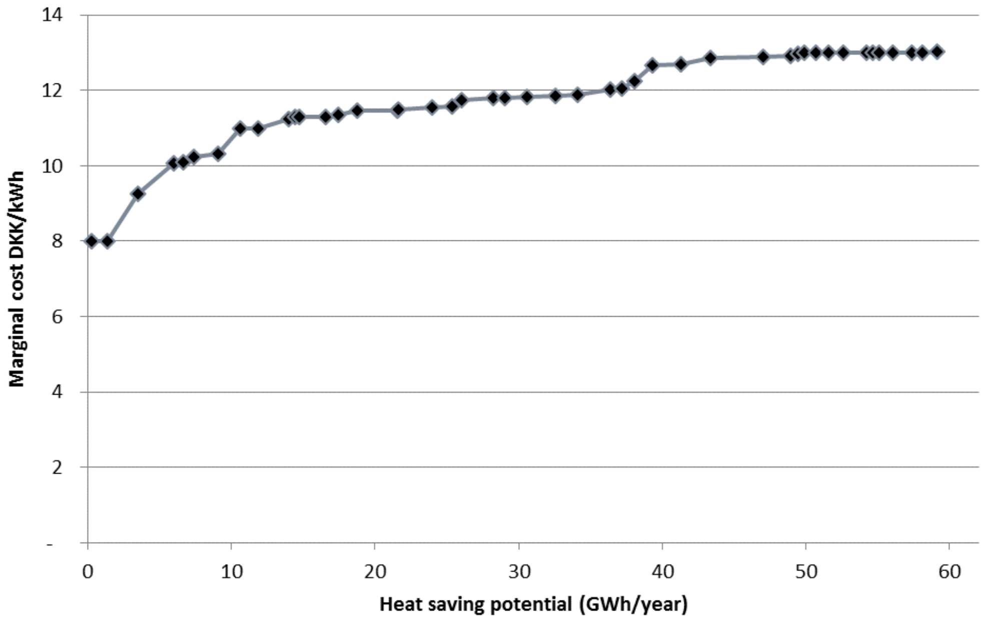


Figure 56: Heat saving potential sorted by marginal cost in Inner Nørrebro.

The graph illustrates that for Inner Nørrebro, as with the rest of the municipality, the heat saving costs do not vary much in the majority of the blocks. Only three blocks have a marginal cost below 8 DKK/kWh and the rest between 10 and 13 DKK/MWh. As the cost increase curve is very flat, this suggests that the order of implementation is not as important. Again, it should be highlighted that the costs and potentials found in the heat atlas are based on Danish average estimations and therefore more detailed maps give higher uncertainties. But the maps can be used as a screening tool to initiate a more specific search for information regarding heat consumptions and renovation costs.

5.4.4 Energy efficiency in buildings and district heating for energy efficient buildings

Heat savings are extremely important in a future renewable energy system. In Lund et al. [13], it was investigated to which extent heat should be saved rather than produced and to which extent district heating infrastructures, rather than individual heating solutions, should be used in future renewable smart energy systems. Based on a concrete proposal to implement the Danish governmental 2050 fossil-free vision, the report identifies marginal heat production costs and compares these to marginal heat savings costs for two different levels of district heating. On the overall Danish level a suitable least-cost heating strategy seems to be to invest in an approximately 50% decrease in net heat demands in new buildings and buildings that are being renovated anyway, while the implementation of heat savings in deep energy renovations that are not being renovated anyway for other purposes at present hardly pays from a socio-economic perspective. In the City of Copenhagen there are however examples of buildings that can be renovated cost-effectively with energy conservation being the only renovation purpose. Moreover, Lund et al. [13] points in the direction that a least-cost strategy will be to provide approximately 2/3 of the heat demand from district heating and the rest from individual heat pumps.

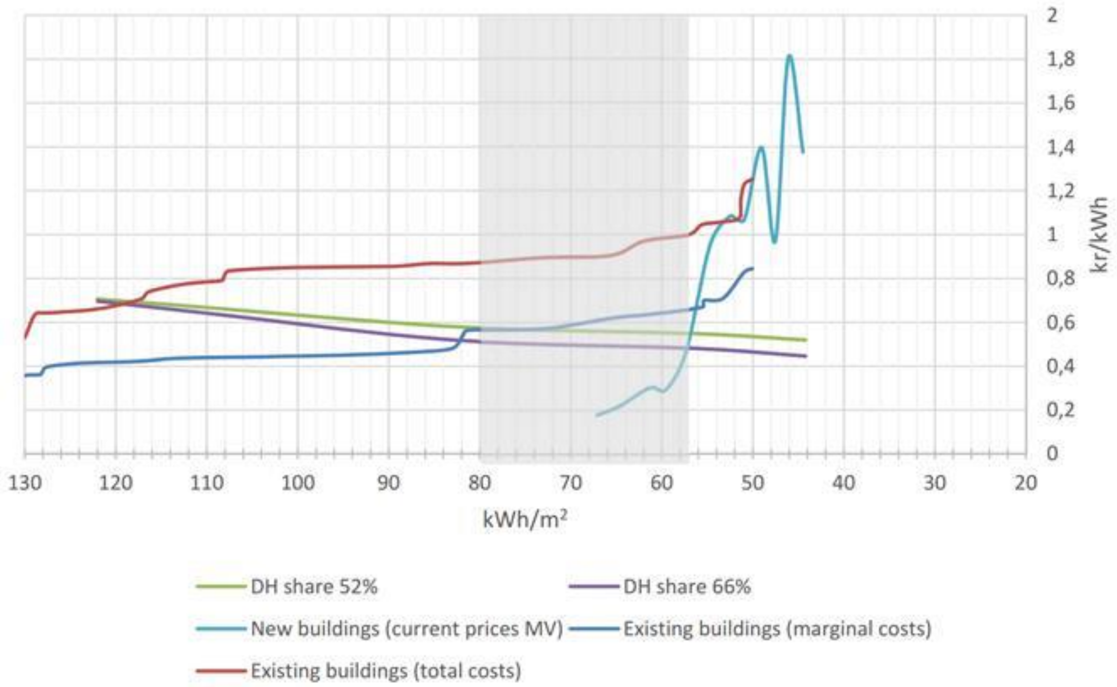


Figure 57: Marginal cost of heat production in the overall energy system in year 2050 compared to the marginal cost of improving the energy efficiency in a new building, an existing building (total costs) and an existing building being renovated anyway (marginal costs). New buildings are here represented by a 150 m² single-family house and existing buildings as the total m² of single-family houses, farmhouses and terrace houses. The costs of both new and existing buildings are shown as a function of the average heat demand per unit in the buildings [13].

Figure 57 shows the results of these analyses:

- The least-cost heating strategy seems to be found with 35% to 53% savings; i.e., when the average heat demand per unit is decreased to 35-53% of the current level, equal to a decrease in the net heat demand per unit from the current 122 kWh/m² to approx. 58-80 kWh/m². However, because the graph only takes into account single-family houses, farmhouses and terrace houses, and more cost-efficient savings are expected in apartment blocks and offices, the least-cost strategy is expected to be closer to 50% than 35%.
- Savings should primarily be implemented in new buildings and in existing buildings if renovation is being carried out anyway. Otherwise the marginal costs are substantially higher than the heat production costs.
- There is only a minor difference between the marginal costs in new buildings compared to existing buildings, if investments in savings are identified as marginal when renovation is

being carried out anyway. This is due to the assumption that, in both cases, marginal costs become more or less equal to material costs.

- A least-cost heating strategy points in the direction of increasing the district heating share to approx. 2/3, while the remaining share should be individual heat pumps for Denmark in general.

The results of the analysis highlight the importance of identifying long-term heating strategies, since the identified least-cost solution can best be implemented with a long time horizon. Thus, savings should mostly be implemented when renovations are being carried out anyway and a suitable district heating infrastructure should be developed over a long period of time.

5.5 Different Transport Pathways for a Renewable Energy System in Copenhagen

5.5.1 Transport Demand

Reductions in the energy demand are as important in the transport sector as in the heat and power sector. The driver of transport demand is highly imbedded in the modern urban settings and infrastructure; for example, the highly developed road infrastructure enables long commuting distances and shopping malls located distant from city centres or housing areas motivate people to travel there by car. These urban planning related aspects lie outside the scope of this project, but it is important to consider the reduction of structural transport demand in cities as well as the initiatives directly impacting the energy consumption for transport.

In the CEESA project, a number of different transport demand scenarios have been developed to represent different possible developments. The two scenarios described here involve a high and a medium increase in transport demand towards 2050. These are here named *CEESA High 2050* and *CEESA Medium 2050,* respectively. In CEESA High 2050, the increase in the transport demand is assumed to continue as now, but with the fuels and energy sources changed as described in Chapter 1. In CEESA Medium 2050, the transport demand is assumed to increase until about 2030 and then maintain a stable level until 2050. In this scenario, there is a focus on modal shift as well, which means that more car or truck transport is replaced by train. CEESA Medium 2050 is used as the main transport scenario in CEESA.

In Figure 58, the energy demand for transport is presented for the different demand scenarios, here for Denmark and for Copenhagen. The reference columns are based on historical data for Denmark and The City of Copenhagen, respectively. The two following columns in the figures represent the energy demand for transport for CEESA High 2050 and CEESA Medium 2050, respectively. In the Copenhagen part of the figure, the tendencies in the CEESA scenarios are simply applied to the reference energy demand for Copenhagen. It can be seen that car and truck transport makes up significantly lower shares in Copenhagen than in the rest of the country, and on the other hand, that bus and air traffic make a relatively larger share of the energy demand.

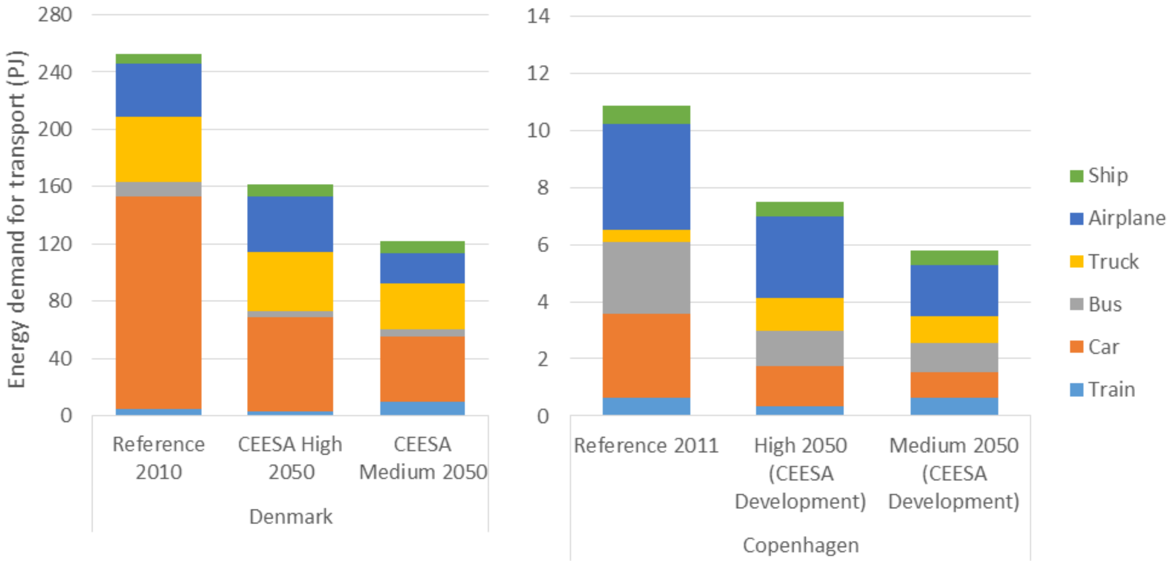


Figure 58: Energy consumption for transport in Denmark and The City of Copenhagen in 2011 and CEESA 2050 divided in terms of means of transport.

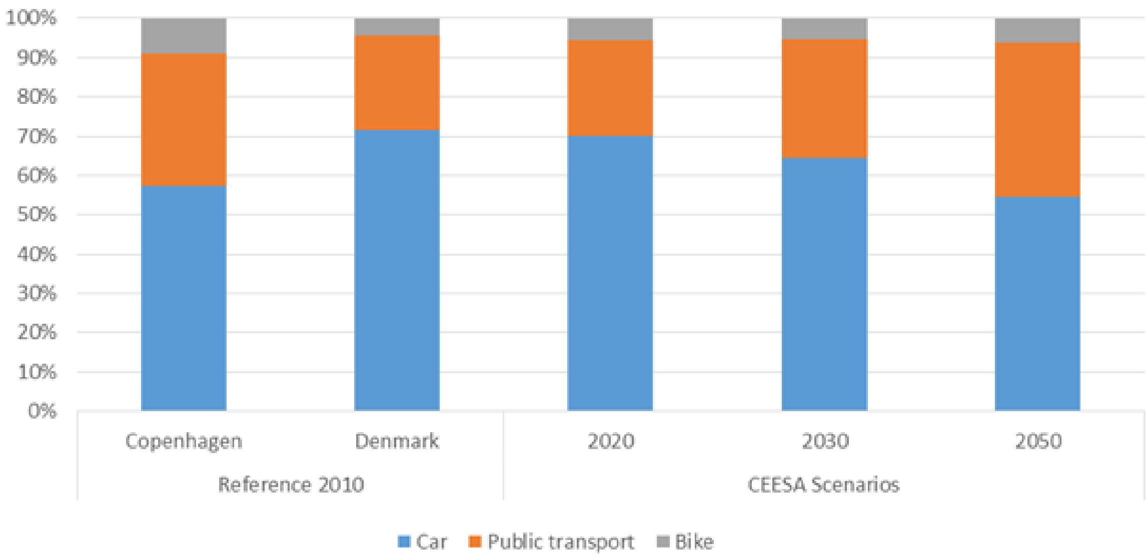


Figure 59: Shares of passenger transport in Copenhagen and Denmark in Reference 2010 and in the CEESA scenarios for 2020, 2030 and 2050. (Here Copenhagen includes the municipalities of Copenhagen, Frederiksberg, Gentofte, Gladsaxe, Herlev, Rødovre, Hvidovre, Tårnby and Dragør).

In Copenhagen, the transport demand will have to change from private vehicles to higher shares of public transport and non-motorised transport. With the high population density in Copenhagen, the city plays a central role in investing in public transport instead of new road based transport infrastructure. Figure 59 shows how the market shares for modes of transport will change towards a 100% renewable system in 2050. The same tendencies also apply to Copenhagen. There is a need for large amounts of modal shifts from car to public transport or bike or walking and from public transport to bike or walking. This will require policy changes, in Copenhagen as well as nationally, to influence the incentive structures related to the choice of transport mode.

