Copenhagen Energy Vision

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

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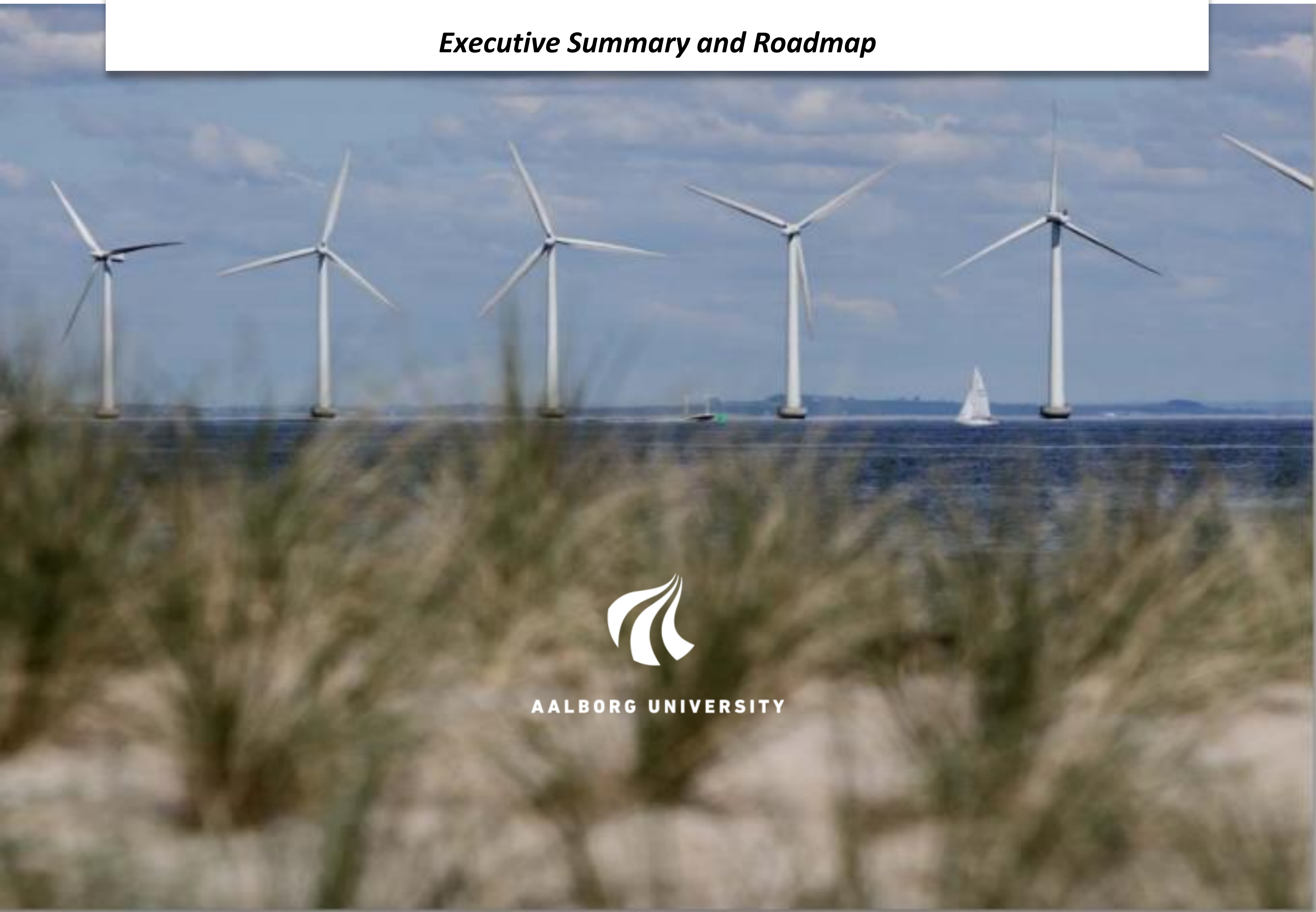

AALBORG UNIVERSITY

COPENHAGEN ENERGY VISION 2050
A sustainable vision for bringing a capital to 100% renewable energy

Executive Summary and Roadmap

March, 2015

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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).

