Roadmap to 2050

A recommended future Danish energy system and guidelines for policy changes

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10th semester

Master of Science
in
Energy Technology

Master Thesis

May 22nd, 2017

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SDU

Printed by: Print & Sign, SDU
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“The aim of this study is to provide recommendations for policy decisions on how to change the regulatory incentive structure in Denmark to better achieve long-term political targets related to renewable energy implementation and greenhouse gas emission reduction.”

Abstract

Denmark is committed to the fight against climate change on both national and international levels. The country has a long-term target of becoming a *low emission society* by 2050, also defined as a highly resource efficient society. We argue in this report that there is an urgent need for policy-makers to decide on a common strategy for the future energy system development in both the short- and long-term. An early adoption of a common direction will enable the cross-sectoral development of technologies that complement each other well, rather than risking that too many resources are invested in technology capacities, which reduce the possibility of a least-cost development for society.

In this report, we use a partial equilibrium energy system model called TIMES-DK to investigate the expected development of the Danish energy system under a *Frozen Policy* scenario, i.e. with no changes to the existing regulatory framework. Based on this analysis, we estimate that the energy system will remain responsible for around 15 million ton of CO_2 emissions per year in 2050, thereby not achieving the 2050 target. This emission level corresponds to a reduction of 72 % compared to 1990 level.

We proceed to construct a recommended energy system for 2050 using TIMES-DK, which is in compliance with the 2050 target. This is called the *R2050* scenario. We recommend an energy system characterized by a large degree of electrification across all sectors, where especially electric heat pumps and hybrid plug-in vehicles play a key role. Electricity should be produced from intermittent renewable energy sources, district- and residential heating should be produced by heat pumps and solar heating, and the transport- and industry sectors should use biofuels and electricity.

Lastly, we provide recommendations for policy changes, which can guide Denmark in the direction of the *R2050* scenario, and hence a full compliance with the 2050 target. We identify 8 changes, which combined is expected to increase the capacity of offshore wind, increase domestic production of biofuels, transition the heating sector towards electric heat pumps and excess heat, and convert the entire transport sector to electricity and biofuels.

Preface

The motivation for this study has been to provide to the Danish energy sector and policy makers, what we believe is missing in the debate on how to structure the Danish energy system in the process of transitioning to a low emission society. Throughout our studies at The University of Southern Denmark, we have worked with the energy scenarios set forth by the Danish Energy Agency in their report "*Energy scenarios for 2020, 2035 and 2050*". In this report, they provide potential scenarios for the future energy system, but do not consider the instruments required to realize the scenarios. We hope by presenting the results in this report to contribute with concrete suggestions for changes to the existing regulatory incentive structure, which will guide Denmark towards a future energy system without fossil fuels.

Getting access to a tried and tested energy system model was paramount to the success of this project. We would therefore like to thank Kenneth B. Karlsson, Olexandr Balyk and the rest of the Energy Systems Analysis Group at DTU Management Engineering for helping us get access to the TIMES-DK energy system model and providing important guidance throughout the process of this project.

This Master Thesis was carried out by Jannick H. Buhl, Asbjørn Z. Hegelund and Mikkel B. Simonsen at the Maersk Mc-Kinney Moller Institute at the Faculty of Engineering, University of Southern Denmark during the final semester of the M.Sc. in Energy Technologies program. The study was carried out during the spring of 2017. The report and preceding analysis has been made in collaboration between all students, but the following overall responsibilities have been assigned:

Jannick H. Buhl has been main responsible for understanding and modelling in TIMES-DK.

Asbjørn Z. Hegelund has been main responsible for developing the new incentive structure.

Mikkel B. Simonsen has been main responsible for understanding the existing incentive structure.

The supervisors are Henrik Wenzel, professor at the Department of Chemical Engineering, Biotechnology and Environmental Technology at the Faculty of Engineering, University of Southern Denmark and Niels Erik Holm Nannerup, Ph.D. and lecturer at the Department of Business and Economics at the Faculty of Business and Social Sciences, University of Southern Denmark.

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Glossary and abbreviations

Abbreviation	**Meaning**	**Danish translation**
	Climate Law	Klimaloven
	Government Program	Regeringsgrundlag
BF17	Baseline Projection 2017	Basisfremskrivningen 2017
CHP	Combined Heat- and Power plant	Kraftvarme anlæg
DEA	Danish Energy Agency	Energistyrelsen
ETS	Emission Trading System	CO_2 kvote markedet
DCCC	Danish Council on Climate Change	Klimarådet
GHG	Greenhouse gas	Drivhusgas
DH	District heating	Fjernvarme
IH	Individual heating	Individuelle varmebehov
FP	Frozen Policy	
IS	Incentive Structure	Incitamentsstruktur
R2050	Recommended 2050	Anbefalet 2050
RE	Renewable energy	Vedvarende energi
DMT	Danish Ministry of Taxation	Skatteministeriet

Executive summary

Climate- and energy policy targets for Denmark

Denmark is committed to the fight against climate change on both national and international levels. The country has a long-term target of becoming a *low emission society* by 2050, also defined as a highly resource efficient society. Denmark is well underway with this challenge in the electricity- and heating sectors, with more than 42 % electricity from wind in 2015 and more than 50 % renewable energy in district heating in 2016. However, the transport sector is lacking behind with 95 % of fuel consumption today being fossil fuels.

Urgent need for a common strategy

There is an urgent need for policy-makers to decide on a common strategy for the future energy system development in both the short- and long-term. The electricity supply is moving towards more wind power, while the heating sector is seeing a large increase in bioenergy technologies. This combination does not take advantage of the potential system benefits. An early adoption of a common direction will enable the cross-sectoral development of technologies that complement each other well, rather than risking that too many resources are invested in technology capacities, which reduce the possibility of a least-cost development for society.

The Danish Energy Agency estimate that investment in new renewable capacity will stagnate after 2020 under the existing regulatory framework, resulting in a likely increase in greenhouse gas emissions towards 2030. This expected development strongly points to a need for policy makers to agree on a direction for the mid- to long-term energy system development well before 2020. Furthermore, the energy supply and industrial sectors need a stable direction and regulation in order to limit their risk on investment. An unstable regulatory framework increases investment risk, which is directly transferred to higher requirements for investment returns. This increases the overall cost of transitioning to a 100 % renewable energy system.

Providing policy recommendations using scenario modelling

We use TIMES-DK for providing recommendations for the future energy system development and policy changes. TIMES-DK is a partial equilibrium energy system model based on the ETSAP TIMES code covering all sectors in the Danish energy system. The model is developed and maintained in a collaboration between DTU ME and the Danish Energy Agency. In short, "*a TIMES run configures the energy system of a set of regions, over a certain time horizon, in such a way as to minimize the net total cost of the system, while satisfying a number of constraints*". (Loulou, et al., 2016)

This report attempts to provide clarity on three key objectives

1

Will we reach the 2050 target under current energy policy?

First, we try to answer this key question by simulating the development of the energy system until 2050 in the TIMES-DK energy system model under a frozen policy scenario. The projected development will provide a good indicator for what decisions will be taken by individuals and companies in the future, if the regulatory framework remains unchanged.

2

We propose a future energy system for 2050

Second, using the TIMES-DK energy system model, we construct an energy system based on renewable energy for 2050, which is both cost-efficient and sustainable in the long-term. In this scenario, called the *R2050* scenario, we give the model "free hands" to construct a low-cost mix of technologies and commodities without the interference of policies on economic parameters. This results in an energy system, which has low costs and is fossil-free.

3

We provide guidelines for policy changes

Third, we provide recommendations for policy changes that are likely to help realize the recommended future energy system. Thus, we provide a comprehensive recommendation for how to change the Danish energy policy in order to ensure a smooth transition towards 2050. In the process of doing so, we discuss the policy recommendations provided in recent reports from the Energy Commission, the Danish Council on Climate Change and the 6-part analysis by the Danish Ministry of Taxation. In our recommended incentive structure, we aim to ensure that regulatory barriers are removed, and that future policies do not limit or prohibit the development of technologies and use of energy carriers that provide net system benefits.