Although the transport demand will grow, the growth needs to be limited by urban planning measures and the modes of transport need to gradually change. In order to obtain such a scenario, the CEESA scenario assumes an increase in the share of biking and walking in the transport sector from 4.5% today to 6.3% in 2050. The public transport share needs to increase from 24% to about 39% and the vehicle transport – although being at the same level as today – needs to decline from 72% to 55% of the transport in 2050 (see Figure 59). It can be seen that Copenhagen has significantly more bike and public transport than the average of Denmark. As the biggest city in Denmark, Copenhagen should contribute to the national average by having more transport by bike and public transport in the future than the rest of the country, because in other municipalities it will be much harder to reach the same high level as in Copenhagen. Public Transport Incentives

The unavoidable traffic and transport demand should be met by means of transport that are as energy efficient as possible. Public transport is an important measure, especially in a densely populated city as Copenhagen. In the short distance transport, bikes should be promoted as much as possible because this form of transport is almost free of energy consumption. All the means that will improve the accessibility by bike and public transport will make these options more likely to be chosen. On the other hand, the better the accessibility by car, the more likely this option is to be chosen. The prioritisation and improved conditions for biking and public transport will improve the energy efficiency of the transport and reduce the need for a potential substitution of fossil fuels by renewable energy.

An example is the proposed harbour tunnel connecting two highways around Copenhagen, making it easier to get through the city by car. This will improve the incentive to take a car for example to the airport, even though public transport connections are good. Different studies also show that increased road capacity generates more car traffic, which will be working in the opposite direction of the target to reduce car traffic and congestion [75]. Another example is the earlier proposed congestion charge zone around Copenhagen that would require a fee for cars driving into the centre of Copenhagen and thus improve the incentive to use public transport or biking to go to the city centre. This solution will not solve all the problems connected to the car traffic and should be combined with other initiatives, but it will influence the choice of transport means for some people.

5.5.2 Fuel and Energy Sources for Transport

In Section 4.3 from page 30, it is shown how a number of different technological pathways can lead to a renewable energy supply of the transport sector. The pathway suggested in the CEESA project is to electrify as much of the transport sector as possible with direct electricity supply (as for trains) or battery electric vehicles. For medium and long distances, light transport hybrid vehicles (of battery electric and electrofuel combustion engines) can be utilised. The remaining share of the transport demand that cannot be electrified, which is mainly heavy truck transport, ships and aviation, should be fuelled by an electrofuel such as methanol and DME. This approach is similar to that proposed in the CPH 2025 Climate Plan where it is suggested to have the light person transport covered by electric cars, mainly battery electric cars and to an increasing extent hydrogen electric cars. For the transport not suitable for electricity, it is suggested to use biofuels, and biogas and bioethanol are specifically mentioned as options.

The electrofuels methanol and DME have the benefit that the production of these can flexibly use electricity. This is a benefit because the energy from, e.g., wind can substitute some biomass consumption compared to the alternative case in which the energy in the fuel comes solely from biomass. Another benefit is that the production flexibility can be utilised to balance the electricity supply and demand.

For pure biofuels such as biogas and bioethanol, these benefits cannot be gained and when using these to cover the transport demand, the total biomass consumption for the transport sector will be higher. Hydrogen electric cars have the benefit that they have a longer range than battery electric cars; on the other hand, they are less resource efficient and they are approximately twice as expensive in investment. Another issue for hydrogen electric cars is that the basic hydrogen distribution infrastructure is not yet very developed, whereas distribution systems for electricity, gas and liquid fuels are more developed. This together means that the total costs of the system will be higher.

To illustrate the differences in the energy consumption between today and the suggested CEESA 2050 scenario, a simple summary of the demands is presented for Denmark and Copenhagen, respectively. Figure 60 shows the same demands as the figure above, but here divided into fuels. This figure illustrates how the change in vehicle types and more electrification can cover the same or an increasing demand with less energy. The transport demand for Reference 2011 is the energy consumption for transport, as presented in Section 3.1.3 on page 12, based on a transport energy balance for The City of Copenhagen. It can be seen in the figure that electricity for transport will be covering a significantly larger share of the energy demand for transport, in Copenhagen as well as in the rest of the country.

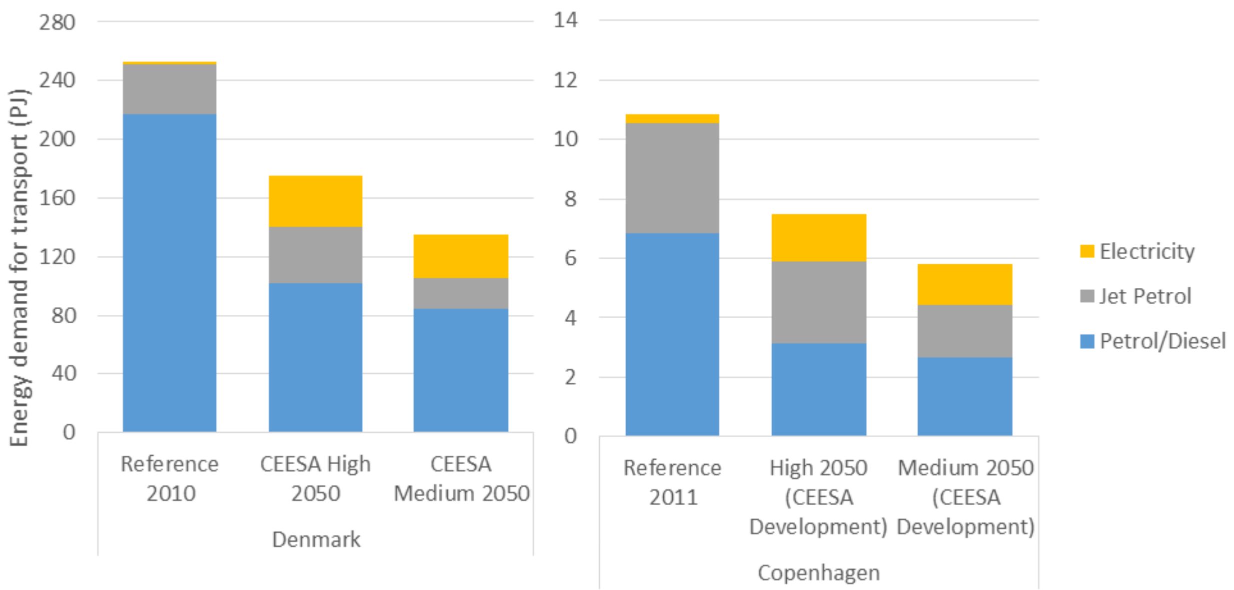


Figure 60: Energy consumption for transport in The City of Copenhagen in 2011 and CEESA 2050 divided into energy sources.

5.5.3 Environmental Effects

One of the main purposes of converting energy systems to renewable energy supply is to reduce the environmental effects of the energy consumption. The environmental effects of the energy use for transport are connected both to the energy sources and to the conversion process in which the energy sources are converted into mechanical energy for transport. The effects of converting the energy source are, e.g., emissions of CO_2 and SO_2 from the carbon or sulphur content in the fuel when combusted in an engine. Hydrogen electric vehicles for example do not have these emissions. Effects connected to the conversion process are for example the emissions of NO_x from vehicles. These emissions are generated in combustion engines by the high pressures and temperatures from the nitrogen in the air and not from the fuel. Also noise emissions from transport can be considered an effect of the conversion process. Combustion engines generally have more and larger environmental effects than electric vehicles because of both the fuel and the conversion process.

For Copenhagen, it is important to consider these aspects also in the development of strategies for the future transport sector. Yet, not much research has covered the environmental effects of methanol or DME as fuels for transport, as suggested in CEESA, but as these are assumed to be applied in conventional internal combustion engines, some of the same local environmental effects can be expected for these fuels. The sulphur content of non-fossil fuel is generally much lower than of fossil fuels, but there may be some sulphur emissions. Also NO_x and particle emissions can be expected for these fuels. These emissions mainly have local impacts and for that reason, they are important to consider in dense urban areas like Copenhagen. Battery and hydrogen electric vehicles may have some of the same effects at the power plants where the electricity or hydrogen is produced, but these are not emitted directly in the city and therefore the use of these vehicles does not have the same local effects.

5.6 Strategic Energy Planning in Copenhagen

This section gives an introduction to how the role of municipalities can be seen in strategic energy planning. It gives suggestions and recommendations to The City of Copenhagen, municipalities in the Greater Copenhagen Area and other key authorities / relevant stakeholders in strategic energy planning, for how to improve the planning process and coordination between actors.

5.6.1 The Role of Municipalities in Renewable Energy Systems

The energy systems resulting of the transition described in Chapter 1 are to a higher extent based on local resources than the current energy systems in which the energy production is more centralised. In the traditional system, the fuel is brought into the system from outside and transported, stored, converted and distributed to the consumers as petrol, gas, electricity or district heating. In the renewable energy system, the production of the energy will take place locally in the country, in terms of wind turbines, biogas plants, geothermal energy or solar thermal production. These local energy sources will feed into local energy systems, e.g., a CHP district heating system with large heat pumps. To balance the local energy system, an exchange of resources as biomass, manure, electricity, district heating, etc., will takes place with the neighbouring regions.

These local processes and the utilization of the local renewable energy sources require knowledge about the local systems, potentials and conditions. The municipalities play an important role in this regard, as the local energy planning authority, in implementing projects that will contribute to the national targets. In the municipal energy planning, the national visions and targets have to be refined and converted into concrete actions. Here, the local resources and the specific potentials can be pointed out and integrated. This could be the conversion of heat and electricity production facilities, the connection of individual and natural gas heated areas to district heating, heat savings in buildings, the utilisation of waste heat from industry, and improvements of local and public transport systems.

While it can be argued that local energy planning to a certain extent follows national policy goals, local authorities also tend to emphasize those areas in which they possess some ability to act [16,17]. This means that local energy planning on the one hand has become more comprehensive, including more sectors and components of the energy system as well as taking more policy goals into account. On the other hand, especially municipal energy planning still seems to remain most effective within those fields in which local authorities and local energy companies have the executive powers; i.e., leading to the implementation of concrete projects. Other areas in which responsibilities are unclear or are with other actors than the local authorities and local energy companies, the planning does not as effectively lead to the implementation of concrete projects [18].

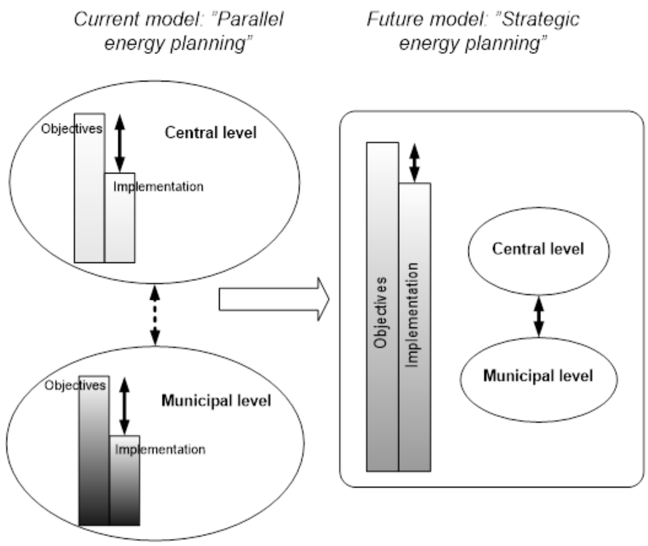


Figure 61: Simplified illustration of the current energy planning system in Denmark and how this system could be adapted to facilitate the transition to a 100% renewable energy system in the future [16].

This indicates that there might be a potential in strengthening the coordination between the national energy strategies and the municipal energy planning to better reaching the national targets, see Figure 61. While there is limited coordination between the state and the municipalities in the current system, in a strategic energy system, central and local energy planning must be stronger integrated. It is also suggested by [16] that the roles of the municipalities and the government in the energy planning should be clarified as the municipalities are given the appropriate planning instruments to be able to effectively carry out the energy planning within all energy related sectors.

Sperling et al. argue that there is a need for both a centralisation and a decentralisation of the energy planning and a creation of a synthesis between the two currently "parallel" levels in energy planning [16]. In Denmark, some regions are taking the initiative in developing strategic energy planning projects to strengthen the regional development within the energy sector and to improve the cooperation between the municipalities. However, there is a need for integrating energy planning into the municipalities in a more structured way to make sure that all actors work in the same overall direction and with the same goals, thus avoiding sub optimisation. Five principles have been developed in Wejs et al. [76] to address these issues, specifically to secure a systematic coherent planning of energy and climate:

- Long-term planning
- Based on scenario analyses
- Internal coordination of planning process
- External coordination of planning process
- Local ownership and involvement [76]

These principles highlight the holistic approach to the energy planning process taking into account not only the short-sighted and straightforward implications of the planning, but also long-term cross-sectorial implications. To strengthen the implementation and avoid some barriers, the process of the energy planning should be coordinated across the municipal departments, other municipalities in the relevant region, and with local interests and possible stakeholders involved in the plans.

5.6.2 Suggestions and Recommendation for Copenhagen: Organisational Framework for Strategic Energy Planning

As mentioned, The City of Copenhagen is a central municipality in the development of a national renewable energy system because of its size and because it is the capital of Denmark. The size can also be a problem though, since there are many different interests and different people involved in different administrations and departments of The City of Copenhagen. Therefore, the above-mentioned five principles are particularly important in Copenhagen. In the following, a number of concrete suggestions and recommendations for strategic energy planning in Copenhagen are outlined:

- *To continuously do long-term analyses of different alternative scenarios for the energy systems development*
  This should create awareness of different technical alternatives and the implications of these as a foundation for qualified and informed decisions.

- *To create an executive board in the municipality across municipal departments*
  This should promote the cross-sectorial cooperation in the municipality and the ability to make decisions that require decisive power from several municipal departments.

- *To coordinate the energy planning initiatives with the other municipalities in the region*
  This is to make sure that investments in large infrastructure, available resources, and the development in energy related demands are coordinated in a larger geographical area and to avoid sub optimisation.

- *To ensure the coordination between municipalities, DH transmission companies and DH supply companies*
  This is to increase the coordination and planning of the development of DH systems and avoid sub optimisation between individual companies. This could be by merging companies in the same field or creating coordinating bodies.

- *To have continuous focus on local involvement in the planning of energy infrastructure and possibly ownership*
  This is to keep local support and avoid some resistance against the plans and construction of infrastructure such as wind turbines.