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 million[1]. 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.

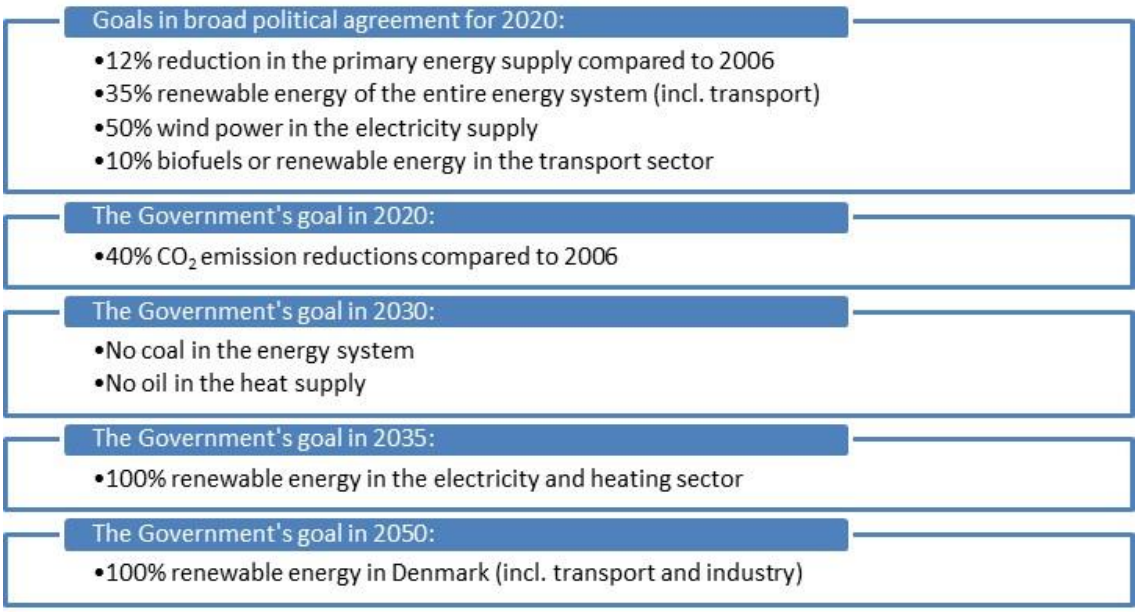

Figure 1: Important goals in the Danish future energy planning process.

[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).