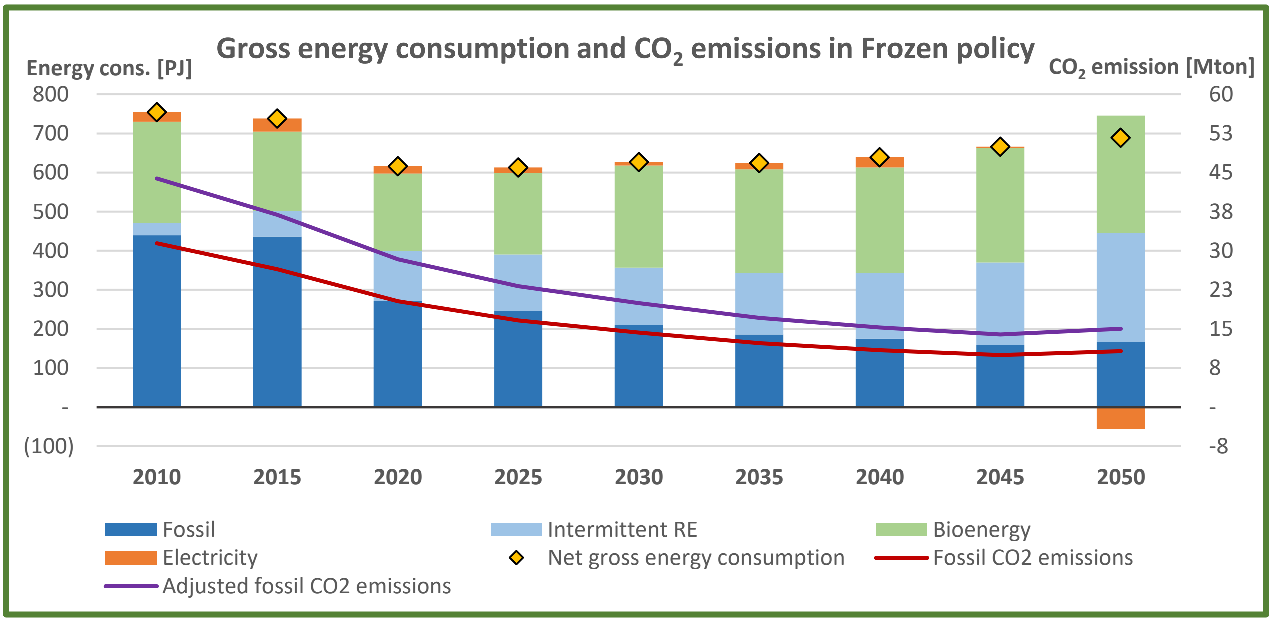
We hope to provide important input to decision makers for future energy system development, and more importantly; how to realize such development

The current regulation will not achieve a low emission society

The first objective of this report is to investigate if the current regulatory incentive structure is likely to ensure compliance with the GHG emission reduction targets for 2030 and 2050. Thus, to provide an indication of the direction of the energy system under frozen policy, and the likelihood of target compliance, we have used TIMES-DK to model a *Frozen Policy* scenario until 2050. This scenario both tells the story of where the energy system is going, but also provides valuable input for the third and final objective of this report, namely to provide recommendations for policy changes, which ensure compliance with GHG targets both in the short- and long term.

The *Frozen Policy* scenario is modeled with similar assumptions as the DEA *Baseline Projection*, and includes all planned constructions of energy plants, such as new offshore wind farms and planned bio-conversions of CHP units. Furthermore, our *Frozen Policy* scenario includes the recent statement from DONG Energy saying that they will phase out coal by the beginning of 2023.

In the *Frozen Policy* scenario, the existing legislation is included for as long as it applies. This means that all taxes are included throughout the model horizon (i.e. until 2050), while subsidies are being removed at different times in the model horizon, as stated in the applicable legislation.



The results show a continuous decrease in fossil fuel use, which is expected to be replaced by more intermittent renewable energy sources and bioenergy. However, the decrease is not enough to meet the long-term target in 2050, with annual fossil CO_2 emissions from the energy sector estimated to 15 Mton in 2015 (adjusted with historical difference between actual values and the model). The electricity- and heating sectors are expected to become 100 % renewable under current policies, while the transport sector will continue to lack behind with only 50 % renewable energy in 2050. The industrial sector is expected to become 88 % renewable in 2050, with the remaining 12 % being primarily coal for high temperature process heat and diesel for machinery.

Recommendations for a future energy system

Our proposed energy system for 2050 includes the following characteristics.

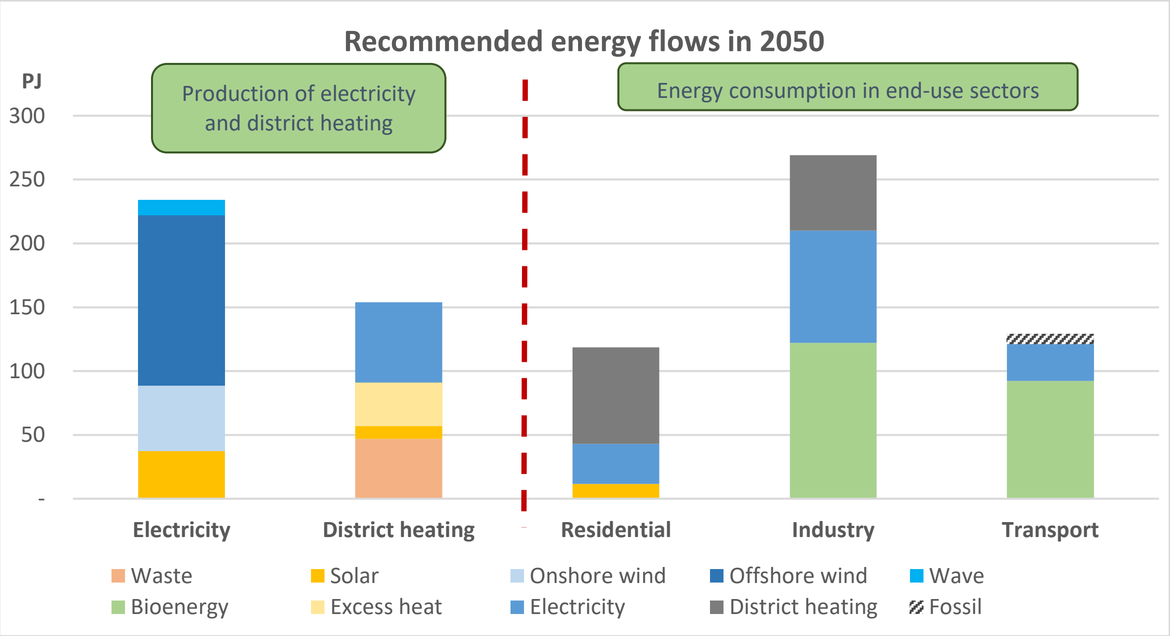
- Electricity should be produced from intermittent renewable energy sources, such as wind, solar and wave power. Some thermal capacity remain for delivering peak production and reserve capacity.

- The district heating sector should be based on large-scale electric heat pumps, waste combustion and solar heating. Excess heat from industry and from production of biofuels should be used in district heating.

- Residential heating should be district heating where possible combined with electric heat pumps and solar heating in non-district heating areas.

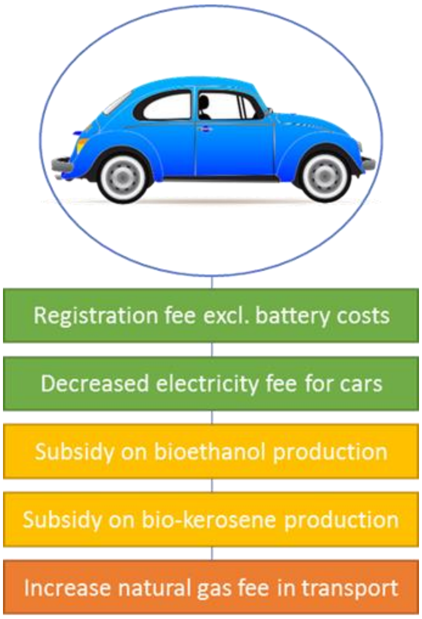
- The industry should use bioenergy for those processes, which require high temperature heat, and for machinery and vehicles, which require a combustion engine. The remaining energy demands in the industry should be supplied with district heating and electricity from the grid.

- The transport sector should use biofuels and electricity. Rail transport should be electrified, while personal cars should be hybrid vehicles, which use both electricity and bioethanol. Truck transport should use biodiesel, while aviation should be completely fueled by bio-kerosene.

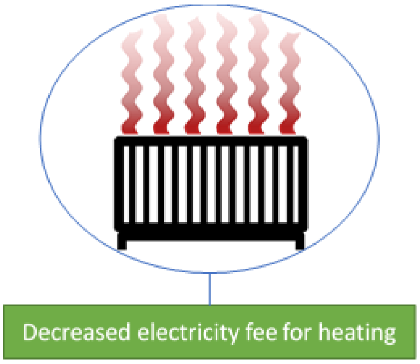


Guidelines for policy changes

- Subtract the battery cost from the calculation of the registration fee for electric- and hybrid cars, and reduce the electricity fee for cars to 230 DKK/GJ. This will help ensure a more electrified transport sector.
- Introduce a subsidy on bioethanol production of 25 DKK/GJ and a subsidy on bio-kerosene production of 125 DKK/GJ to ensure domestic production of these fuels, which can help the transport sector catch up on emission reductions.
- Increase the energy fee on natural gas for transportation to 65.5 DKK/GJ. This will ensure an early shift to liquid biofuels rather than natural gas.