- *To continuously identify barriers to local implementation and communicate such barriers to the national level.*
  This can help identifying new policy measures at the national and local level, e.g., new cross-cutting institutions needed, new support schemes, or the elimination of technical barriers as well as educational and knowledge barriers.

5.6.3 Suggestions and Recommendation for External Key Actors: Strategic Energy Planning in Copenhagen and Denmark

Energy planning for 100% renewable energy is an issue that cannot be solved by municipalities alone but require active cooperation with national, regional and other local actors and authorities. Some of the important issues in strategic energy planning that lie outside the authority of the municipalities are listed here as recommendations for the relevant stakeholder level:

- *Region: To develop coherent energy plans in line with national goals addressing different resources and capacities of the municipalities*
  This is important to avoid sub optimisation between municipal energy plans. The regional plan should provide a framework or guidelines for the municipalities for how to focus their initiatives most efficiently to reach national targets.

- *National: To put forward guidelines for the role of the regions in the energy planning*
  This should be done because there are no current specifications of which role the regions should play in strategic energy planning even though they can play a very important role in the coordination of the municipal initiatives.

- *National: To introduce more specific requirements for the municipalities to do strategic energy planning*
  This can push municipalities that are currently not making any significant attempt to support or implement renewable energy initiatives or promote energy savings, even though some of these can be done with low investments and short payback times. It can also help The City of Copenhagen to improve its coordination opportunities with the surrounding stakeholders.

- *National: To use national energy and transport scenarios for 2050 to create an official framework for local stakeholders for how to reach 100% renewable energy in transport in 2050. This should be updated regularly.*
  This can ensure constructive dialogue and ensure that short-term initiatives are also suitable in the long-term renewable smart energy systems.

6 Conclusions

This study analyses the role of The City of Copenhagen and the Greater Copenhagen Area in the national development towards a 100% renewable energy supply. Copenhagen has already taken some important initial steps with the CPH 2025 Climate Plan. However, a number of points should be considered and improved to be in line with the overall development towards a 100% RE supply in Denmark. Converting to 100% RE is economically viable in Denmark, but some key technological changes will be required at the national level. These include the development of onshore wind power capacities, PV, the implementation of heat pumps in individual buildings and in DH systems, the expansion of DH areas, and the implementation of savings at the end-user level. Copenhagen will play a key role during this transition for two key reasons: firstly, Copenhagen is the home of 10% of the population of Denmark, so actions made in Copenhagen have a major impact on the overall national progress, and secondly, the implementation of new technologies will require actions at a local/municipal level. For example, it is important that the local governments have long-term strategies identifying how they will reach their energy targets, such as the CPH 2025 Climate Plan. This study adds to the knowledge in the CPH 2025 Plan by focusing on some critical areas that will impact the longer-term ambition of becoming 100% renewable at both a local and national level. These issues and the main conclusions from the analysis are summarised below.

Flexible CHP, Power Plants and renewable energy

In a future RE system, the CHP and power plants play an important role in integrating fluctuating RE. With up to 80% electricity production from these fluctuating sources, it is important that the CHP and power plants are able to regulate actively and consistently without large commitments in base load operation. The CHP and power plants will be operating fewer hours than today. In this study, four scenarios for different power plant types are analysed: CCGT, CFB-low, CFB-High, and APF. The results suggest that CCGT plants should be implemented as the most suitable type of CHP and power plant for a 100% RE system. The CCGT units result in lower annual costs and use less biomass. They utilise the gas grid which should be supplied with gas produced from gasified biomass and potentially upgraded in a hydrogenation process. In an intermediate period, natural gas could be used instead of biomass. The analysis shows that the CCGT scenario is most feasible for society. Applying small capacities of CFB plants will only make the system slightly more expensive and use slightly more biomass – providing that all other CHP and power plants are CCGT, which is currently not the case. With large CFB capacities, the system performance will be significantly lower. Sensitivity analyses of the scenarios with varied interconnection capacities and electricity prices show that the CCGT plants are cheaper in all cases.

In relation to Copenhagen, the city needs to contribute more to the development of onshore and offshore wind power as well as PV. To be specific, as Denmark gets closer to a 100% renewable energy system in 2050, Copenhagen should aim towards 500 MW of PV and approximately 1500 MW of wind power capacity (onshore or offshore). For wind power capacity targets should be increased by a factor of 4 for 2050 and for solar PV a factor of 10 compared to the targets in the CPH 2025 Climate Plan.

As the city will have difficulty establishing onshore wind power, this could be balanced by more offshore wind power and PV in Copenhagen, while other municipalities in Denmark could establish more onshore wind power.

Heat Savings in Buildings and New Heat Sources

Heat savings and the development of DH systems in Copenhagen are important parts of developing a renewable energy system in a cost-effective way. The DH system is essential for the integration of different energy sources, but the future demand and heat sources should be considered carefully already now. In the future, the mix of heat sources will be different than today; CHP and fuel boilers should contribute less and heat pumps, geothermal energy, solar thermal energy, and excess heat from fuel production should play a much larger role. Low temperature DH should be implemented in the distribution systems and potentially also in the transmission systems to accommodate the low temperature heat sources.

Heat savings are important to the planning of future systems as they influence the economy of the system. Therefore, the conversion, transmission and distribution systems should be designed for expected demands to reduce the system costs. Results from this study indicate that the heat-saving potentials in Copenhagen are larger than in the rest of the country because of the higher average age of the building mass (56% compared to a feasible level of 53% in Denmark as such). These heat savings should be implemented together with the expansion of the DH grid in new developments in Copenhagen and a plan for how to convert to low-temperature district heating supply.

Transport Energy Supply

The transport sector accounts for a large share of the total energy consumption which is harder to convert into renewable sources than electricity and heating. Battery electric vehicles represent the most cost-effective way of converting light-duty transport away from a fossil fuel supply. The heavy-duty transport should be covered mainly by electrofuels such as methanol or dimethyl ether that are produced from gasified biomass and hydrogen.

In Copenhagen, it is firstly important to reduce the need for car transport, which causes the fuel consumption. This can be done by promoting alternatives like bikes, trains, and busses, and reducing the accessibility of cars to the city – i.e., also avoiding the expansion of road based transport and parking facilities. Secondly, battery electric cars should be promoted, for example by reserving parking areas for electric cars and planning for an extensive development of charging infrastructure for electric vehicles in the city and near public transport transit points. Thirdly, a planning process should be initiated for biomass gasification plants and the production of electrofuel.

Appendices

Appendix 1 CEESA Scenario Specification and Assumptions

This section presents the main specifications for the Reference 2010 model and the CEESA 2050 Recommendable model. Some of the important issues in relation to the scenarios are discussed and elaborated as well.

Model Specifications

Table 6 presents the main specifications and assumptions used in the Reference 2010 and the CEESA 2050 Recommendable models. This is not a full list, but the main part and the important assumptions. The full elaboration and explanation of the assumptions behind the CEESA 2050 system can be found in the CEESA background report [14].

Table 6: Scenario assumptions for the Reference 2010 model and the CEESA 2050 Recommendable model

	Reference 2010	CEESA 2050 Recommendable
Demands		
Electricity (TWh/year)	35.22	20.60
Heating – Central CHP areas (TWh/year)	22.67	24.34
Heating – Decentralised CHP areas (TWh/year)	10.42	11.09
Heating – Local DH areas (TWh/year)	2.78	2.96
Individual heating (TWh/year)	22.90	9.30
Transport: Electricity (Bkm/year)	0.40	8.22
Transport: Fuel (Bkm/year)	69.88	32.15
Renewable Electricity Generation		
Onshore wind power capacity (MW-e)	2,934	4,454
Offshore wind power capacity (MW-e)	868	10,173
Solar PV capacity (MW-e)	0	5,000
Wave power capacity (MW-e)	0	300
Centralised CHP areas		
Condensing power capacity (MW-e)	5,022	7,833
Condensing power efficiency[1]	0.40	0.60
CHP capacity (MW-e)	2,500	2,500
CHP efficiency (Electric/thermal)	0.31/0.53	0.6/0.31
Fuel boiler capacity[1] (MW-th)	7,978	7,574
Fuel boiler efficiency	0.93	0.95
Heat pump capacity (MW-e)	0	600
Heat pump COP	-	3.50
Solar thermal production (TWh/year)	0	0.91
Geothermal production capacity[2] (MW-th)	0	410
Thermal storage capacity (GWh)	10	10
Waste incineration[3] (TWh/year)	5.91	2.70
Waste incineration efficiency (Electric/thermal)	0.19/0.75	0.27/0.77
Industrial CHP production (TWh-e)	1.01	0.89
Industrial surplus heat supply (TWh-th)	0.96	2.65
Electrofuel production capacity (MW-gas)	0	3,703
Biomass gasification capacity (MW-gas)	0	3,522
Biomass gasification efficiency (Gas/surplus heat)	-/-	0.1/0.84

Table continues on the next page

Decentralised CHP areas		
CHP capacity (MW-e)	1,945	1,945
CHP efficiency (Electric/thermal)	0.37/0.46	0.58/0.37
Fuel boiler capacity[1] (MW-th)	3,667	3,484
Fuel boiler efficiency	0.93	0.95
Heat pump capacity (MW-e)	50	300
Heat pump COP	1.95	3.5
Solar thermal production (TWh/year)	0	2.08
Thermal storage capacity (GWh)	40	50
Waste incineration[3] (TWh/year)	3.21	1.46
Waste incineration efficiency (Electric/thermal)	0.19/0.75	0.27/0.77
Local DH areas		
Fuel boiler capacity[1] (MW-th)	1,067	1,003
Fuel boiler efficiency	0.93	0.95
Solar thermal production (TWh/year)	0.01	1.33
Thermal storage capacity (GWh)	0	80
Waste incineration[3] (TWh/year)	0.07	0
Waste incineration efficiency (Electric/thermal)	-/0.80	-/-

[1] *Condensing power plant and fuel boiler capacities in the scenarios are defined in such a way that they can meet the peak demand occurring during a year plus 20% to account for potential unexpected fallouts of units. This means that in the model a situation will never occur in which electricity has to be imported.*

[2] *Geothermal heat production is assumed to come from absorption heat pumps driven by steam from a CHP plant, here waste incineration plants. This means that when the heat production from the geothermal plant is not needed, the steam is not drawn from the CHP process and thereby increasing the electric efficiency.*

[3] *The amounts of waste in the CEESA 2050 scenario are determined by looking at examples from other countries of how much the waste amounts for incineration can be reduced by increased focus on reuse and recycling of materials.*

Cost Assumptions

The costs in the scenarios are mainly based on the catalogue of "Technology Data for Energy Plants" published by the Danish Energy Agency [69]. This is applied to all costs related to technologies and investments, where nothing else is mentioned.

The cost for wood chips is assumed to be 42.2 DKK/GJ and the cost for wood pellets is assumed to be 63.3 DKK/GJ.

The CO_2 cost is assumed to be 107.3 DKK/t in 2010. The system of 2050 does not emit any CO_2 so here the CO_2 cost is not relevant.

The discount rate included in the scenarios is 3% in both 2010 and 2050. This is only applied to the calculation of the investment annuity payment.

Biomass Assumptions

Regarding the type of biomass, it is assumed that in 2050 the largest amounts of biomass will be in the form of wood chips. Besides this, there will be small amounts of biomass in other forms, e.g., wood pellets or firewood, mainly for individual consumption.

Biomass is in the CEESA project seen as a limited natural resource rather than a product allocated by supply and demand on a market. This means that the biomass should be used intelligently and in consideration of the natural limit in the resources to have a sustainable consumption. In Denmark, there is a larger biomass potential per area and per capita than the average of the EU or the world because of the high share of arable land in the country (see Figure 32 in section 4.3 on page 31). The potential of 240PJ is larger than what would be the value today, and this is assuming that the efficiency of collecting residual biomass is increased compared to today as the demand increases towards 2050.

In CEESA, the value of 240 PJ (66.6 TWh) of biomass for energy purposes is larger than the estimated world averages because of the large potential in Denmark, but it is still not a full utilisation of the Danish potential since it is assumed that some of the biomass will be used in countries with lower biomass potential. The limit to biomass consumption for energy purposes in Denmark could alternatively have been set at the EU average of biomass potential, which would be lower, and that would have made the energy system significantly more expensive because of the lost flexibility that biomass as fuel implies. In that case, more intermittent energy sources would have to be integrated together with more electrolysis and more energy storage facilities.

If the consumption exceeds the level recommended here, there will be a higher risk that the energy system becomes too dependent on biomass and this will increase the cost sensitivity of the system because the fuel prices are impossible to predict. Even though biomass for energy purposes is a cheap solution today, it may not continue being so. In the alternative case, where the biomass dependency is lower and the system is based on investments in, e.g., wind turbines, the sensitivity to fuel price fluctuations is lower. Another consequence of increased biomass consumption of the energy systems in the short term is that the infrastructure investments will support an inefficient system and a locked-in situation in which it will be harder to develop other system flexibility measures, like heat pumps or power-to-gas.

Appendix 2 Calculations of Energy Supply and Demand

This chapter presents the methodology of calculation of the supply and demand data presented in Section 3.1. It is divided into the same three categories as in Section 3.1; Energy consumption, Electricity and Heat Production, and Transport.

Energy Consumption

The electricity consumption is calculated on the basis of the national energy statistics by DEA scaled according to the population in the municipality of Copenhagen. This is built on the assumption that the electricity consumption per capita in The City of Copenhagen does not deviate significantly from the consumption in the rest of the country.

The energy consumption for heating is extracted from the Heat Atlas [35] for The City of Copenhagen. The Heat Atlas is based on data from the BBR register and contains a calculated heating demand with inputs of building area, building age, type of heating installation, and fuel type.

Electricity and Heat Production

The fuel consumption for electricity and heat production at the CHP plants and peak load boiler units are summarised using the "Energy producer count" (Energiproducenttællingen) from 2011 produced by the Danish Energy Agency, where the total fuel consumption for heat and electricity production for one year can be found. The data is summarised for production units connected to the DH grids for CTR, VEKS and Vestforbrænding because, as mentioned, the DH production system in the Greater Copenhagen Area is very closely connected and the sum of the total system gives a good representation of the shares used for supply in Copenhagen.

Data for wind turbines is collected from the "Master Data Register of Wind Turbines" from 2013. Here each single wind turbine in Denmark is registered with municipality, on- or offshore location, production capacity, actual historical electricity production, etc. This data is used for the calculation of the wind power production in which annual values for 2012 are used.

Transport

The energy consumption for transport is calculated in four categories; Train, Ship, Road Transport and Aviation. These are based on a review and energy balance made by PlanEnergi [11].