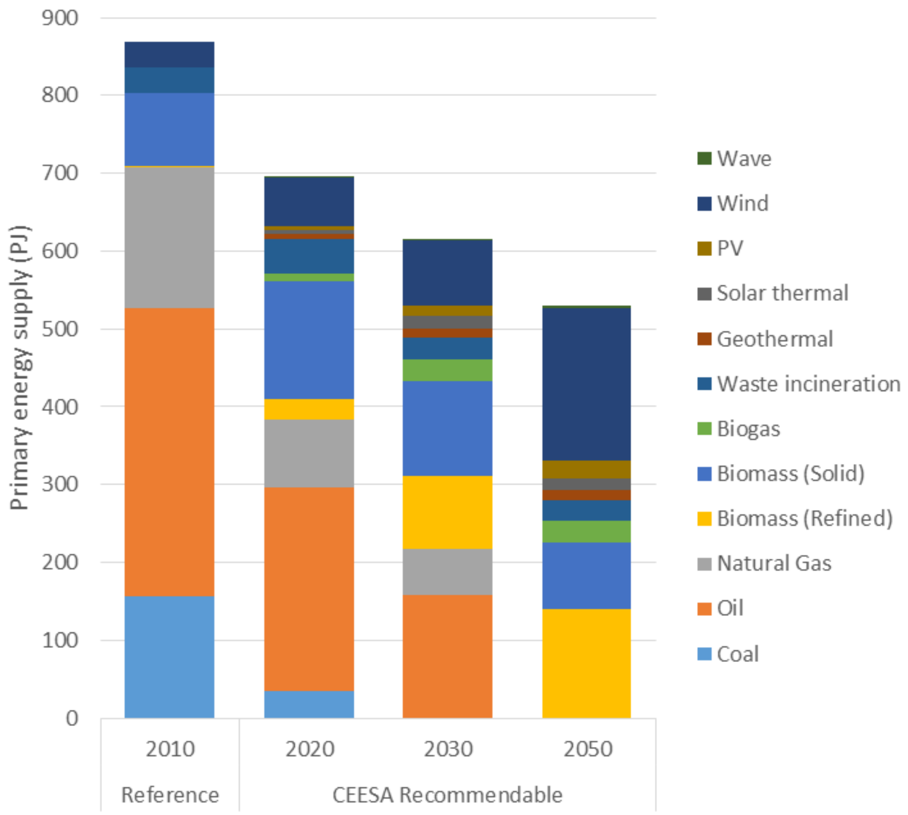

Figure 2: The primary energy supply for Denmark in 2010, in the CEESA Recommendable scenario.

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.

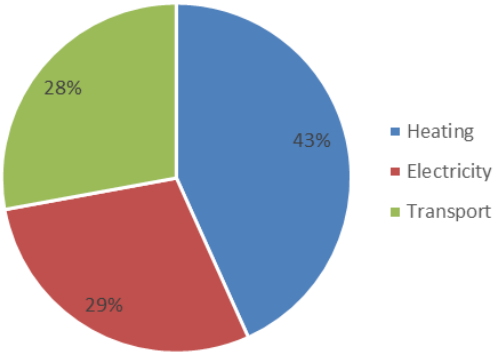

Figure 3: Shares of energy consumption in the three categories: Heating, electricity and transport for The City of Copenhagen in 2011. Main references: [11] and [12]. Calculations and references are elaborated in Appendix 1.

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.

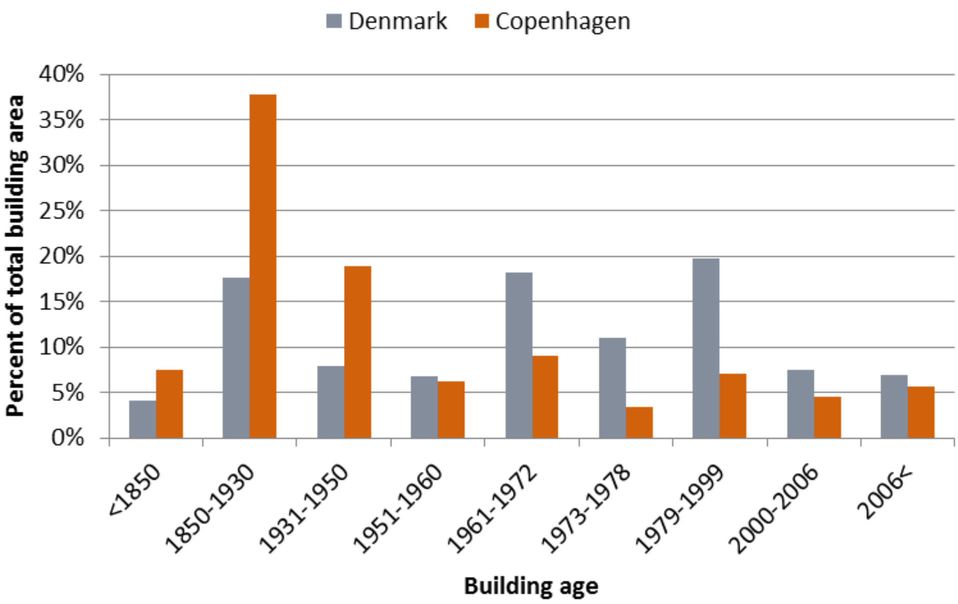

Figure 4: Shares of the building stock divided into intervals of the age of the building for Denmark and The City of Copenhagen, respectively (The percentage of building area relates to the floor area).

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.