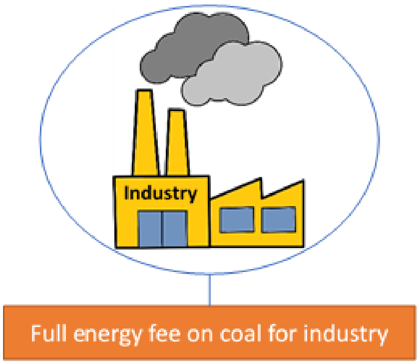


- Reduce the electricity fee for heating to 40 DKK/GJ, both in the district heating sector and the residential sector. This will ensure a larger share of individual- and large-scale electric heat pumps. Furthermore, we estimate that a reduction in the electricity fee will increase the net tax revenue due to an increased consumption of electricity.



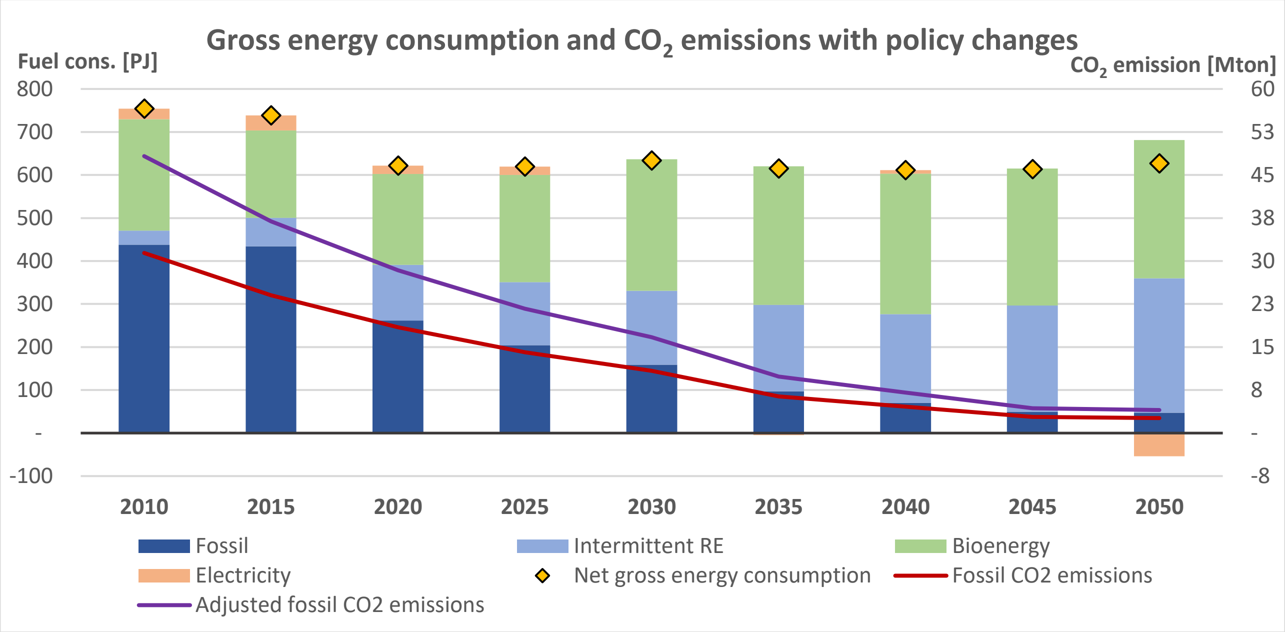
- Extend the existing subsidy scheme for wind power until 2030 for offshore wind turbines, and continue with a decreased subsidy equal to 4/5 of the current rate until 2035. This, combined with the above incentives for increased electricity consumption, will ensure an increased capacity of offshore wind in both the short- and long-term.

- Increase the energy fee on coal for industrial processes from the EU minimum level to the same level as for non-industrial use, i.e. to 54.9 DKK/GJ. While this will make it harder for some industries to compete on international markets, it sends a strong message to the industry that Denmark has to become free of fossil fuels, and that the industry will have to adapt.



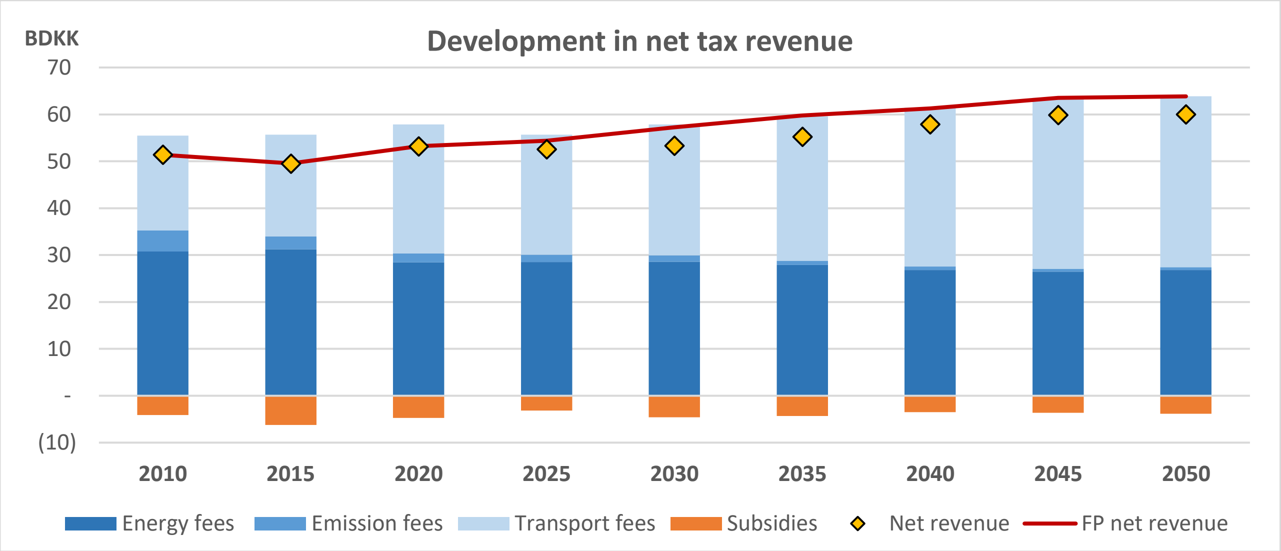
Guidelines will increase efficiency and reduce emissions

We estimate that the recommended changes to the existing incentive structure will result in a much larger implementation of intermittent renewable energy sources and a higher degree of electrification across all sectors. This will increase overall system efficiency, lower gross energy consumption and reduce fossil CO_2 emissions to a minimal level in 2050.



Changes have an impact on net tax revenue

The suggested changes to the existing energy policy will have an impact on the net tax revenue from the energy sector in the future. Compared with the *Frozen Policy* (FP) scenario, we estimate an average loss of tax revenue of about 3 BDKK per year from 2020 to 2050. However, we believe this is a relatively low cost for transitioning the Danish energy system to a low emission system.



Introduction

Denmark is committed to becoming a low emission society by 2050. This means that the country must be entirely independent of fossil fuels in the energy sector, including the electricity, heating and transport sector. This is a major ambition that will require major changes to the existing Danish energy system in order to be achieved.

The country is already well underway with this challenge in the electricity and heating sectors. As an example, electricity from wind turbines supplied over 42 % of all electricity consumed in Denmark in 2015 (Energinet.dk, 2016a). This share is expected to increase to about 50 % in 2020 based on new projects in the pipeline as decided by the Danish Parliament in the *Danish Energy Agreement of March 2012* (Ministry of Climate, Energy and Building, 2012). Another example is the large shift from coal and natural gas to renewable energy sources in the district heating sector. More than 50 % of the district heating in Denmark came from renewable energy sources by the end of 2016 (Danish District Heating Association, 2016a). However, the transport sector, which accounts for a third of Denmark's final energy consumption, is lacking behind in the transition to renewable energy with fossil fuels still covering 95 % of the energy consumption in the sector today (Danish Energy Agency, 2017a).

Achieving the remaining reductions in fossil fuel use in the electricity and heating sector, as well as the large reductions needed in the transport sector, will require cooperation between the different supply- and demand sectors and a consistent, reliable and agreed direction for the energy system. In this report, we discuss the urgent need for deciding on a common direction if we want to be successful in achieving the remaining energy policy targets. We explain how the achievement of any fossil-free 2050 scenario will require companies and individuals to make the right decisions when choosing between different technologies and behaviors. The most direct way of influencing their choices and investment decisions from a political point of view is to provide society with the right regulatory framework or incentive structure.[1] Thus, the primary aim of this study is to provide recommendations for policy decisions on how to change the regulatory incentive structure in Denmark to better achieve long-term political targets related to renewable energy implementation and greenhouse gas (GHG) emission reduction. The aim is therefore to provide important input to the discussion of which direction the energy sector should develop, and more importantly; how to realize such development.

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[1] A regulatory incentive structure can comprise different elements that can influence the behavior of actors in markets. Such elements include taxes/fees, subsidies, prohibitions and orders, etc.