Train

In the calculation of the train transport, the S-train, the metro and the regional trains have been included. The S-trains and metro are calculated specifically for The City of Copenhagen, whereas the share of regional trains has been calculated by the national total values scaled down by population figures. The values for S-trains and metro are based on a prognosis made in connection with the future development of the public transport in the capital region.

Ship

The ship transport uses fuel oil and diesel and the amounts for The City of Copenhagen are calculated from national values and scaled down by population figures.

Road Transport

The road traffic predominantly uses diesel or petrol and only a small share uses electricity, which is not quantified here. In the diesel consumption, there is a 3.77% share of biodiesel, and in the petrol consumption, there is a 3.33% share of bioethanol. These shares are included in the following section about the renewable energy supply. The energy consumption is calculated for The City of Copenhagen based on traffic counts and calculations of travelled km for the different types of transport.

Aviation

The airplane traffic is calculated based on national values of the consumption of JP1 and scaled according to population figures for The City of Copenhagen. In the energy consumption for airplane transport, there is a share of petrol as well, but less than 0.2%.

Appendix 3 Definition of Greater CPH 2025 Reference Scenario

The Copenhagen 2025 Reference is based on the EnergyPLAN scenario of the 2010 Reference, also used for the CEESA project, with a number of changes to make it specific for the energy system context of the municipalities connected to the DH system in the Greater Copenhagen Area. This is used as a basis for including the initiatives in the CHP2025 Climate plan.

The changes from the 2010 Reference are:

- All demands and capacities are reduced to 25% according to the relative population of the municipalities in the DH system of the capital region, compared to the whole country.
- District heating (DH) demands from DH groups 1 and 2 are moved to DH group 3, since the described area is covered by DH from centralized power plants.
- The capacity is defined according to the electric capacities listed in Table 2.
- All waste incineration is moved to DH group 3.
- Individual heat demands are moved to DH group 3, so that the DH corresponds to 70% and individual heating to 30% of the total heating demand, equivalent to 95% DH in Copenhagen and 55% DH on average in the remaining municipalities.

The specific changes from the CPH2025 Climate Plan that have been included in the CPH 2025 Reference model are listed here:

- 8% reduction of DH and individual heat demands
- 6% reduction of electricity demand (4% in households and 8% in industry averaged)
- Photovoltaic has been added to cover 0.4% of the electricity demand (50 MW)
- 360 MW additional wind power (180 onshore and 180 offshore)
- All CHP and DH boilers are run on biomass
- 50 MW geothermal heat production has been added
- 4% reduction in diesel and petrol demands
- 4 times higher demand for electric cars (0.40 TWh/year)
- 4% of waste moved to biogas production (0.05 TWh biogas for the grid)

All the initiatives that are included from the CPH2025 Climate Plan have been scaled down from covering the 10% of the population which The City of Copenhagen makes up, to the proportional amount in the larger system of The Greater Copenhagen Area by a factor 10/25. This is equivalent to the population in The City of Copenhagen relative to the population in the Greater Copenhagen Area. The Greater Copenhagen Area 2025 Reference scenario has been compared to the 2010 Reference scenario and the CEESA 2050 Recommendable scenario in Figure 38 to Figure 41. The 2010 Reference is based on historical data and the CEESA 2050 Recommendable is based on the CEESA study of 100% renewable energy scenarios in 2050.

Appendix 4 Power Plant Analysis

This chapter provides assumptions, methodological details, and details of the results of the power plant analysis carried out in connection to this project, mentioned in section 1.1 from page 20.

Assumptions for Technologies

In this section, the three analysed types of CHP plants are presented with their assumptions. The two technologies based on biomass fired steam turbine plants are presented first, followed by the combined cycle gas turbine plant. Lastly, the specific data applied to the analyses are presented.

Biomass Fired Steam Turbine CHP Plant

A biomass fired steam turbine CHP plant works by burning a biomass fuel, straw, wood pellets, etc., in a boiler to produce steam that drives a steam turbine. The steam turbine powers a generator which produces both electricity and heating. In this study, two different plant technologies for biomass fired boilers driving a steam turbine are handled; Circulating Fluidized Bed (CFB) and Advanced Pulverized Fuel (APF) boilers.

The CFB boiler CHP plants are characterised by low investment costs, low electricity-to-heat ratio and higher total fuel efficiency, as it is assumed that it is combined with a flue gas condensation facility. The CFB boiler is flexible in terms of fuel type as it can use wood waste material, wood chips and other low grade biomass sources. These plants may be able to bypass the turbine, which means that the electricity production is reduced and the heat production is increased; thus, the plant is potentially working as a biomass boiler. These plants may be able to operate the bypass rather fast to regulate for fluctuations in, e.g., wind power production.

The APF boiler CHP plants, compared to the CFB plant, have substantially higher investment costs, higher electricity-to-heat ratio, and the ability to operate in condensing mode, which means that it produces electricity only. This type of power plant is a proven technology and currently the most common type of large power plants in Denmark. The APF technology does not have the same fuel flexibility as the CFB type and needs a high quality fuel such as wood pellets.

The main advantage of the biomass fired steam turbine for CHP is the high overall energy efficiency. Today, the efficiency of this type of plant is around 90-95% and is expected to increase further in the future [69]. The main disadvantage of these plants is the low ability for load regulation. Even though the electricity-to-heat ratio can be reduced by bypassing the turbine, the ability of the plant to regulate the production is rather low. The plant, moreover, has to produce continuously at a minimum load because of the costly and time consuming start-up of the plant, especially the CFB type. See the details in Table 7.

Biomass Gasification and Combined Cycle Gas Turbine

Biomass gasification and a combined cycle gas turbine as one system basically converts biomass into electricity and heating like the biomass fired steam turbine. This system requires four different components in the energy system: 1) A gasification plant to convert biomass to gas, 2) an electrolysis plant to convert electricity to hydrogen, 3) a hydrogenation plant to combine gasification gas and hydrogen to an upgraded synthetic gas, called syngas, and lastly 4) a combined cycle gas turbine plant to produce heat and electricity from the syngas. All of these components do not have to be located at the CHP plant. The idea is just that the CHP plant should be able to use the synthetic gas in a combined cycle gas turbine, since the other components have other purposes in the energy system than just producing fuel for the CHP plant, e.g., the production of transport fuels. This means that if the power plants use synthetic gas instead of solid biomass, the required capacities for the gasification and fuel synthesis plants increase as well.

A share of the heat loss from the electrolysis, gasification and hydrogenation in the system may be recovered for district heating production, but this is only included to a modest extent here, because of the uncertainties involved. All the above components do already exist and have been demonstrated individually, but not in an integrated system as suggested here. The gasification of biomass for CHP is currently undergoing demonstration projects and it has not been applied in large scale yet. Another issue that is being assessed is the grade of biomass that can be gasified. Currently, mainly higher grade biomass is being used in gasification, whereas it is expected that the gasification of lower grade biomass in coming years will also be feasible. See further details about the development of gasification technologies in 0.

The main advantage of this system is that it contributes to the general energy system flexibility in a number of ways. The CCGT itself has a relatively high regulation ability compared to the alternatives and high electric efficiency. The combined cycle plant also gives the option to run only the gas turbine, so-called simple cycle, with lower efficiency but faster regulation ability. The system with gasification also gives flexibility to systems outside the power plant mainly to the production of fuels for transport. If many components are connected to a gas grid, like power plants, gasification and electrolysers, peak load boilers, chemical synthesis plant, and gas storages, this enables a large flexibility of absorbing fluctuations in electricity production, producing electrofuels for transport or heat and power at times where each of these are needed to balance the system. The disadvantages are the lower fuel efficiency at the plant and the fact that the total system has not yet been demonstrated.

Technology Data

In the following Table 7, the data applied to the analysis are presented for the three analysed technologies; combined cycle gas turbine, and the two biomass fired steam turbine technologies CFB and APF.

Table 7: Technical specifications of combined cycle gas turbine and biomass fired steam turbine. Potential values for 2050. [69] (*) indicates the sources [77]. (**) Indicates assumed total efficiency of 101% including flue gas condensation.

	Combined cycle gas turbine CHP	CFB boiler driven steam turbine CHP	APF boiler driven steam turbine CHP
	Technical data		
Electric efficiency, condensation (%)	61.5	-	53.5
Electric efficiency, back pressure (%)	57.2	40*	45.3
Heat efficiency, bypass operation %)	-	101**	-
Heat efficiency, back pressure (%)	32.7	61**	48.8
Technical lifetime (years)	25	25*	40
	Financial data		
Nominal investment (MDKK/MW-e)	5.9	6.59*	14.2
Fixed O&M (MDKK/MW/year)	0.23	0.34*	0.46
Variable O&M (DKK/MWh)	18.8	16.5	16.5

Regarding the CFB boiler steam turbine, some assumptions have been made, since this technology has not been implemented on a large scale for heat and power production in Denmark earlier. It has not been possible to get exact data about this type of plant or how it more exactly could be expected to operate in a Danish context. It is assumed that the total efficiency of the plant can reach a level of 101% including flue gas condensation, which can be observed for similar plants, e.g., waste-to-energy plants. It is also assumed that the total efficiency remains at this level for both full back pressure mode and for bypass mode. Furthermore, it is assumed that the variable operation and maintenance costs are similar to those of conventional steam turbine plants.

Ramping rates of individual plants are not included in this analysis because of the time resolution of one hour of the simulation, which allows both the CCGT and APF plants to regulate from maximum to minimum or opposite within one time step. For example, if a plant can regulate 2% of max load per minute, it will be able to regulate from 0 to 100% in 50 minutes. The reduced efficiency of operating at partial loads is included in the total efficiency of the plants, but it should be kept in mind that the plants here are modelled at an aggregated level, hence reducing the necessity to model partial loads. For example, if the electricity demand goes from 100% to 50% not all of the plants have to go to 50% load, but it could as well be 50% of the plants that shut down and 50% remain running at full load instead.

Methodology for Power Plant Analysis

The analysis is a technical energy systems analysis and is performed by using the CEESA 2050 Recommendable scenario, representing a 100% renewable energy supply for the Danish energy system, as a reference. The scenario simulates the system operation with steam turbines as the type of power plant, instead of gas turbines as in the CEESA scenario, and the parameters defining the type of power plant were changed according to this change. The analyses of the scenario energy systems are performed by using the EnergyPLAN energy systems modelling tool [22].

Definition of Scenarios

The scenarios are defined to reflect the different strategies inherent in the different types of CHP plants. The four scenarios are; 1) Combined cycle gas turbine, 2) CFB boiler driven steam turbine with low capacity, 3) CFB boiler driven steam turbine with high capacity, and 4) APF boiler driven steam turbine.

The combined cycle gas turbine scenario is identical to the CEESA Recommendable 2050 Scenario where combined cycle gas turbine technology is applied to CHP plants. In this scenario, the fuel for the plant is gas from the natural gas grid. An amount of gas equivalent to the share that the CHP plants consume is produced through the gasification of biomass (wood chips). All the gas in the grid in this scenario is based solely on renewable energy.

The CFB boiler driven steam turbine scenario is based on the CEESA Recommendable 2050 Scenario, but with a number of changes to represent the different types of CHP plants. It should be noted that the capacity for condensing power production here remains as a combined cycle gas turbine as in the CEESA scenario, because the CFP plant is not able to operate in condensing mode. Two different versions of the scenario have been analysed with different installed capacities, as the installed capacity is very important to this type of plant. These two scenarios are here referred to as *low* and *high,* respectively. The main changes are the following:

- Efficiencies of the CHP plants have been changed to represent the CFB boiler steam turbine plant. (See Table 7 on page 72)
- The fuel type in CHP plants has been changed from gas to wood chips
- The national capacity of large CHP is reduced from 2,500MW electric and 1,300MW thermal capacity to:

  Low: 850MW electric and 1,300MW thermal capacity

  High: 2,000MW electric and 3,050MW thermal capacity
- The operation of the CHP plants has been set to run base load in the heating season and not to run in the remaining months. The plants are operated between October and May, but only half of the plants (half of the total capacity) operate in the two months of October and May to include different times of start and stop. This makes a total of about 5,100 full load operation hours.

The APF boiler driven steam turbine CHP scenario is also based on the CEESA 2050 Recommendable scenario with a number of changes to represent the different types of CHP units. The main changes are listed here:

1. The efficiency of the CHP plants and condensing power plants has been changed to represent the APF boiler steam turbine plant. (See Table 7 on page 72)
2. The fuel type in CHP plants and condensing power plants has been changed from gas to wood pellets.
3. The national capacity of CHP is set to operate at a minimum load of 20% of the total capacity to represent the characteristics in connection to start-up and load regulation. This means that at least 20% of the large power plant capacity in Denmark is assumed always to be in operation.

The scenarios are different in terms of a number of parameters including excess electricity production. In the CEESA scenario, there is an excess electricity production of 1.75 TWh/year. Excess electricity production (TWh/year) occurs when the electricity production is higher than what can be consumed within the same hour. This is for example the case if there are high amounts of intermittent electricity production like wind power, but it can also be caused by inflexible power production units like waste incineration or large power plants that run base load production. The production that cannot be consumed in these hours will have to be exported or curtailed. This means that higher excess electricity production indicates lower flexibility of the total system and less efficient integration of fluctuating resources. The electricity may be exported to neighbouring countries, but it is very uncertain to which price it may be sold. For these reasons, the value of this excess electricity is assumed to be 0 DKK/MWh.

To make the different scenarios comparable on this issue, the wind power capacity has been adjusted in the alternative scenarios, meaning that they all have an excess electricity production of 1.75 TWh/year. This is done by adjusting the capacity of offshore wind power. In the case of higher excess electricity production, the wind power capacity is reduced and the scenario ends up with an excess production of 1.75TWh/year. This would also mean that the costs for wind power capacity are reduced for this scenario. If the excess electricity production is lower, then oppositely the wind capacity is increased.

Indicators

The output of the EnergyPLAN analyses of the scenarios is compared on a number of different parameters, indicating the impact of changing the type of power plant in the system. The inputs are the same as used in the CEESA project, except for the mentioned changes for the power plants which are applied to the analysis to simulate the operation of the different types of power plants. This means that the differences in the results will be rather small in percentage because the changes of the power plants only affect some parts of the energy systems. The absolute changes in the results between the scenarios should for this reason be noticed. The chosen indicators are Total costs and Biomass consumption. The indicators are elaborated in the following.

The Total costs (DKK/year) is the sum of all the costs included in the scenario such as investment costs for power plants, boilers, heat pumps that are used for the energy supply, the costs of fuels used at power plants, heat supply at individual households, transport fuels, fuel handling costs, and costs for operation and maintenance (O&M). This means that the Total costs are rather high because they cover most of the Danish energy system. The values are given per year for the given system, and to do this, the investment costs are annualised for the lifetime of the investment with a discount rate of 3%. The cost for biomass consumption in 2050 is assumed to be 42.2 DKK/GJ for wood chips and 63.3 DKK/GJ for wood pellets.