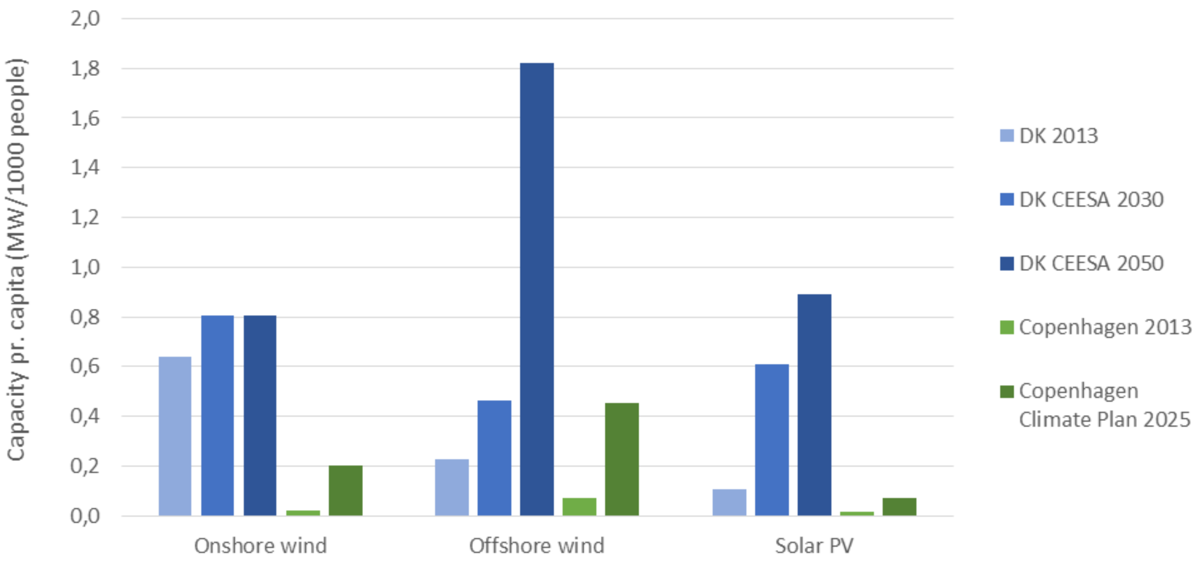

Figure 5: Capacity per capita of onshore wind, offshore wind and solar PV under five conditions. The DK and The City of Copenhagen 2013 values are historical data; the CEESA scenarios are the values from the CEESA scenario analysis, and the Copenhagen Climate Plan 2025 is the planned capacities for 2025 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 (see Table 1). 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.