Problem statement

In this report, we seek answers to a number of objectives. First, we try to answer an important question in regard to the energy policy targets, i.e. will we reach the remaining future targets under current energy policy? We do this by simulating the development of the energy system until 2050 in the TIMES-DK energy system model under a scenario called the *Frozen Policy* scenario. In this scenario, there are no constraints representing certain policy targets that must be met in the simulation. Therefore, the predicted development will provide a good indicator for what decisions will be taken by individuals and companies in the future, if the regulatory framework remains unchanged.

Second, we propose a future energy system, which meets the political targets. This scenario is called the *R2050* scenario. In short, the method for doing this is to allow the TIMES-DK energy system model to calculate the cheapest energy system development, which reaches zero fossil fuel dependency in 2035 and remains fossil-free thereafter. The reason for moving the target forward in this simulation is to force the model to construct a long-term solution for 2050, i.e. a solution which will also be cost-efficient after 2050. In this scenario, all existing taxes (except for taxes on externalities) are removed from 2020[2], while existing subsidy schemes are removed after they expire. The reason for this is to give the model "free hands" to construct the cheapest energy system without the interference of policies on economic parameters.

Third and last, we provide our recommendation for how to realize our *R2050* scenario using our *Incentive Structure* scenario. Thus, we provide a comprehensive recommendation for how to change the Danish energy policy in order to ensure a smooth transition towards 2050. In the process of doing so, we discuss some of the policy recommendations provided in recent reports from the Energy Commission, the Danish Council on Climate Change (DCCC) and the 6-part analysis by the Danish Ministry of Taxation (DMT). In our recommended incentive structure, we aim to ensure that some of the regulatory issues discussed in these reports are resolved and that future policies do not limit or prohibit the development of technologies and use of energy carriers that provide net system benefits.

Our method for providing recommendations is based on scenario modeling using the TIMES-DK model, which is a technical and economic energy system model of Denmark containing all sectors. The TIMES-DK model is a TIMES model, which is a partial equilibrium model. The model optimizes between all sectors to find the cheapest solution while meeting specific policy targets.

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[2] The taxes are not completely removed, but are set equal to the minimum tax rates set forth by the EU (European Commission, 2003). The minimum tax rates are very small compared with existing taxes, so the effect of the taxes on the system development is drastically reduced.

Similar studies providing energy policy recommendations

The subject of this study is well aligned with the ongoing debate on how the incentive structure should be changed in order to achieve the long-term target of a low emission society in 2050. The current Danish Government created the *Energy Commission* in the spring of 2016, which is a group of individuals from various universities and companies. Their purpose is to provide recommendations for future Danish energy policies that will pave the way towards 2050 and help reach international climate commitments.

The Danish Ministry of Taxation is currently also finalizing their work on a 6-part analysis of the Danish tax- and subsidy scheme in the energy sector, which focus on different cases of incentive structure issues that have been debated over the past years.

Another example of a similar study came in June 2016 from the Danish Council on Climate Change under the title "*Charges which transform*", which is a proposal for climate-friendly tax restructuring. As described on their webpage, the DCCC *"provides recommendations on climate initiatives in the transition to a low-carbon society based on independent professional analyses centered on the overall objective for 2050"* (Danish Council on Climate Change, 2017a).

The recommendations from these analyses will be described in more detail and similarities and differences between these and our results are discussed in Section 3.4.5 in Chapter 3.

Report structure

This report is divided into three chapters: In Chapter 1, we provide a detailed overview of the political targets that must be met, the suggested pathways from the Danish Energy Agency (DEA), overview of the current incentive structure and our methodology for providing recommendations.

In Chapter 2, we describe the modeling that has been used in providing these recommendations, including the model function and relevant inputs. This chapter contains a detailed description of the model and can be used as reference material.

Finally in Chapter 3, we discuss the results of the modeling of 3 scenarios: First the development of the Danish energy system under *Frozen Policy*. Second, we describe our recommended scenario *R2050* and why it should be the goal for the development of the Danish energy system. Third, we compare the 2 scenarios and analyze the differences in order to methodically come up with our recommendations for changes to the existing incentive structure. We call this scenario our *Incentive Structure*. Lastly we will conduct sensitivity analysis based on qualitative information from other sources.

CHAPTER 1

Overview of political targets for renewable energy and the current incentive structure

Chapter 1

1.1 Overview

In this chapter, we first provide an overview of the political targets that Denmark has committed itself to in both national and international contexts. Second, we give an update on how far we are in reaching those targets, in order to see if we are on track or if efforts need to be increased or changed. Third, we provide a description of the DEA scenarios and describe how they can serve as examples for future energy system development scenarios, which can achieve compliance with the political targets. Fourth, we describe some of the instruments that can help achieve a desired development scenario. In this section, we focus on taxes and subsidies, and we provide an overview of the existing structure for these instruments in Danish energy policy. Lastly, we introduce the remaining chapters in this report, and explain briefly our method for providing policy recommendations. A more detailed description of methodology is given in Chapter 2.

1.2 Danish energy policy targets

The Danish commitment in the fight against climate change has materialized in a number of political targets, which can be categorized in three levels: National, regional and global. These are summarized in Table 1.1 below. On the national level, Denmark has a long-term target of reaching a so-called *low emission society* by 2050, which is further described as a highly resource efficient society. A similar target of 100 % renewable energy in 2050 was originally established in the *Energy Agreement of March 2012* and since then re-defined in the *Climate Law of 2014*, which was passed by the Danish parliament (Ministry of Climate, Energy and Building, 2012) (Danish Ministry of Energy, Utilities and Climate, 2014). While the target is not very well-defined in terms of what should be achieved in practice, it is commonly mentioned as a target of becoming independent of fossil fuels by 2050. A variation of this definition was also adopted by the government in 2015, which included a target of being entirely independent of fossil fuels in the electricity, heating and transport sectors in their Government Program (Danish Government, 2015). Whenever referenced in this study, we refer to the 2050 target as a target of zero fossil fuel dependency and hence no emissions from fossil fuel combustion.

Year	Commitment	Agreement	Goal
2012	Global	UN: Kyoto	21 % reduction in GHG emissions from 1990
2020	Regional	EU: 2020	20 % reduction in GHG emissions from 2005 30% renewable energy in the energy sector 10 % renewable energy in transport
2030	National	Government Program 2016	50 % renewable energy in primary energy consumption
2030	Regional	EU: 2030	Total EU: 40 % reduction in GHG emissions from 1990 EU combined: 27 % renewable energy across all sectors
2030	Global	UN: Paris	Same as EU: 2030
2050	National	Climate Law 2014 Government Program 2015	Low emission society No fossil fuels

Table 1.1: Overview of the Danish climate commitments (Danish Energy Agency, n.d.).

On a regional level, Denmark is committed to reach certain targets, which are based on common EU targets for 2020 and 2030. The targets for 2020 include a 20 % reduction in GHG emissions from buildings, agriculture and transportation compared with the 2005 level. This target has been met already with a reduction in 2016 of 24 % compared with 2005 level. Furthermore, Denmark is committed to reaching a 30 % share of renewable energy in the total gross energy consumption and a 10 % share in the transport sector (Danish Energy Agency, n.d.). Denmark has already met the target of 30 % renewable share in total gross energy consumption, and is expected to increase this share to around 40 % by 2030 (Danish Energy Agency, 2017a). However, the DEA estimates that the transport target of 10 % renewable energy input will not be reached, but is estimated to reach 8.7 % in 2020. Furthermore, the EU has set a common EU-wide target of achieving a 40 % reduction in GHG emissions compared with 1990 level by 2030. This target has yet to be split into sub-targets for each EU member state (Danish Ministry of Energy, Utilities and Climate, n.d.).

In addition to the national and regional targets, Denmark is also committed on a global level. This commitment includes targets set forth by the UN (United Nations) in both the Kyoto Protocol from 1997 and the recent Paris Agreement. The target set in the Kyoto Protocol was to reach a 21 % reduction in GHG emission compared with 1990 level by 2012. This target was met with an actual reduction of 25 %.[3] The Paris Agreement mentions the same target for 2030 as the EU 2030 target mentioned above, i.e. an overall 40 % reduction in GHG emissions compared with 1990 level (Danish Energy Agency, n.d.). In fact, the GHG emission in 2016 was also very close to the 2030 target of a 40 % reduction compared with 1990 level. The Danish GHG emission and the targets are shown in Figure 1.1. The figure also shows the DEA's expected development under their most recent *Baseline Projection*, which is based on a model of a frozen policy scenario. Thus, it shows the expected development under current legislation and if no new policies are introduced (Danish Energy Agency, 2017a).