The costs in this analysis reflect a socioeconomic point of view, which means that the analysis seeks to include the costs for the society as a whole rather than the economy of a company or a single plant for example. The difference is that fuel taxes, subsidies and other economic regulations are not included. This means that the system with the lowest socioeconomic cost will not necessarily be the same as the scenario with the lower business economic costs. The purpose of doing this is to show how the system can potentially and technically operate in the best way for society.

The Biomass consumption (TWh/year) is the sum of the biomass consumed by all sectors in the energy system. Biomass is not separated into different types of biomass like waste, wood chips or straw, but just measured in total energy content of the consumed biomass. All biomass consumption in the primary energy supply is in solid form. All bio-energy in gaseous and liquid forms is the product of conversion of solid biomass; thus, solid biomass is a primary input that is counted. The consumption of biomass is depending on many interdependent factors in the energy system. The capacity of wind and other intermittent renewable sources and the system ability to integrate these are a central focus. The biomass consumption is important to take into account, because in a system based on 100% renewable energy, the biomass will be a critical resource and there will be a demand for it in several sectors.

Presentation of Analysis Results

The results of the analysis indicate that gas turbines with gasified biomass are more efficient than steam turbines when accounting for the rest of the energy system. Although the steam turbine plant is more efficient from a simple input-output point of view, at plant level or in a small systems perspective, it is not as efficient in a 100% renewable energy system, as it is not able to regulate for the wind power in a resource efficient way. The results and parameters of the total energy system are presented in Table 8.

Figure 62 shows the impact of implementing the other power plant alternatives compared to the combined cycle gas turbine solution. The alternatives use more fuel than the reference system and the figure shows that the decentralised CHP plants are also affected to some extent by the changes in the power plants in the central CHP areas. These changes are caused by the different electric characteristics of the plant types. As it can be seen, the decentralised CHP plants are activated more in the CFB Low scenario because the decentralised plants are more flexible than the CFB plant and will therefore supplement these in some hours. The consumption for condensing power production increases for all of the alternative scenarios because the less flexible systems require a supplementary power production capacity to regulate for the fluctuating resources.

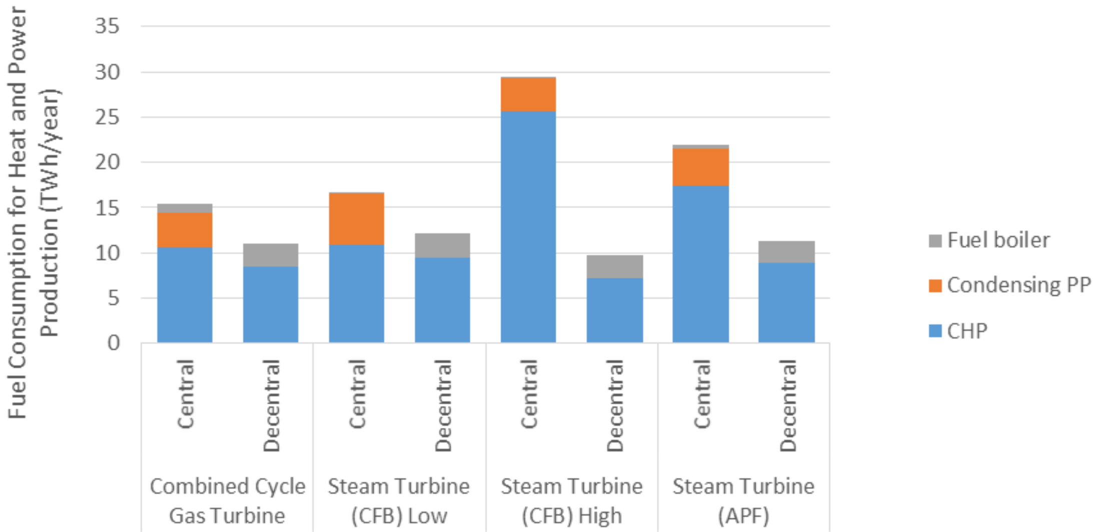


Figure 62: Fuel consumption for heat and power production in the different scenarios divided into central and decentralised district heating areas.

If the CFB boiler steam turbines with low capacity are utilised in the centralised power plants instead of gas turbines, the CEESA 2050 Recommendable scenario for Denmark would use 0.8 TWh/year more biomass and cost 0.6 BDKK/year more. If a high capacity is assumed, the biomass share would increase by 13.3 TWh/year and the cost would increase by 2.5 BDKK/year. In the case of an APF boiler type CHP plant, the system would use 4.1 TWh more biomass resulting in an increase in cost of 9.4 BDKK/year. The critical excess electricity production is also higher for the three steam turbine scenarios, which is an indication of the lower flexibility of these plants. Here the wind power capacities have been reduced to give the same excess electricity production.

Table 8: Comparison of main results of the analysis of the types of power plants analysed.

Annual values	Combined cycle gas turbine	Steam turbine (CFB) Low	Steam turbine (CFB) High	Steam turbine (APF)
Total scenario costs (BDKK)	146.6	147.1	149.1	156.0
Biomass consumption (TWh)	66.6	67.4	73.9	70.7

The difference in the costs and primary energy supply of the four scenarios have been broken down into components and presented in Table 9 and Table 10. The total scenario output values are presented for the steam turbine scenarios and the differences in outputs compared to the combined cycle gas turbine scenario are separately indicated only where the difference is larger than zero.

It can be seen that the largest part of the difference in costs is related to the variable costs such as fuel costs and fuel handling costs. This means that the fuel efficiency is important both from a resources perspective and an economic perspective. In the operation and maintenance costs, there is a difference between the scenarios only in relation to the CHP and condensing power production, whereas in the investment cost section, there is also a difference under "Synthetic gas and fuel production." This is due to increased costs in the combined cycle gas turbine scenario connected with the gasification of biomass to fuel for the CHP plant. The operation costs remain the same because the electrolysis and fuel synthesis are used for other purposes as well and these have the same peak capacity in all the scenarios; they are just operated differently from scenario to scenario.

In Table 10, the primary energy supply is divided into different categories of energy sources that supply the energy demand in the system. It can be seen that less geothermal and heat pump energy is utilised in the steam turbine scenarios. This is caused by the flexibility of the two types of plants. The CFB boiler produces heat in some hours where it is not needed and thereby suppresses potential geothermal and heat pump supply. On the other hand, the biomass consumption increases when changing to steam turbines to cover the remaining production. The changes are similar for the APF steam turbine but less significant.

It is clear, therefore, that when steam turbines are used in a 100% renewable energy system of Denmark, the system becomes less flexible, more biomass is consumed and the socioeconomic costs are higher. This means that gas turbines should be promoted in the system rather than steam turbines, because this will enable the system to absorb more fluctuating electricity production both in a short and long term. Consequently, the long-term fuel consumption and socioeconomic costs will be lower.

Table 9: Breakdown of annual costs from the gas turbine scenario to the steam turbine scenario.

Cost item (BDKK)		CCGT	CFB Low	Difference	CFB High	Difference	APF	Difference
Fuel and fuel handling	**Total**	**14.7**	**14.8**	**0.1**	**17.1**	**2.4**	**19.9**	**5.2**
	Biomass	10.8	10.9	0.1	13.2	2.5	16.0	5.2
	Gas	0.6	0.6		0.5	-0.1	0.5	-0.1
	Petrol/JP	3.4	3.4		3.4		3.4	
Marginal operation		**0.3**	**0.4**	**0.1**	**0.3**	**0.0**	**0.3**	**0.0**
Fixed operation	**Total**	**36.3**	**36.6**	**0.3**	**36.6**	**0.3**	**38.5**	**2.2**
	Wind onshore	1.0	1.0		1.0		1.0	
	Wind offshore	4.4	4.4		4.0	-0.4	4.1	-0.3
	Solar PV	0.1	0.1		0.1		0.1	
	Solar thermal	0.3	0.3		0.3		0.3	
	Wave power	0.0	0.0		0.0		0.0	
	CHP plants	1.2	1.0	-0.3	1.4	0.1	1.8	0.6
	Boilers	0.5	0.5		0.5		0.5	
	Power plants	1.8	2.3	0.6	2.3	0.6	3.6	1.9
	Heat pumps	0.5	0.5		0.5		0.5	
	Energy storage	0.4	0.4		0.4		0.4	
	Biogas plant	2.5	2.5		2.5		2.5	
	Synthetic gas and fuel production	1.6	1.6		1.6		1.6	
	Vehicles	21.5	21.5		21.5		21.5	
	Transport infrastructure	0.0	0.0		0.0		0.0	
	Other energy sector costs	0.6	0.6		0.6		0.6	

Table continues on next page

Cost item (BDKK)		CCGT	CFB Low	Difference	CFB High	Difference	APF	Difference
Investments	**Total**	**95.2**	**95.2**	**0.1**	**95.0**	**-0.1**	**97.3**	**2.1**
	Wind onshore	2.6	2.6		2.6		2.6	
	Wind offshore	7.7	7.7		7.1	-0.7	7.2	-0.5
	Solar PV	1.9	1.9		1.9		1.9	
	Solar thermal	2.0	2.0		2.0		2.0	
	Wave power	0.3	0.3		0.3		0.3	
	CHP plants	2.2	1.7	-0.5	2.1	-0.1	2.9	0.7
	Boilers	1.2	1.2		1.2		1.2	
	Power plants	2.7	3.5	0.8	3.5	0.8	4.8	2.2
	Heat pumps	2.6	2.6		2.6		2.6	
	Energy storage	3.7	3.7		3.7		3.7	
	Biogas plant	1.5	1.5		1.5		1.5	
	Synthetic gas and fuel production	3.8	3.5	-0.2	3.5	-0.2	3.5	-0.3
	Vehicles	28.4	28.4		28.4		28.4	
	Transport infrastructure	18.6	18.6		18.6		18.6	
	Other energy sector costs	16.1	16.1		16.1		16.1	
Total costs		**146.6**	147.1	**0.6**	149.1	**2.5**	156.0	**9.4**

Table 10: Breakdown of annual primary energy consumption for the two compared scenarios.

Cost item (BDKK)		CCGT	CFB Low	Difference	CFB High	Difference	APF
Total primary energy supply	**155.9**	**154.4**	**-1.5**	**152.8**	**-2.1**	**154.3**	**-1.6**
Wind power	54.4	53.8	-0.6	47.5	-6.9	51.7	-2.7
Solar PV	6.5	6.5		6.5		6.5	
Wave power	0.8	0.8		0.8		0.8	
Solar thermal	4.2	4.2		4.2		4.2	
Geothermal	3.5	3.5		1.8	-1.6	2.9	-0.5
Heat pump (Heat source)	20.0	18.3		13.1	-6.9	17.6	-2.5
Biomass	66.6	67.4	0.8	73.9	13.3	70.7	4.1
- of here gasified	*38.9*	*29.6*	*-9.3*	*27.6*	*-11.3*	*22.1*	*16.8*

The Figures below show the hourly power production for a selected period of time for each of the scenarios. This is used to illustrate the different flexibility of the power plant types and it can be clearly seen how these plants are able to regulate according to the wind power production.

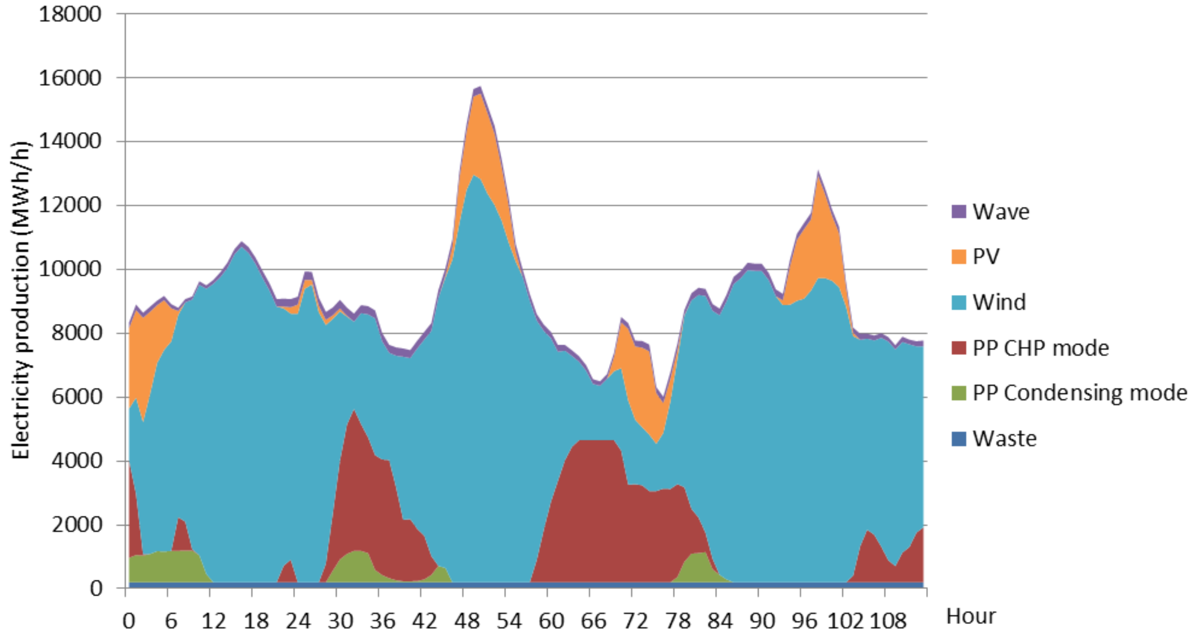


Figure 63: Hourly electricity production in the CCGT Scenario in a selected period of time in the spring.