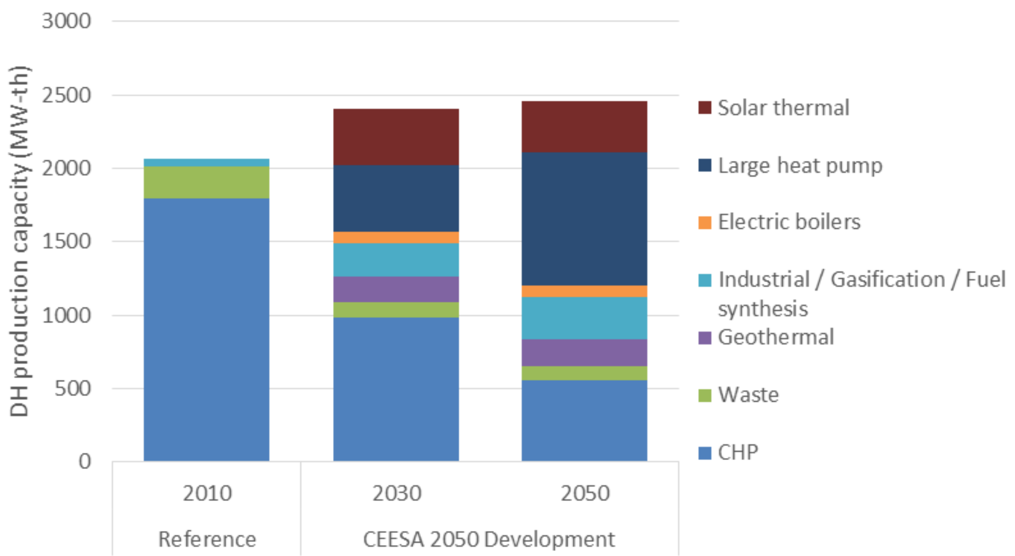

Figure 6: Heat production capacities in The Greater Copenhagen Areas assessed on the basis of the national average and assuming that the development in CEESA is reflected in The Greater Copenhagen Area. Fuel boilers are not included in this figure, but it is assumed that they are able to cover the expected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

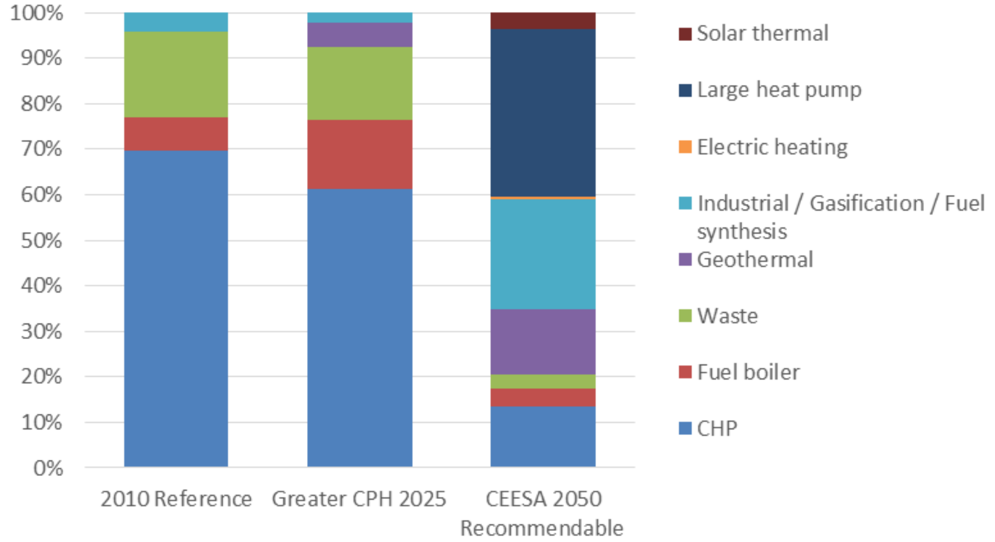

Figure 7: District heating production composition in central CHP areas in the 2010 Reference and in the CEESA 2050 Recommendable Scenario compared to a system model of the initiatives in the CPH 2025 Climate Plan.

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.