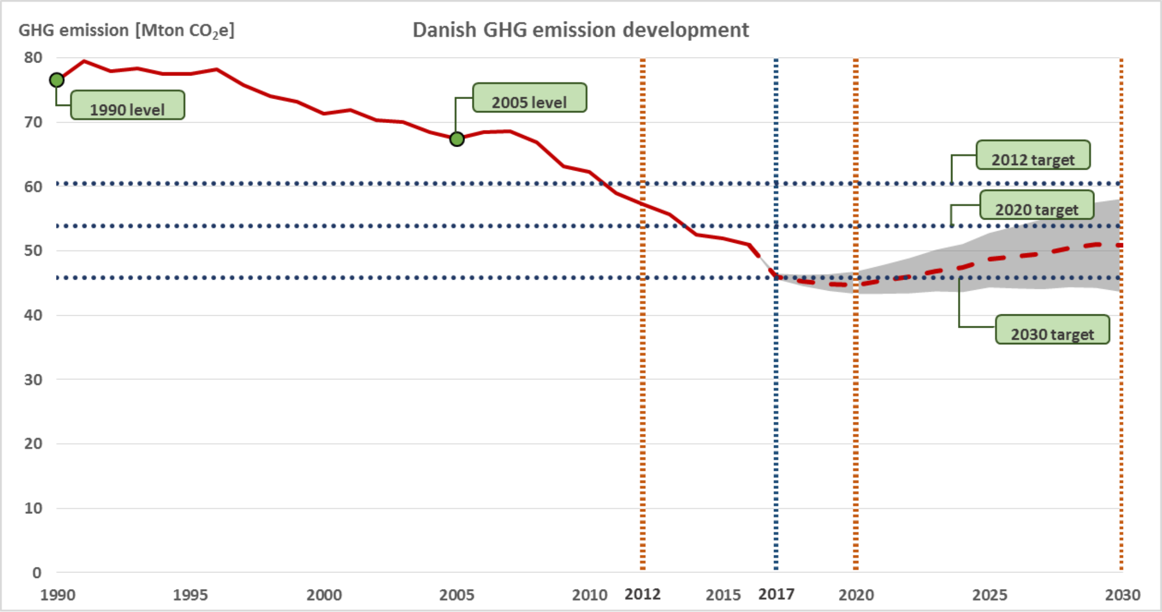

Figure 1.1: Development in GHG emissions in Denmark since 1990 and the expected development towards 2030 as estimated by the DEA. Including the targets in 2012, 2020 and 2030.

As the figure shows, the GHG emission can be expected to remain constant or increase towards 2030 (when taking the uncertainty into account) if no changes are made to the existing legislation, or if no new policies are introduced. A major reason for this development can be attributed to the ending of existing subsidy schemes for renewable energy before 2023 (Danish Energy Agency, 2017a). If these subsidy schemes are prolonged or other measures are enforced, there is a greater

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[3] Calculated based on data from (Danish Energy Agency, 2017a).

chance of a continuous decrease in GHG emissions after 2020, and hence a greater chance of meeting the 2030 target.

In terms of reaching the 2020 target of 30 % renewable energy in the energy- and transport sectors combined, Denmark has already reached a renewable energy share of 30.8 % in 2015 according to the latest data from Eurostat (European Commission, 2017). Thus, the country is in a good position to continue the upwards trajectory for the renewable energy share and reach the national target of 50 % renewable energy in gross energy consumption. However, this also requires further political initiative to be achieved.

In the following section, we introduce potential pathways for energy system development that will ensure the continuous increase in renewable energy share and reduction in GHG emissions from the energy sector.

1.3 Energy scenarios for 2050

It can be said from the above that Denmark has so far reached all agreed targets and seems to be well underway with the transition to a low emission society. However, it is also clear that the energy system still has a long way to go before it can be categorized as a fossil-free energy system. While there are many ways to reach the targets described above, it is essential to find pathways that minimize the socio-economic cost of transition and are possible to achieve in practice. The Danish Energy Agency has outlined four potential scenario for a fossil-free energy system in 2050 in their report *Energy scenarios for 2020, 2035 and 2050*. These scenarios have the following names: 1) *Wind scenario*, 2) *Bio scenario*, 3) *Bio+ scenario* and 4) *Hydrogen scenario*. Each scenario describes how different parts of the energy sector should develop in order to reach the 2050 target. These scenarios are good examples of potential feasible directions for the energy system to develop towards. Each of them provide an example of a technically feasible energy system which comply with the constraint of being fossil-free in 2050. The scenarios are not supposed to be viewed as the only possible ways of reaching the target, nor should they be understood as prognoses for the energy system development. In short, they provide an overview of potential directions for the energy system to take, which can supply all energy service demands in a technically feasible and sustainable manner. The scenarios are not mutually exclusive, but can be combined to a certain extent. However, it is necessary to ensure that all parts of the energy system are developing in the same direction, which is for the benefit of the entire system.

The DEA scenarios are based on both the 2050 target, but also include the now former target of zero fossil fuel dependency in the electricity and heating sectors by 2035. This target was revoked in 2015 by the previous government. Including both targets in the scenarios promotes a steady phase-in of renewable capacity towards 2050 and reduces the possibility of a sudden change to renewables at the far end of the time horizon.

The DEA has constructed each scenario after the same formula. First, they estimate the necessary capacities in the transport sector as well as the biofuel refinery capacity, which is included in all the scenarios. Second, the capacities for process heating, individual heating and district heating are estimated. Finally, the electricity sector capacities are estimated based on the needs from the other sectors. A main framework for the scenarios is the amount of bioenergy available in the scenario. Each scenario operates with a different amount of bioenergy, as shown in Table 1.2. This is to illustrate the need for bioenergy for different directions of energy system development. Bioenergy is a scarce resource, and some scenarios have a larger demand for bioenergy. Deciding on a common strategy for bioenergy reliance can help determine the most appropriate direction for the energy system development.

	Unit	Wind	Bio	Bio+	Hydrogen
Bioenergy consumption	PJ	255	443	710	192
Self-sufficiency	%	104 %	79 %	58 %	116 %
Gross energy consumption	PJ	575	590	674	562
Socio-economic cost	BDKK	140.5	136.2	159.2	143.2

Table 1.2: Overview of the energy scenarios made by the Danish Energy Agency.

Each scenario is described shortly in the following. For a comprehensive overview, we refer to the DEA report (Danish Energy Agency, 2014).

The *Wind scenario* is designed to include a maximum bioenergy consumption equal to the bioenergy potential of Denmark, which is estimated to 265 PJ. This does not mean that all of the bioenergy has to be produced within Denmark but it limits the possibility for import. This limit requires a large level of electrification in all energy sectors.

The *Bio scenario* is designed with an annual bioenergy consumption of around 450 PJ. This requires a net amount of bioenergy import of around 200 PJ. This is still not enough to replace all existing fossil fuel capacity, so a large level of electrification is still required.

In the *Bio+ scenario*, bioenergy is assumed to replace the existing fossil thermal capacity, which requires a bioenergy amount of around 700 PJ, which is similar to the fuel consumption today. The expansion of wind turbine capacity is kept at the expected 2020 level, which is contrary to the other scenarios, where a larger penetration of wind energy is generally assumed. The 2020 level of wind capacity can cover about 50 % of the electricity demand in 2020.

The *Hydrogen* scenario aims to minimize the use of bioenergy to below 200 PJ, and instead rely on the use of hydrogen technologies, thereby requiring an even larger amount of wind capacity than the *Wind scenario*. According to the DEA, a bioenergy level of 200 PJ is similar to the bioenergy consumption today, but it is used for different purposes in this scenario e.g. bio-kerosene production rather than combustion for electricity and heat production.

1.3.1 Need for a common strategy

While the DEA scenarios provide good examples of directions that the energy system can develop towards, and many more pathways can be defined by combining them, there is a need for deciding on a general direction in the short-term. This is true if we want to keep the total cost of transitioning to 100 % renewable energy low, since an early adoption of a common direction will enable the cross-sectoral development of technologies that complement each other well. For example, if the strategy is to move towards an energy system primarily based on intermittent, renewable energy sources, such as wind turbines, then it is important to promote a large penetration of electricity-consuming technologies in the other sectors, in order to take proper advantage of the large peaks in the electricity production that will characterize such a system. If this direction is not properly ensured across all sectors, then there is a risk of a large penetration of other energy technologies, which do not provide the same system benefits. This issue exists today, where the electricity supply is moving towards more wind power, while the heating sector is seeing a large increase in bioenergy technologies. This combination does not take advantage of the potential system benefits. In fact, the combination seems to limit the development of each type of technology, since more bioenergy in the heating sector limits the potential for integration of more wind energy in the system. At the same time, the increase in wind power is pushing electricity prices down, which reduces the attractiveness of using bioenergy for electricity production in CHPs. Thus, there is a need for deciding on a common strategy, and making a choice between a bioenergy-based energy system and an energy system based on intermittent, renewable energy sources. Making this decision and maintaining the chosen direction in the short- and long-term is important, because energy infrastructure has high investment cost and are long-term investments, which limits the possible transition rate. Furthermore, the energy supply and industrial sectors need a stable direction and regulation in order to limit their risk on investment. An unstable regulatory framework increases investment risk, which is directly transferred to higher requirements for investment returns. This increases the overall cost of transitioning to a 100 % renewable energy system.