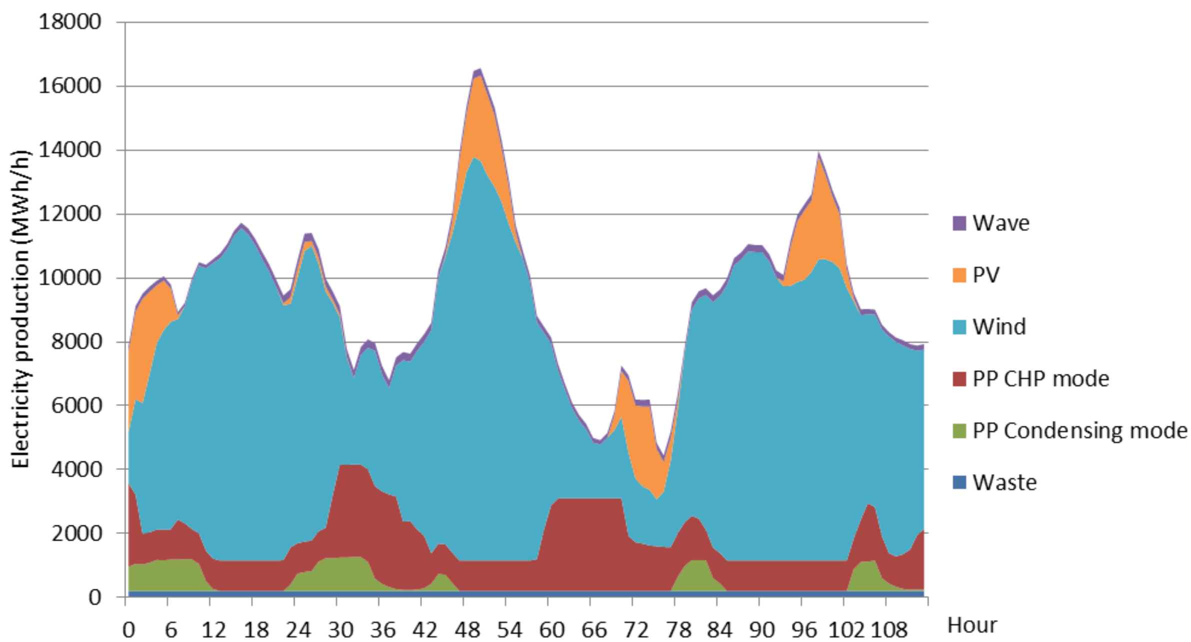


Figure 64: Hourly electricity production in the CFB Low Scenario in a selected period of time in the spring.

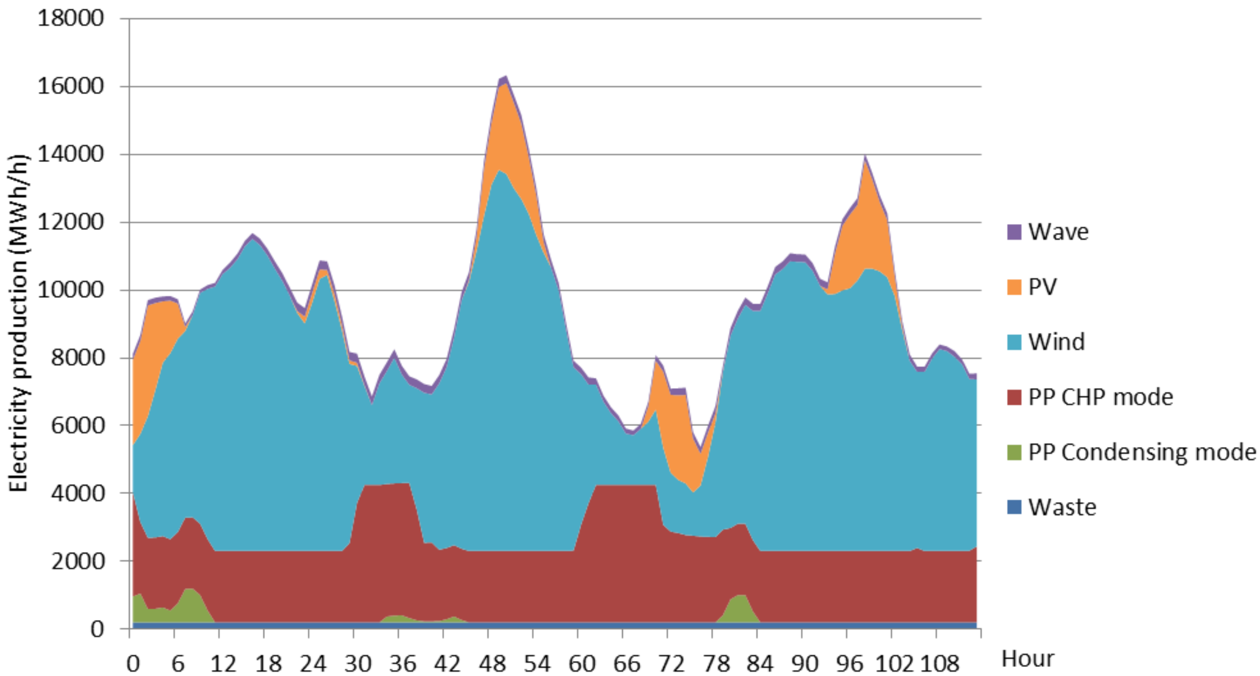


Figure 65: Hourly electricity production in the CFB High Scenario in a selected period of time in the spring.

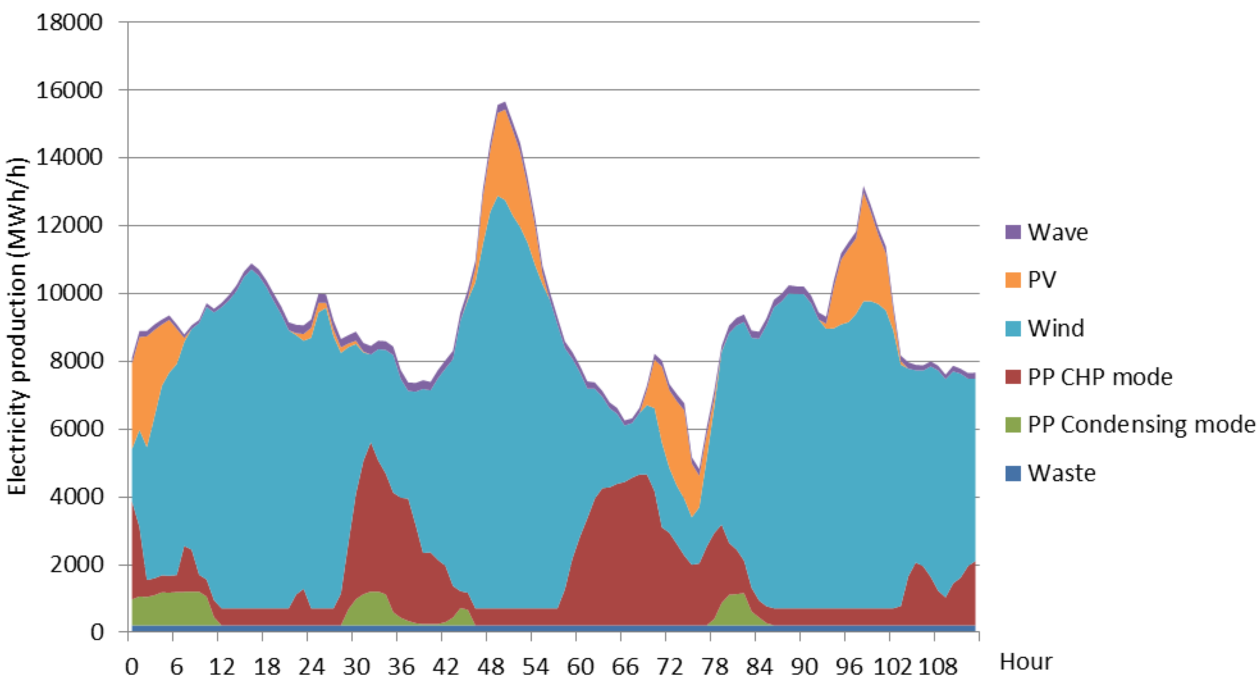


Figure 66: Hourly electricity production in the APF Scenario in a selected period of time in the spring.

As it can be seen from the figures, CCGT plants can regulate flexibly for fluctuating resources. The other power plant types have some amount of inflexible production and therefore allow a smaller amount of fluctuating resources in the systems.

Electricity Exchange Potential of the Scenarios

In this section, an analysis of the electricity exchange potential of the four scenarios is presented. The purpose of this analysis is to identify the potential economic benefit of selling and buying electricity on the electricity market of the different scenarios.

Methodological Considerations

The same scenarios as the ones in the technical analysis are analysed here and the market economic optimisation strategy is applied. This means that the production units in the systems are operated by the marginal production costs to cover the demand. This includes the possibility of import or export of electricity under conditions where this is economically favourable. The marginal costs include taxes on fuels and production facility type and they are used to determine the production price of each facility. According to this, the facilities are prioritized based on the lowest costs. The taxes are only included in determining the merit order of the plants and not in the total socioeconomic cost results of the scenarios.

In the market economic analyses, the handling of critical excess electricity has been changed to make the results of the scenarios easier to compare. The change removes the ability of large electrolysers to utilize excess electricity, but these still operate normally except for the excess electricity. The resulting biomass consumption is significantly higher for the systems without interconnection capacity. The increase is very similar for all the scenarios and does not change the relation between the scenarios, but only the level of costs and biomass consumption.

Here the scenarios are analysed with regard to different interconnection (IC) capacities to neighbouring countries. The 0 MW represents a system with no connection to other countries and 5,400 MW is the average traded capacity available today. A lower capacity (2,000 MW) and a higher capacity (8,000 MW) are included to show how different capacities influence the economy of the systems. The costs related to the infrastructure of the IC cables are not included in the analyses.

Different levels of electricity prices on the external electricity markets are included in the analysis:

- An average price level of 541 DKK/MWh
- A low electricity price level representing a “wet year” with a high amount of hydropower production in Norway and Sweden with an average of 359 DKK/MWh
- A high electricity price level representing a “dry year” with a low amount of hydropower production in Norway and Sweden with an average price of 972 DKK/MWh.

Hourly distributions of electricity prices from Nordpool-Spot, wind power production in Denmark, and electricity demand in Denmark from 2012 have been applied to all the analyses.

Different biomass prices are not directly included in this analysis, but the balance between the biomass prices and the electricity prices is important because this balance will determine in many situations if electricity should be produced in the system or imported from external markets. When the electricity price varies and the biomass price is fixed as in this study, this balance is changed. It is expected that the same tendencies can be seen if the biomass prices are increased, as when the electricity prices are reduced, but this is not shown here.

Scenarios for Electricity Exchange Analyses

The four scenarios are the same as in the technical analysis but with few minor changes to make the scenarios easier to compare. These are elaborated here.

The condensing power plant capacity has been increased in all the scenarios because under some of the modelled conditions, the consumption and potential export are larger than the production capacity in some hours. Therefore, an additional 6,000 MW condensing power capacity has been included. This is done in all scenario configurations to make these comparable. It does not change the relation between the other scenarios but increases the cost level of all scenarios.

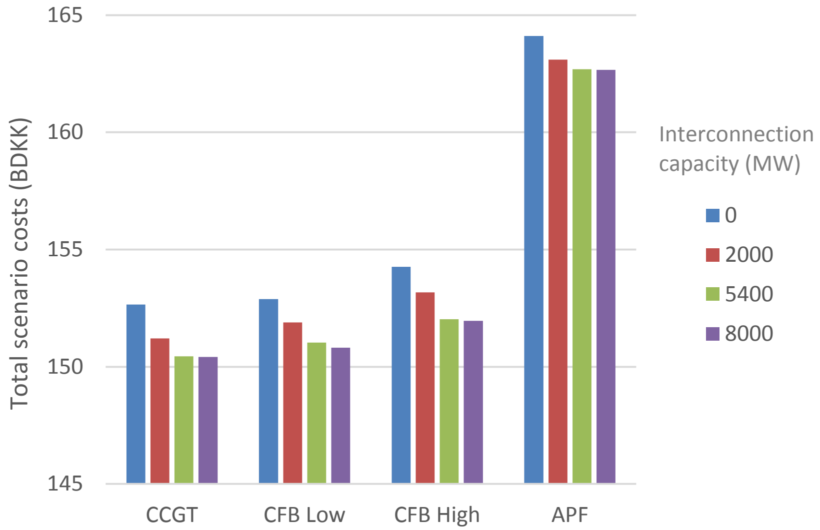
Another change to the original scenarios is that an economic constraint is added to the consumption of biomass at district heating boilers. This is done to limit the feasibility of the consumption of biomass for heat-only production and thereby reduce the biomass consumption, so that the total biomass consumption in the system reaches an acceptable level. The value applied is 57.8 DKK/GJ of biomass consumed in district heating boilers in 2050, which is added to the costs and taxes for biomass. The main change in the system is that the CHP benefit, and thereby the better fuel efficiency, is utilised much more with the constraint on biomass. The consequences of the economic constraint are elaborated for total scenario costs and biomass consumption in the following sections.

Scenario Costs with Electricity Exchange

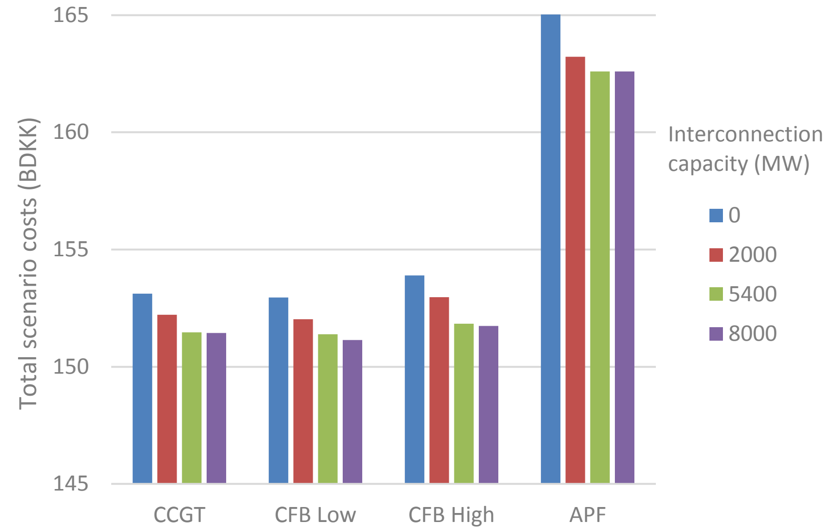
In Figure 67A-D, the development of the scenario costs with increasing IC capacities can be seen. The general trend is that the total costs decrease with increasing IC capacity until the point of 5,400 MW from where they stagnate. The costs are reduced with increased IC capacity because this allows the system to export electricity at times with higher external prices than the production costs, and import electricity in the opposite situation. The tendency stagnates because the number of hours left in which additional capacity can be utilised gets lower and lower.

Overall the least-cost option of the analysed systems is the CCGT scenario. As mentioned, an economic constraint has been added to biomass boilers in DH to reduce the biomass consumption to an acceptable level. In Figure 67A, the scenarios have been analysed with the biomass constraint, and in Figure 67B the same analysis has been performed, but having the biomass constraint removed. It can be seen that the CCGT scenario has lower costs with the biomass constraint, but in the situation in which it is removed, the CFB Low scenario would be the least-cost solution. It should also be noted that the total costs are lower in the system in which the biomass constraint is applied. For the CCGT in the situation without the biomass constraint, the biomass boilers supply most of the heat demand, but when it is applied, the CHP is much more feasible to run, which creates better fuel efficiency in the total energy system.