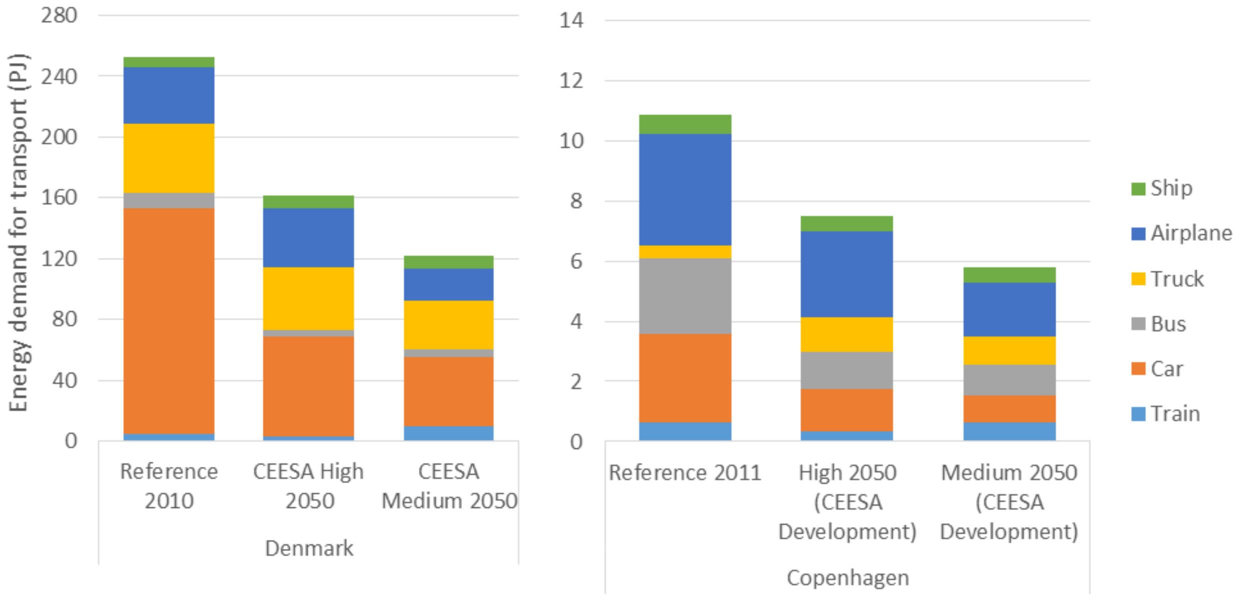

Figure 8: Energy consumption for transport in Denmark and The City of Copenhagen in 2011 and CEESA 2050 divided into means of transport.

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.

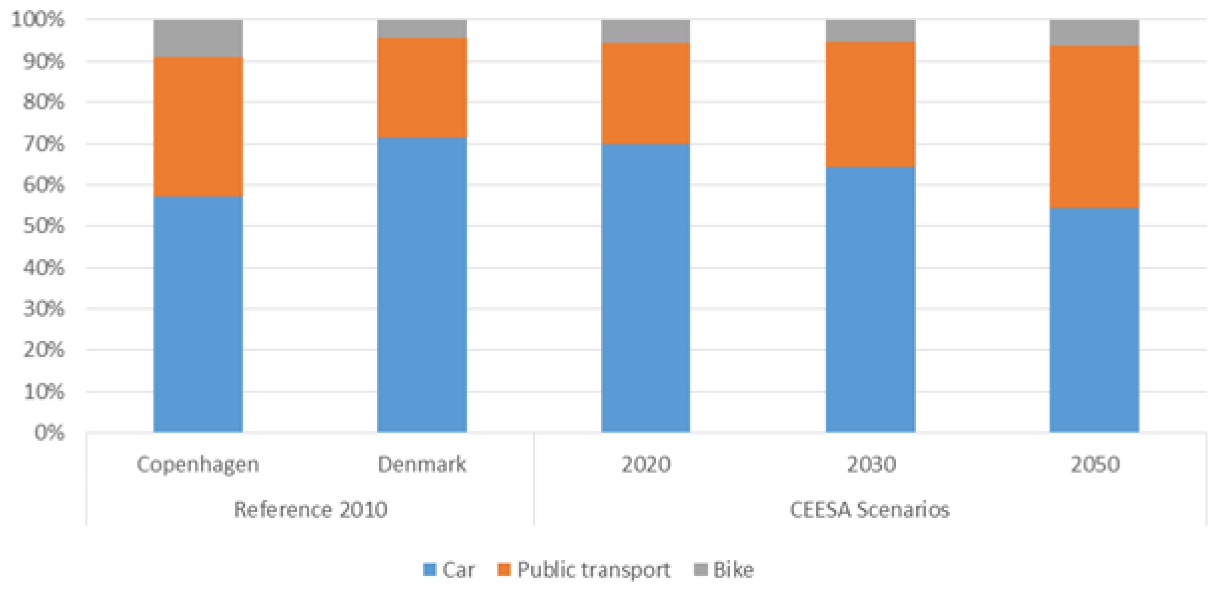

Figure 9: Shares of passenger transport in Copenhagen and Denmark in Reference 2010 and in the CEESA scenarios for 2020, 2030 and 2050 (Here Copenhagen includes the municipalities of Copenhagen, Frederiksberg, Gentofte, Gladsaxe, Herlev, Rødovre, Hvidovre, Tårnby and Dragør).

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.

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