Currently there is no firm consensus on the desired direction of the Danish energy system towards 2050. The most recent version of the DEA's annual *Baseline Projection* suggests that, under current policy, there will be a large transition to biomass and wind power in the electricity and district heating sectors until 2020 (Danish Energy Agency, 2017a). This is aligned with recent years' general movement towards biomass in the district heating sector, with more capacity expected in the coming years, especially in decentral areas, where a large number of existing natural gas engines and –boilers are expected to be replaced by solar heating and biomass due to their current subsidy schemes being removed in 2018 and 2019 (Danish Ministry of Energy, Utilities and Climate, 2016a) (Danish Energy Agency, 2017a). The DEA estimates that this development will stagnate after 2020, primarily due to the existing subsidy schemes ending post 2020. The transport sector is only expected to transition to renewable energy in a small scale towards 2030, and the DEA estimates that succeeding with the 10 % renewable energy target in the transport sector by 2020 will require additional political initiatives. The expected stagnation of renewable energy development strongly points to a need for policy makers to agree on a direction for the mid- to long-term energy system development before 2020, and before too many resources have been invested in technology capacities, which reduce the possibility of a least-cost development for society.

1.4 Instruments for realizing a strategic energy system development

Simply deciding on a strategic direction for the future energy system development and telling it to the public will most likely not be sufficient to actually realize the proposed development. Individuals and especially companies tend to weigh their own profit maximization highest when making decisions, and generally make economically rational decisions. Thus, their decisions regarding technology investments and operation patterns will be determined by the expected cost and revenue parameters of investment and operation in different alternatives. This means that, when given the choice between two technologies with the same output, they will pick the one which can generate the highest profit. In short, their choice is dictated by the market prices for each technology and for the commodities consumed and produced by that technology.

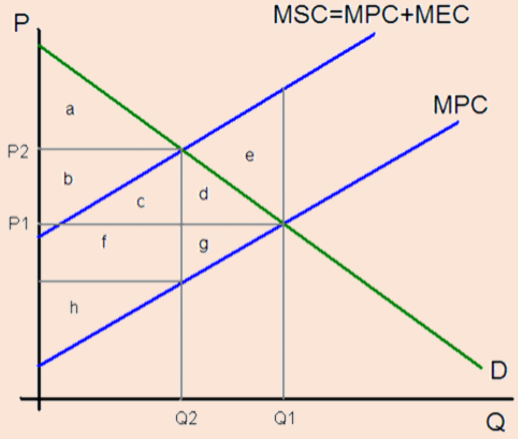
Policy makers can use various instruments to affect the costs and revenues of different technologies in the market, and thereby directly affect the investment- and operation decisions made by companies and individuals. Such instruments include excise duties (referred to as taxes or fees interchangeably in the remainder of this study) and subsidies. Additionally, investment decisions can be affected through legal prohibitions or mandatory orders. We generally refer to the combination of these instruments as the regulatory *incentive structure*. A short description of the fundamental economic theory on externalities, taxes and subsidies is provided in Box 1.1, and the following sections provide an overview of the current Danish incentive structure.

Box 1.1 – Externalities in microeconomics

Externalities are consequences of an economic activity, which are experienced by third-parties not related to the activity. Externalities can be either positive or negative, meaning that they have a positive or negative impact on a third-party. A common example of a negative externality is the emission of CO_2 and other pollutants from combustion of fossil- and biofuels. Thus, when companies combust coal to produce electricity, the rest of society experience a negative impact, i.e. a cost for society. Typically, this socio-economic cost is not taken into account when the company makes the decision to combust coal for electricity production, because the cost is not included in the cost of coal.

A common method for *internalizing* an externality into the economic decision-making of companies is to impose a tax on the economic activity, which is causing the externality. Consider the following example, which is illustrated in the figure below.

From basic microeconomics, we know that the equilibrium price in perfect markets will be at the intersection of the Demand curve (D) and the Marginal Private Cost curve (MPC) at point (Q1,P1). When the production of a good results in a negative externality, there is an added cost for society, which is illustrated in the figure as the Marginal Social Cost curve (MSC). This is the sum of the MPC and the Marginal External Cost (MEC), the latter being the difference between MPC and MSC. The externality can be internalized by imposing a tax equal to MEC, which shifts the supply curve upwards from MPC to MSC. This in turn results in a different equilibrium price, which is now at (Q2,P2).



Shifting the equilibrium price from (Q1,P1) to (Q2,P2) results in a different distribution of economic surpluses in society. Before adding the tax, the consumers were experiencing an economic benefit, or Consumer Surplus (CS), equal to areas *a+b+c+d*, which is caused by the equilibrium price being lower than the Willingness To Pay (WTP) for all but the last consumer. In addition, the producers experience a Producer Surplus (PS) equal to areas *f+g+h*, which is caused by the equilibrium price being higher than the marginal cost of all but the last producer. While this equilibrium price maximizes the sum of CS and PS, it also incurs a Social Cost (SC) equal to areas *c+d+e+f+g+h*.

When adding the tax and shifting the equilibrium price to (Q2,P2), the distribution of surpluses change. At this point, the CS is equal to area a, while the PS is equal to area h. Areas *b+c+f* are now considered a Governmental Surplus (GS), since it equals the money being paid in taxes. The tax results in a *deadweight loss* equal to areas *d+g*. The benefits represented by the other areas are simply being transferred between parties in the economy, but the deadweight loss is lost and represents a cost to society. However, the new equilibrium price results in a reduction in externalities equal to areas *d+e+g*. Thus, by subtracting the deadweight loss (*d+g*) from the gained benefit (reduced cost) to society (*d+e+g*) there is a *net social benefit* equal to area *e* from adding the tax.

While the tax does not fully remove the externality (areas *c+f+h* still also represent externalities), it internalizes the externality into the cost of the good and thereby maximizes the socio-economic benefit from the market.

1.4.1 Framework of the Danish incentive structure in the energy sector

The regulatory framework and incentive structure in the Danish energy system is very complex. It consists of a number of different elements, e.g. taxes, subsidies, exemptions and reimbursements. In this section, we provide a brief overview of the most important rules that apply to different parts of the energy system.

1.4.1.1 Taxes in the Danish energy system

Currently, taxes are being applied on emissions, commodities and transport investments with different purposes. These are described in the following sections.

1.4.1.1.1 Taxes on emissions

As mentioned in Box 1.1, the combustion of different fuels results in emission of different pollutants such as carbon-dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen-oxides (NO_x). These have harmful effects on the climate and environment, and as such are considered externalities to the combustion of fossil- and biofuels[4], because they incur a cost to society which is not included in the cost of the products produced by combustion. In order to internalize these external costs into the cost of the output products, the Danish legislation includes so-called *emission taxes*, which are taxes on the emission of these pollutants. In the electricity and heating sectors, the taxes are applied at the point of emission, i.e. the taxable amount of pollutant is (in theory) measured at the chimney of the heating- and/or power plant. Since it can be costly to invest in measuring equipment, utilities can instead be taxed on their fuel input based on emission factors specified annually by the DEA (Danish Ministry of Taxation, 2011; Danish Ministry of Taxation, 2013; Danish Ministry of Taxation, 2015). The emission taxes on CO_2, SO_2 and NO_x are shown in Table 1.3. The average 2016 EU ETS[5] price is included in the table to illustrate the difference between the cost of CO_2 emissions inside and outside the EU ETS.

	Unit	**CO_2**	**SO_2**	**NO_x**
Tax on emissions	2016-DKK/ton	171.4	11,600	5,000
EU ETS price	2016-DKK/ton	39.3	-	-

Table 1.3: Overview of emission fees for CO_2, SO_2 and NO_x in the energy sector. The EU ETS price is included as reference. (Danish Ministry of Taxation, 2016c)

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[4] Biofuel is considered a renewable energy source, and is therefore not considered to produce an externality from emission of CO_2. However, the emission of SO_2 and NO_x is also considered an externality from biofuel combustion.

[5] The EU ETS is an abbreviation for the EU Emission Trading Scheme.

In the transport sector it is rarely possible to have measuring equipment at the point of emission. Therefore, the externalities from fuel combustion in the transport sector are internalized by adding the tax on the fuel instead of the emission (Danish Ministry of Taxation, 2011). In the case of combustion engines for cars, the tax level is calculated based on the average emissions of each car type (e.g. diesel or gasoline). Thus, the tax paid on emissions for an average car will be approximately equal to the emission taxes shown in Table 1.3.

There are some exemptions to the emission taxes on CO_2, SO_2 and NO_x. For this study, the most important exemption is the combustion of biomass. Since biomass is considered a renewable energy source, the use of biomass is exempt from paying the tax on CO_2 emission. However, the taxes on SO_2 and NO_x also apply to the combustion of biomass and other biofuels. There are more exemptions to the emission fees, however they will not be repeated here. We refer to the applicable legislation for the full description (Danish Ministry of Taxation, 2011) (Danish Ministry of Taxation, 2015) (Danish Ministry of Taxation, 2013).