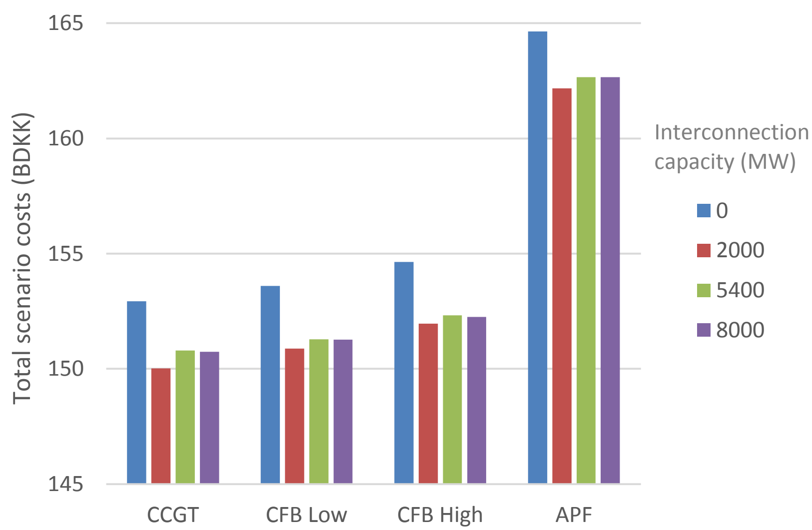
In the Figure 67C and D, the costs for the scenarios with different electricity prices on the external markets can be seen. For the high electricity prices, it can be seen that the capacity of 2,000 MW does not follow the trend of decreasing costs for increasing IC capacities. This is caused by bottleneck income because the differences in the prices are very large and the low IC capacity creates a bottleneck that generates a large income.



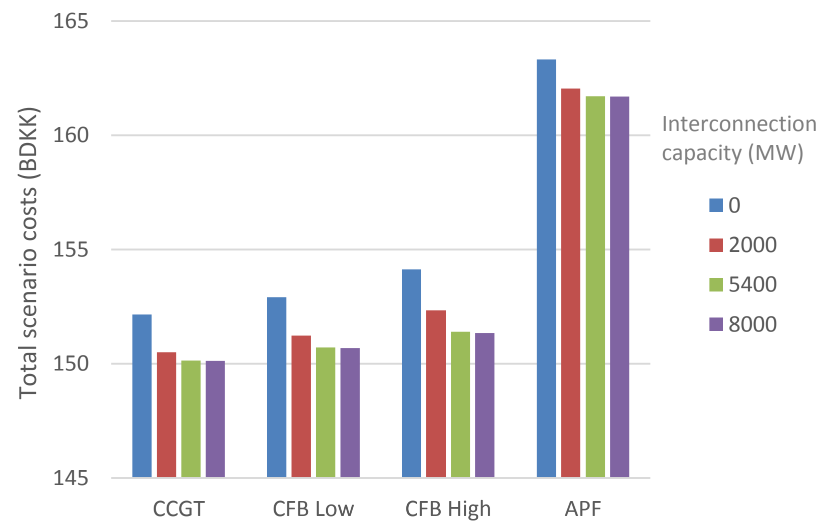
A: Standard external electricity prices



B: Standard external electricity prices without economic constraint on biomass boilers in district heating



C: High external electricity prices



D: Low external electricity prices

Figure 67: Scenario costs of the four scenarios simulated with market economic optimisation and with four different IC capacities.

For the larger IC capacities, the bottleneck situations are much fewer and here the incomes are not significant. In the case of the low electricity prices, the bottleneck income is not enough to compensate for the larger IC capacity from 2,000MW to 5,400MW.

It can be seen in Table 11 that both in the case of higher electricity prices and of lower electricity prices, the CCGT scenario is the least-cost option. The table shows the results for 5,400 MW IC, but this applies to all IC capacities, which underlines the recommendation of the CCGT scenario.

Table 11: Comparison of scenario cost of the scenarios for different external electricity price levels at 5,400MMW IC capacity.

(BDKK/year)	Standard	High	*Change*	Low	*Change*
CCGT	150.4	150.8	0.4	150.1	-0.3
CFB Low	151.0	151.3	0.3	150.7	-0.3
CFB High	152.0	152.3	0.3	151.4	-0.6
APF	162.7	162.7	0.0	161.7	-1.0

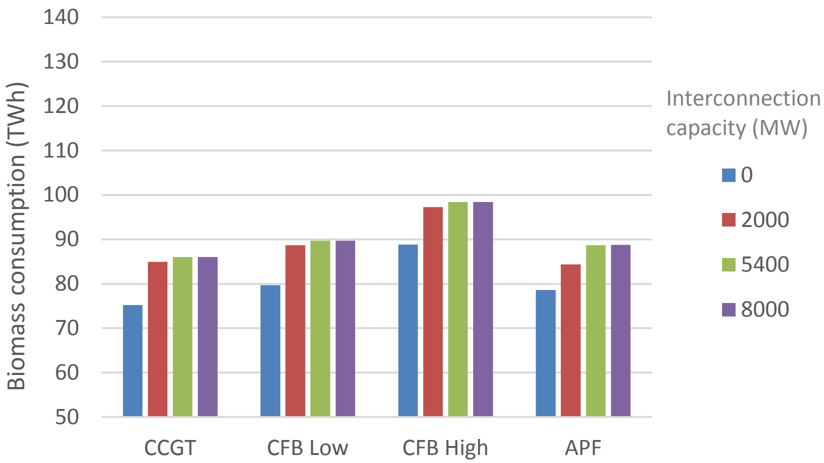
Biomass Consumption with Electricity Exchange

The biomass consumption is closely related to the amount of electricity that is exported from the system. For example, if the external prices are high, it may be feasible to produce more electricity with CHP or condensing power plants in the system to export it and thereby consume more biomass inside the system. In this case, another fuel or energy source at a power plant is replaced and thereby the fuel or energy consumption at this place will be reduced. Opposite if the external electricity prices are low and electricity is imported, biomass in the system is replaced with another source at a power plant outside the system.

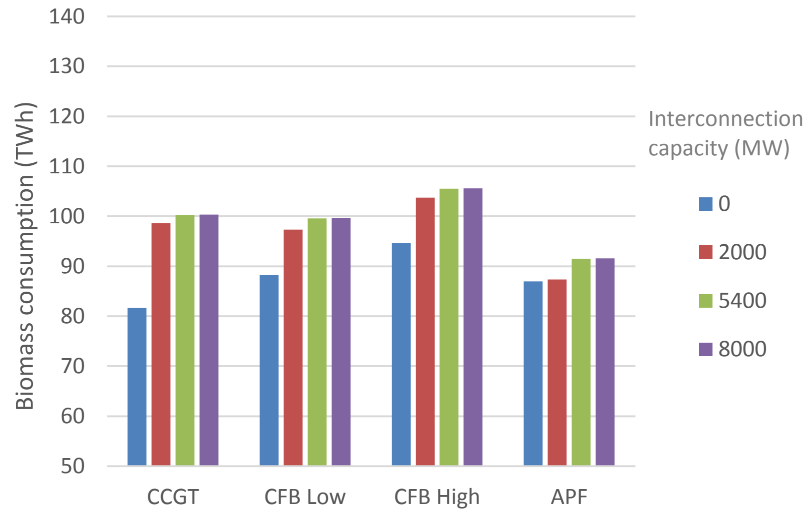
It is therefore important to notice the biomass consumption at 0 MW IC capacity because this indicates the fuel efficiency of the particular scenario configuration. Here only the demand inside the system is covered and not demands elsewhere. This is to have a point of reference because all scenarios will behave differently in relation to the external electricity market, but the systems with no IC capacity can easily be compared.

As it is explained in the above sections, the biomass constraint applied has an impact on the systems and limits the biomass consumption. In Figure 68A, the scenarios are presented for the different IC capacities with the biomass constraint, and in Figure 68B, the same analysis can be seen without the constraint. Here it can be seen that the biomass consumption is significantly higher in the configurations without the biomass constraint. This is mainly due to the increased operation of the biomass boilers because of the lower feasibility of using CHP.

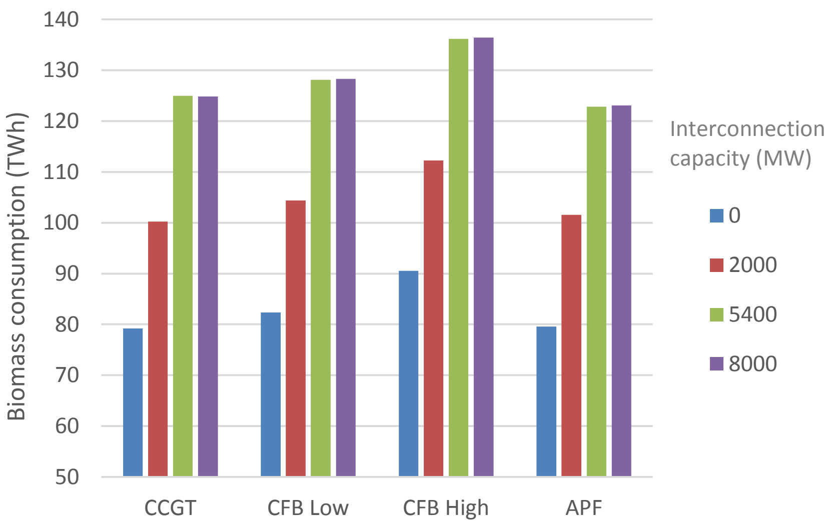
In Figure 68C, it can be seen that the biomass consumption increases dramatically with increased IC capacity until 5,400 MW. The increase is caused by the increased export of electricity from the system. The opposite tendency can be seen in Figure 68D where the consumption of biomass is reduced with increasing IC capacity because the system imports more electricity instead of generating it as that is more profitable.



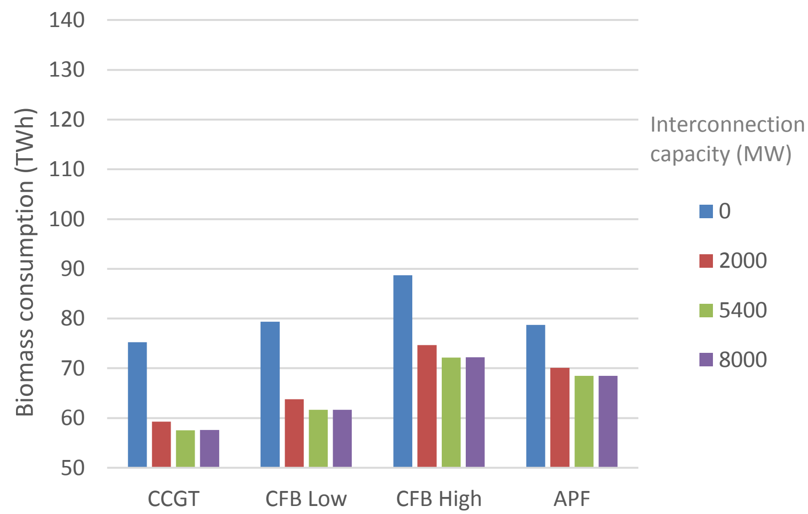
A: Standard external electricity prices



B: Standard external electricity prices without economic constraint on biomass boilers in district heating



C: High external electricity prices



D: Low external electricity prices

Figure 68: Biomass consumption of the four scenarios simulated with market economic optimisation and with four different IC capacities.

It can be seen that the biomass consumption for the CCGT is lowest in all the scenario configurations with biomass boiler constraint including the configurations with 0 MW. This indicates that the CCGT scenario operates most fuel efficiently with both higher and lower electricity prices. Only the APF scenario with high prices with an average of 972 DKK/MWh and an IC capacity at 5,400 MW and above uses marginally less biomass, which is caused by the poor ability to trade and therefore lower export in this scenario.

Electricity Trade Balance and Net Trade Benefit

The electricity trade balance presented in Figure 69 shows how much the different scenarios import and export in terms of costs and income, respectively. Together with the total reduction in scenario costs achieved by introducing electricity trade, it can be assessed how the different systems are able to utilise either high or low price levels.

In Figure 69A, it can be seen that all of the scenarios export more than they import. Import and export are almost the same in the first three scenarios, but the APF scenario exports a bit less and imports a bit more than the others. This is caused by the relatively high production costs of this scenario and can also be seen in a lower net trade benefit. The net trade benefit of the CFB Low scenario is lower than in the CFB High scenario because the system generates less excess electricity and therefore has a lower export potential. The total scenario costs of the CFB Low scenario remain lower (see Figure 67A).

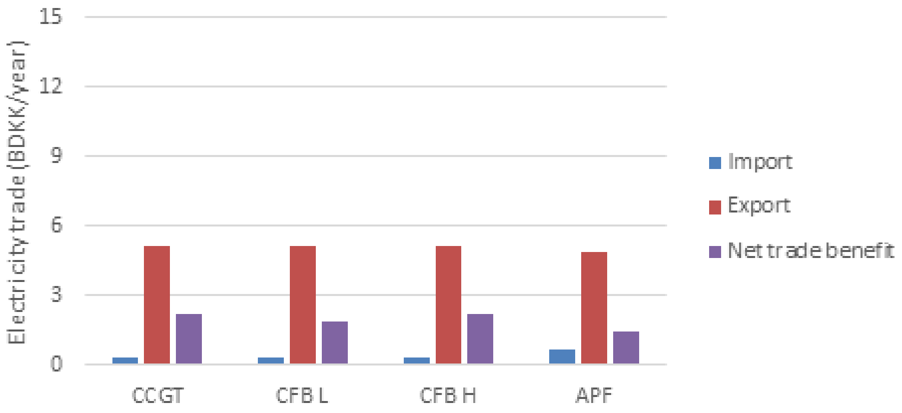
In Figure 69B, it can be seen that with the high electricity prices, the export almost triples for all of the scenarios and the import is reduced to almost nothing. Here there is a tendency that the CFB scenarios will save more on the trade that the CCGT and the APF scenarios, but the CCGT remains the overall least-cost scenario. In case of the low electricity prices, which can be seen in Figure 69C, the import of electricity is larger than the export in all of the four scenarios. The export is larger in the CFB Low scenario than in the CCGT and even larger in the CFB High. In these systems, there is a large fixed production of electricity and some parts of this which is excess electricity without IC capacity is here exported. This is also the reason why the net trade benefit is larger for the CFB scenarios, but the total scenario costs remain higher than the CCGT scenario as seen in Figure 67D.