1.4.1.1.2 Taxes on energy commodities

Another type of tax being applied in the Danish energy system are *energy taxes*. Energy taxes must be paid on the consumption of most energy commodities, such as coal, natural gas, diesel and electricity. These taxes can serve multiple purposes. First, they provide an incentive to consume less energy by increasing the end-users price for energy services. Second, they provide a relatively large tax revenue for the state's treasury (about 34 billion DKK or 12 % of total revenue from excise duties in 2015) (Danish Ministry of Taxation, 2017a). Energy taxes on fossil fuels[6] for heating are set in such a way that they are the same on an energy content basis, i.e. they all equate to 54.9 DKK per GJ fuel consumed (2016 value) (Danish Ministry of Taxation, 2016a). This effectively provides an incentive structure which does not favor any fossil fuel types over others, but simply shifts the supply curves for these fuels by the same amount. Biomass fuels are exempt from paying energy fees, because they are regarded as renewable energy.

Fuel consumption for electricity production is exempt from paying energy taxes. The reason for this is that electricity is sold on an international market, and imposing a national tax on fuel input would limit the Danish companies' ability to compete in the electricity market, because it would increase their marginal cost of production. On the other hand, production of heat is sold on isolated, local district heating grids, where there is little or no competition between companies. Also, because the district heating grids are national, all competitors face the same regulation. Therefore, it is possible to impose a tax on fuel input for district heating, because it will not distort the utilities' competitiveness.

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[6] Fossil fuels for heating in this context include coal, fuel oil and natural gas.

While the fuel input for electricity production is not imposed a tax, there is an energy tax on the consumption of electricity, which is paid by the end-user of electricity. This electricity tax serves the purpose of reducing the overall electricity demand, and thereby reduce the consumption of primary fuels used in electricity production. The electricity fee is set to 245.8 DKK/GJ (2016 value) for all electricity consumed in Denmark (Danish Ministry of Taxation, 2017d). However, there are a number of exemptions from this rule. The most important are mentioned in the following and summarized in Table 1.4. We refer to the legislation for a complete description of the rules and exemptions.

2016-DKK/GJ	Transport	Space heat production	Process	Electricity production	All other
Coal	-	54.9	4.5	-	54.9
Fuel oil	54.9	54.9	4.5	-	54.9
Natural gas	54.9	54.9	4.5	-	54.9
Gasoline	129.1	129.1	129.1	-	129.1
Diesel	75.2	75.2	4.5	-	75.2
Biomass	-	-	-	-	-
Electricity	245.8 (1.1)	106.4	1.1	-	245.8

Table 1.4: Simplified overview of energy fees depending on purpose. The electricity fee for transport is 245.8 DKK/GJ for non-public transport, while it is 1.1 DKK/GJ for public transport (Danish Ministry of Taxation, 2016a).

As shown in Table 1.4, there are a number of different values for the electricity fee depending on where the electricity is consumed. While the full electricity fee is 245.8 DKK/GJ, the consumption of electricity for processes in the industry receives a reimbursement on taxes paid. This means that the effective electricity fee paid by industry is 1.1 DKK/GJ, which is equal to the minimum tax rate set forth by the EU (European Commission, 2003). The reason for this is to allow the Danish industry to be competitive on international markets. In general, the industry has a much lower tax rate on all fuels, except gasoline, which ensures their international competitiveness.

The production of space heating from electricity also has a lower tax rate on electricity than the regular tax rate. This promotes, to some extent, the use of electricity-to-heat technologies in district heating and residential/industrial buildings. For electricity for residential heating, the consumer must pay the full tax rate of 245.8 DKK/GJ for the first 4,000 kWh of electricity per year, while the lower tax rate of 106.4 DKK/GJ is paid for all additional electricity consumed (Danish Ministry of Taxation, 2017d).

Public transportation by electric train and -buses is also exempt from the full tax rate on electricity and should only pay the minimum tax rate of 1.1 DKK/GJ. A larger electricity fee on public transport would simply increase the cost of transportation, which would then have to be publicly financed, thereby creating a loop (taxes paid would be returned to the transport operator). All non-public transportation using electricity has to pay the full tax rate of 245.8 DKK/GJ.

1.4.1.1.3 Taxes on the transport sector

There are certain tax rules that apply for vehicles in the transport sector. These include a tax on vehicle registration, a tax on road usage and a tax on fuel efficiency. The registration fee is applied on first-time vehicle registrations in Denmark and the tax rate is based on the investment cost of the vehicle. Selected rules for the registration fee on personal cars and vans are summarized in Table 1.5. The full description can be found in the applicable legislation.

Vehicle type	Vehicle investment cost	Registration tax rule
Cars	Below 99,600 DKK	Tax equal to 100 % of investment cost
	Above 99,600 DKK	Tax equal to 150 % of investment cost
Vans	Above 17,500 DKK	Tax equal to 50 % of investment cost

Table 1.5: Registration fee for selected vehicle types according to current legislation. These rates apply to new vehicles purchased in Denmark (Danish Ministry of Taxation, 2017e).

Electric vehicles and hydrogen fuel cell vehicles have been exempt from registration fee until the beginning of 2016. This exemption improved the competitiveness of these vehicles compared to conventional vehicles by not increasing their cost through a registration fee. Such tax exemption would help these vehicles gain a larger market share earlier than the technological development could secure. However, the previous government decided in 2015 to phase in the full registration fee on electric and hybrid vehicles from 2016 to 2020[7] for electric vehicles and from 2016 to 2023 for hydrogen fuel cell vehicles.

In addition to the tax on registration, all vehicle owners have to pay an annual fee based on the weight of the car and a fee based on the car's fuel efficiency. We refer to these combined as the *ownership fee* on cars. These are shown in Table 1.6 for an average Danish car.

[2014-DKK/year]	Weight fee	Fuel efficiency fee	Total ownership fee
Gasoline car	3,320	1,780	5,100
Diesel car	5,780	4,500	10,280
Electric car	5,780	-	5,780
Hybrid car	5,780	620	6,400

Table 1.6: Overview of annual ownership fees on personal cars (Danish Ministry of Taxation, 2014c) (Danish Ministry of Taxation, 2014a).

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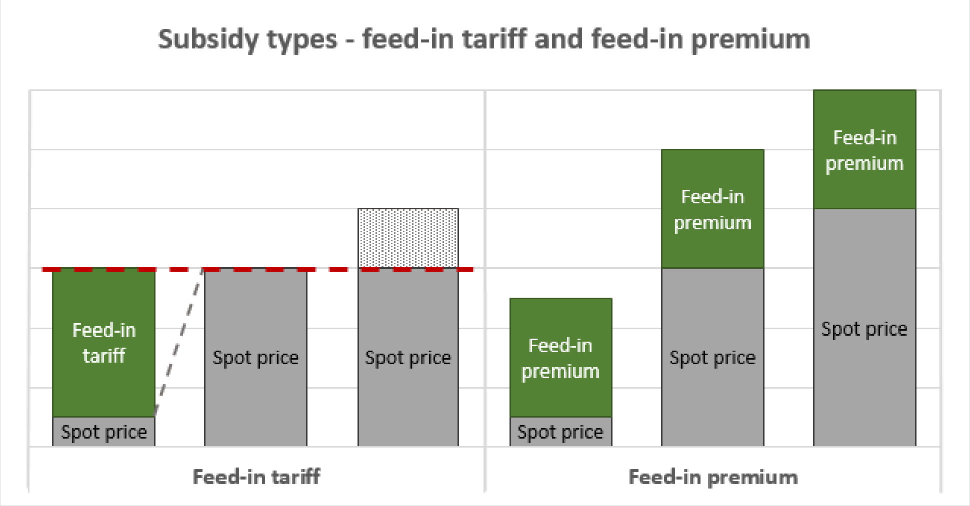
[7] A new agreement has been reached during the process of this project, which extend the phase-in period to 2022.

1.4.1.2 Subsidies in the Danish energy system

All renewable power production is subsidized in Denmark today, including e.g. wind-, solar- and wave power, as well as biomass used for electricity production. In addition, the production of biogas also receives a subsidy. Each type of technology can have different and multiple types of subsidies. The most common types of subsidies given are described below in Box 1.2.