Conclusion and Relevance for Copenhagen

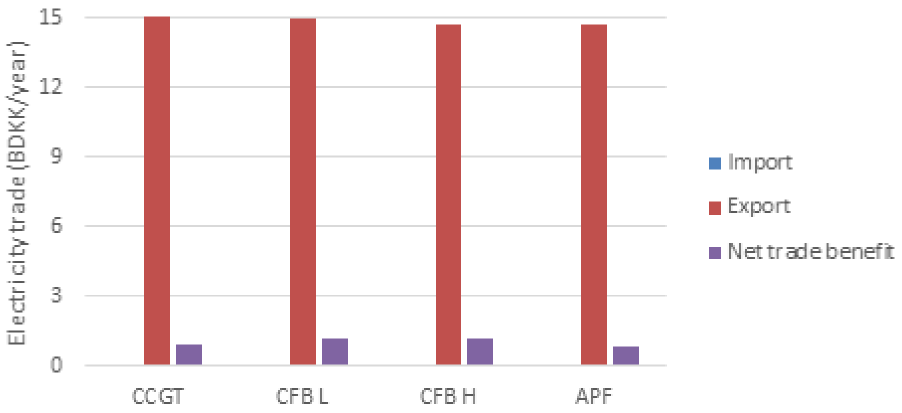
From the analysis of electricity exchange, two main conclusions can be drawn:

1. Using marginal price signals alone without any consideration of limiting the use of biomass boilers does not enable least-cost solutions and increases the biomass consumptions.
2. CCGT CHP plants are more efficient and adapt to operation under different conditions, and the scenario is the least-cost option in all analysed contexts.

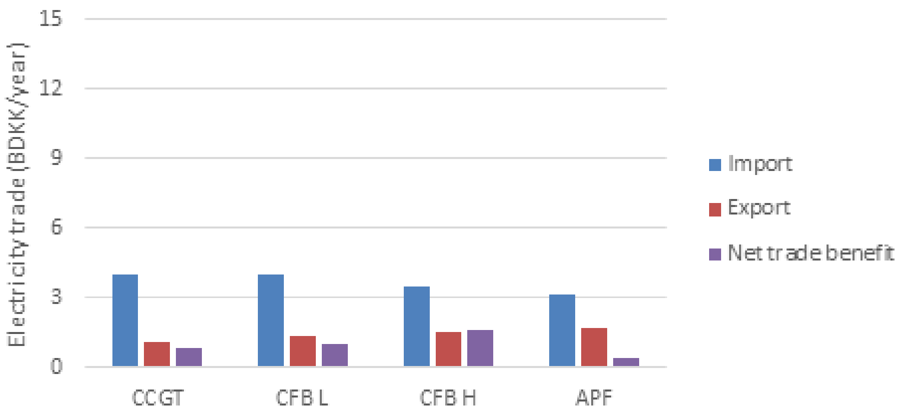
If the biomass consumption is left to be regulated, the biomass consumption will only increase significantly by the marginal price signals on electricity and heat markets with no limits on the use of boilers. This is due to the marginal difference between shifting from heat production with a biomass boiler to using the biomass in a CHP to produce the same heat and additional electricity. This conclusion is in general not sensitive to high or low prices on the electricity markets, but only tied to the relation of costs between using the boiler and the CHP. In order to achieve a least-cost solution (and also limit the use of biomass), the biomass consumption should be limited by some an economic constraint. If this is not done, the overall system costs in all scenarios will increase. In case the boilers are left unregulated, the CFB Low scenario has marginally lower costs than the CCGT scenario.



A: Standard external electricity prices



B: High external electricity prices



C: Low external electricity prices

Figure 69: Economic costs and income for the import and export of electricity and the economic net trade benefit of the trade in the four scenarios with an IC capacity of 5,400MW. The net trade benefit is the reduction in total scenario costs compared to the system without IC capacity.

The CCGT scenario is the least-cost option with the current interconnector (IC) capacity, with lower capacity and with higher capacity. This means that the conclusion and recommendation of applying the CCGT system, from the technical analysis, is solid to future changes in IC capacity.

It can also be concluded that the CCGT scenario is the least-cost scenario in the cases of both high and low electricity price levels. This due to the high system flexibility and higher overall efficiency of the CCGT scenario and its ability to utilise both high and low prices better than the other scenarios. The recommendation to use CCGT technology is also solid to changes in electricity prices.

From Copenhagen's perspective, the possibility of changes in the IC capacity and in the electricity prices on the electricity markets is important to the feasibility and economy of power plants in the future. This analysis underlines that the CCGT power plants are recommendable for sustainable and renewable energy systems even if external conditions change

Appendix 5 Gasification State-of-the-Art

This Appendix is based on the report Ridjan et al. [78] on biomass technologies in Denmark and Sweden. The report includes a more detailed technical presentation of the different technologies and their status in neighbouring countries.

Gasification Technology in Denmark

Denmark has a history in gasification development strategies and it can be said that Denmark is advanced in gasification technologies compared to many other countries. A new updated version of the biomass gasification strategy dates from 2011 [79]. The Danish government goal for a 100% renewable energy system in 2050 has created more interest and encouraged further investments in biomass gasification technologies for different purposes and demonstration plants.

Table 12. Danish gasification stakeholders and their area of operation, adapted from [78].

Stakeholder/Technology group companies	Area of operation	Website
Ammongas A/S	Pilot and demonstration plants	www.ammongas.dk
Babcock&Wilcox Vølund	Demonstration and market introduction	www.volund.dk
BioSynergi Proces ApS	Demonstration plant, developing and marketing	www.biosynergi.dk
Dall Energy A/S	R&D, consultancy on demonstration plants	www.dallenergy.com
Danish Fluid Bed Technology ApS	Consultancy and R&D	-
DONG Energy	R&D, pilot and demonstration plants	www.ltcfb.com , www.pyroneer.com
Haldor Topsøe	R&D, pilot and demonstration plant and market introduction	www.topsoe.com
Organic Fuel Technology	Pilot plant (R&D and demonstration plants are part of the vision)	www.organicfueltechnology.com
TK Energy ApS	Development projects, demonstration plants	www.tke.dk
Weiss A/S	Demonstration plants	www.weiss-as.dk
Skive Fjernvarme I/S	CHP plant operation	www.skivefjernvarme.dk
AAEN Consulting Engineers A/S	Consultancy on demonstration plant	www.aaenas.dk
Danish Gas Technology Centre	Research and development	www.dgc.dk
Danish Technological Institute	Education, R&D, pilot and demonstration plant	www.teknologisk.dk
FORCE Technology	RD&D, feasibility studies, market studies	www.forcetechnology.com

During the last few years, the focus expanded from heat and power production to a wide spectrum of applications of gasification technologies such as fuel production, using gasifiers as a balancing agent in the system and combining gasifiers with fuel cells. The new Strategy is therefore concentrating more on the different R&D efforts relating to gasification so the governmental goals can be reached.

The first gasification project started in 1988, and many years of research and development resulted in two developed gasification concepts that are internationally recognized: a two-stage process that can produce tar-free gas and the Pyroneer technology that can gasify straw and fertilizer. The gasification technologies in Denmark cover a wide range of gasifiers, from small-scale to large-scale CHP plants for district heating. These are at different levels of development ranging from the research and development stage, pilot and demonstration phase, to commercially available technologies. A number of stakeholders are involved in this technology as it can be seen in Table 12.

Biomass Gasification Research and Development

Biomass gasification research and development is quite active in Denmark with five main actors involved: Danish Gas Technology Centre (DGC), Danish Technological Institute (DTI), DTU Chemical Engineering and Biomass gasification group and Force Technology. An overview of their research focus can be seen in Table 13.

The Danish Gas Technology Centre (DGC) is working on the gasification development in close connection with bio-SNG production. Their research focus during recent years has been on the possibility of using bio-SNG in the natural gas grid and the socio-economic and financial aspects of it [80]. They have an increased focus on green energy gases such as biogas, hydrogen and gasified biomass for the development of sustainable gas technology.

The Danish Technological Institute (DTI) has two lab scale projects with pyrolysis and gasification, but their work is also concentrated on the development of new gas cleaning technology. They have been focusing on the development of test reactors for the catalytic decomposition of tar for the existing gasification plants in Denmark (Skive, Harboøre and Græsted). This technology has a potential to be commercialized as they closely collaborate with developer Haldor Topsøe.

The Department of Chemical Engineering, Centre for Harmful Emission Control (CHEC) and the Biomass Gasification group at the *Technical University of Denmark (DTU)* are working with a spectrum of activities such as the development of the circulating fluidized bed gasification, small-scale gasification for heat and power production, the combination of gasification and fuel cells for CHP purposes, and the production of liquid fuels from syngas generated via biomass gasification (mainly focusing on the development of the catalysts).

FORCE Technology is a national team leader for an IEA BioEnergy Task 33 on thermal biomass gasification. FORCE Technology has participated in several biomass gasification development projects and has developed the Danish biomass gasification strategy. FORCE Technology is a well acknowledged international partner on large RD&D projects on gasification.

Table 13. Main research organisations in Denmark and their research focus, adapted from [78].

Organisation	Research focus	Website
Danish Gas Technology Center (DGC)	Production of bio-SNG	www.dgc.dk, www.dgc.eu
Danish Technological Institute (DTI)	CHP generation and fuel production	www.dti.dk
Danish Technical University (DTU)	Entrained flow and fluidized bed gasifiers, fuel production, biomass pre-treatment	www.dtu.dk, www.chec.kt.dtu.dk
FORCE Technology	National team leader Task 33 on biomass gasification, RD&D, strategic consultancy, feasibility studies, market studies	www.forcetechnology.com

Overview of Danish gasification plants and pilot projects

The gasification technologies in Denmark are listed in Table 14, including the type of gasifier, its purpose, and the development stage. The most important gasifier plants are described in this section.

The oldest operating gasifier in Denmark is in Harboøre, **Harboøre Varmeværk**. The production started in the end of 1993 and in the last 12 years, it has operated in CHP mode, covering almost all of the heating demand of the city through district heating. The updraft moving bed wood chip gasifier has 3.5 MW fuel input with 1 MW_{el} and 1.9 MW_{th} output in CHP mode [81]. With more than 120,000 operating hours, the gasifier is supported by the Danish Energy Agency [82].

BioSynergi pilot plant in Græsted is a demonstration open core fixed bed wood chip gasifier plant commissioned in 2003. It has an electrical output of 75 kW and a thermal output of 165 kW. It is used as a core for the development process of large-scale CHP systems [83]. Together with Hillerød Bioforgasning P/S, the BioSynergi Proces ApS is constructing a new demonstration plant for combined heat and power in Hillerød. The plant is a staged open core gasifier fuelled with forest wood chips coupled with an IC engine with a CHP capacity of 750 kW_{th} and 300 kW_{el} [84].

Skive Fjernvarme plant is a single bubbling fluidized bed (BFB) gasifier fuelled with wood pellets or chips and producing gas for combined heat and power. The maximum fuel input to the plant is 28 MW and it can produce 6 MW_{el} and 11.5 MW_{th} for district heating [85]. Technical University of Denmark developed a two-stage wood chip gasifier called **Viking plant** and it was commissioned in 2002. The gasifier has 75 kW of fuel input, with 17.5 kW_{el} and 39 kW_{th} output [86]. This concept was commercialized by Weiss A/S and up-scaled to three different sizes: a 200 kW input facility in Hadsund, the 500 kW unit in Hillerød connected to the electricity grid and district heating grid, and a 100 kW plant which is still not implemented [87].

The Pyroneer is a 6 MW_{th} demonstration gasifier plant fired with straw, manure fibres or local residue. It was commissioned in the spring of 2011 in Kalundborg near the Asnæs power plant. The capacity is 1.5 tons/hour with 95% thermal efficiency (based on fuel input and losses) and it operates at lower temperatures than normal gasifiers [88]. Even though the project was planned to be expanded with a 50 MW plant in 2015 and it could potentially reach up to 150 MW in the future [89], the decision of stopping the expansion was released at the end of October 2014 [90]. As the reason it was stated that there was a lack of outside funding for the upscaling of the project.

Table 14. Gasification technologies in Denmark, adapted from [78].

Gasifier name / Location	Stakeholder/ Technology owner/ Developer	Production start	Type of gasifier	Thermal fuel power MW_{th} or CHP capacity	Fuel type	Purpose	Development stage	Reference
Harboøre Varmeværk / Harboøe	Babcock & Wilcox Vølund and Harboøre Varmeværk	1993	Updraft gasifier with combined heat and power	3.7	Wood chips	District heating	Commercial DH plant	[81]
BioSynergi CHP plant / Hillerød	BioSynergi Proces ApS/ Hillerød Bioforgasning P/S	2013/2014	Staged open core gasifier	1.3 / 0.3 MW_{el}, 0.75 MW_{th}	Forrest wood chips	Power and heat production	Demo / under construction	[91-93]
Skive Fjernvarme/Skive	Aæn A/S	2011	Carbona fluidized bed CHP	28	Wood pellets	District heating	Commercial	[85]
Viking/ Roskilde (Risø)	DTU	2002	2 stage gasification plant	0.07	Wood chips	Heat and power production	Demonstration	[86]
Two stage /Hillerød	Weiss A/S	2011	2 stage gasification	0.5 MW_{el}, 0.9 MW_{th}	Wood chips	Heat and power	Demo/Commercial	[87]
Not in operation or with unknown status due to company closure								
Pyroneer / Kalundborg	DONG Energy	2011	Low temperature circulation fluidized bed	6	Straw	Co-firing coal boiler	Demonstration	[89]
Barrit / Barrit	*Stirling DK*	*2010*	*Updraft gasifier with one Stirling engine*	*0.2 / 0.035 MW_{el}, 0.14 MW_{th}*	*Wood chips*	*Heat and power*	*Commercial*	*[94]*
Close coupled Gasification / Næstved	*EP Engineering ApS*	*2010*	*Vibrating grate fluidizeed bed*	*-*	*Wood chips*	*Heat and power*	*Pilot*	*[95]*
DTU/ Lyngby	*Stirling DK*	*2009*	*Updraft gasifier with one Stirling engine*	*0.2 / 0.035 MW_{el}, 0.14 MW_{th}*	*Wood chips*	*Heat and power*	*Commercial*	*[96]*
BioSynergi CHP plant / Græsted	*BioSynergi Proces ApS*	*2003*	*Continuous open core gasifier*	*0.325*	*Forrest wood chips*	*Power and heat production*	*Pilot*	*[83]*

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