Box 1.2 – An introduction to subsidy types



Feed-in tariff (FIT)	Feed-in premium (FIP)	Fixed annual subsidy
In a feed-in tariff scheme, the plant owners receive a fixed payment for energy produced, which is independent of the market price. The size of the subsidy is calculated for each trading period as the difference between the fixed payment and the spot price. If the spot price exceeds the fixed payment, then the difference is subtracted from the subsidies in the following settlement period. Thus, the plant owners are guaranteed a fixed payment at all times.	In a feed-in premium scheme, the plant owners receive a fixed subsidy on top of the market price. Compared to the feed-in tariff scheme, this subsidy scheme gives the plant owners an added benefit when spot prices are high, but are subject to the risk of lower payment, when spot prices are low.	A fixed annual subsidy is simply a fixed annual payment of a certain amount regardless of production levels, etc. A fixed annual subsidy can help otherwise economically unattractive production units remain available in the market, e.g. for peak load electricity production.

The current subsidy schemes for renewable power production in Denmark can be divided into six major categories. These categories are shown below in Table 1.7 with a complete description of existing subsidy schemes provided in the applicable legislation (Danish Ministry of Energy, Utilities and Climate, 2016b).

Subsidy type	Energy source	Subsidy value [øre/kWh]	Length of subsidy	Subsidy scheme expiration
Feed-in premium	Wind	25$^{(1)}$	25,000 full load hours	2018
Feed-in premium	Biomass	15	Continuous	2018
Feed-in tariff	Other renewables	60 / 40	10 years + 10 years	2018
Fixed annual	Natural gas, biogas, waste	Variable	Continuous	2018/2019
Tender (FIP/FIT)	All renewables	Variable	Continuous	-
FIP + FIT	Biogas (new plants)	Variable	Continuous	2023

Table 1.7: Simplified overview of different subsidy schemes in the Danish energy sector (Danish Ministry of Energy, Utilities and Climate, 2016b).
(1) The subsidy is only applied up to a total payment of 58 øre/kWh, when including both the subsidy and the electricity spot price.

Both onshore and offshore wind power in Denmark is subsidized under the "open door" subsidy scheme[8], unless specific subsidy schemes apply. This subsidy scheme is a feed-in premium for the first 25,000 full load hours of production, after which the subsidy is removed. This subsidy scheme expires primo 2018.

Electricity production from biomass combustion receives a feed-in premium of 15 øre per kWh of electricity produced. This subsidy applies to all electricity production from these units and expires primo 2018.

Other renewable sources than wind, biomass and biogas are subsidized according to the 60/40 rule, which provide a feed-in tariff of 60 øre/kWh for the first 10 years of operation and a feed-in tariff of 40 øre/kWh for the next 10 years of operation. This subsidy thus applies to renewables such as solar and wave power. This subsidy scheme expires primo 2018.

The fourth subsidy category is a fixed annual subsidy on electricity production from decentralized CHP plants using natural gas, biogas and waste. In addition, waste combustion for power-only production is also subsidized. The subsidy rate depends on the individual plant and is paid monthly

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[8] Open door means that the construction of a wind turbine can be initiated without a tender process and as soon as the Environmental Impact Assessment report is accepted. (Danish Energy Agency, n.d.)

with 1/12 of the annual subsidy. There are two subsidy schemes under this category, which expire in 2018 and 2019, respectively.

Occasionally, the Danish parliament decides that new renewable projects should be build (so far typically offshore wind farms) and offers the right to build and operate the plants in a tender process. In this tender process, the companies compete by offering to build and operate the project at their lowest possible rate of subsidy. This means that the company that can provide the plant at the lowest subsidy typically wins the tender. Examples of subsidies being set through a tender process are subsidies for the Anholt Wind Farm and the coming Horns Rev 3 Wind Farm and Kriegers Flak Wind Farm.

There are two subsidy schemes related to biogas, which include a subsidy on electricity produced from biogas and a subsidy on biogas production.[9] The subsidy on electricity produced from biogas is relatively complex. This subsidy only applies to electricity produced on plants commissioned after 2014. The subsidy depends on whether the biogas is pure or mixed with non-biogas, and is comprised of three different subsidies as shown in Table 1.8. The subsidy scheme expires in 2023.

[2012-øre/kWh]	Subsidy 1	Subsidy 2	Subsidy 3
Pure biogas	FIT 79.3	FIP 26	FIP 10
Mixed biogas	FIP 43.1	FIP 26	FIP 10

Table 1.8: Subsidy scheme for use of biogas for electricity production (Danish Ministry of Energy, Utilities and Climate, 2016b). FIT = Feed-In Tariff and FIP = Feed-In Premium.

Two out of three biogas subsidies follow the same rules, while one is different between the two. The first subsidy for electricity produced on pure biogas is a feed-in tariff of 79.3 øre per kWh electricity produced. This subsidy increases annually by 60 % of the net price index.[10] The first subsidy for electricity produced on a mixed biogas blend is a feed-in premium of 43.1 øre per kWh. This subsidy also increases annually by 60 % of the net price index. The remaining two subsidy schemes are the same for both pure and mixed biogas. The second subsidy scheme is a feed-in premium of 26 øre/kWh. This subsidy is linked to the natural gas price, i.e. the subsidy increases when the natural gas price decreases and vice versa. The third subsidy is a feed-in premium of 10 øre/kWh. This final subsidy is being phased out from 2016 to 2020. For electricity produced on mixed biogas, the subsidy only applies to the share of electricity produced on biogas.

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[9] Note: Biogas used for electricity production only receives subsidy at electricity production (and not at biogas production).

[10] The net price index indicates the price development free of changes in taxes and subsidies (Statistics Denmark, 2017a).

Furthermore, the production of biogas for other purposes than electricity production are subsidized with different rates depending on the end-use of the biogas. The applicable subsidy rates for biogas production for non-electricity purposes are shown in Table 1.9 below.

Subsidy [2012-DKK/GJ]	**Base subsidy**	**Feed-in premium 1**	**Feed-in premium 2**	**Feed-in premium 3**
Delivery to natural gas grid	-	79	26	10
Biogas for transport	39	-	26	10
Biogas for industrial processes	39	-	26	10
Biogas for other purposes	-	-	26	10

Table 1.9: Overview of subsidy scheme for biogas production (Danish Ministry of Energy, Utilities and Climate, 2016b).

Similar to the subsidy for biogas used for electricity production, these rates vary over time with the net price index, the natural gas price and phasing out until 2020 for *feed-in premium 3*. For a comprehensive overview of the rules, we refer to the applicable legislation and a recent analysis by the Danish Ministry of Taxation (Danish Ministry of Taxation, 2016a).

1.5 Do we have the right incentive structure?

In recent years, there has been a lot of public debate about how to best structure the energy system towards 2050. However, there is some general consensus on specific aspects regarding the best energy system development. For example, it is generally agreed that an increased level of electrification in all sectors is paramount to ensuring an efficient use of the intermittent, renewable energy sources (Danish Energy Association, 2016). In addition, there are few arguments against taking advantage of the large amounts of excess heat, which are available from the industrial processes.

However, there are various issues with the existing incentive structure, which may prohibit or favor the development of some specific technologies in the energy system - technologies, which are not necessarily promoting an increase in electrification or efficient use of excess heat. Some of these issues are described below.

1.5.1 Need for electrification

Electrification of the district heating sector is typically mentioned as an important part of the future energy system, because it allows for peak electricity production to be stored as district heating and used in periods with less electricity production. However, the district heating sector has not yet seen any substantial increase in the use of electricity-to-heat technologies, such as electric compressor heat pumps or electric boilers. Instead, many large centralized district heating companies have already invested in biomass boilers and CHPs to replace their existing fossil fueled units. Others have more biomass conversions in the pipeline. Furthermore, many existing natural gas engines and -boilers in the decentralized district heating areas are expected to invest in new equipment within the foreseeable future, due to their current subsidy schemes being removed at the beginning of 2018 and 2019 (Energinet.dk, 2014). While it is arguably better socio-economically for these plants to change to electric heat pumps, the current incentive structure is causing the business case for such investments to fall short of their biomass alternatives. Thus, part of the cause can be found in the fact that the incentive structure includes a large tax on electricity consumption (also for heating) and no taxes on biomass combustion for heating (except for emission fees on SO_2 and NO_x). The recent decision to phase out the PSO tariff (Public Service Obligation) from 2017 to 2022 will help the business case of electricity-to-heat technologies to some degree, but in most cases it will not be enough to favor electric heat pumps (Grøn Energi, 2016).

Similar to the above, the residential heating sector in non-district heating areas should also be moving towards electrification. Nevertheless, the situation in this sector is the same as for district heating, since the owners of these buildings will generally be choosing between a wood pellet boiler, solar heating and a heat pump, when replacing their old oil-fired boiler. In most cases, the wood pellet boiler is the best investment decision from a private-economic perspective, since wood pellets are without any taxes, while there is a large tax on electricity consumption. There are issues with solar heating, such as the need for long-term storage, and low solar irradiation during winter, meaning that this is less attractive.

Another way of introducing more electricity consuming technologies into the energy system, which can help with the integration of more intermittent renewables, is to have a greater share of electric vehicles in the transport sector. When aggregated into larger numbers, the batteries in electric vehicles can essentially be used as a large system battery for storing the peak electricity production and using it to provide transport services at a later time. However, while electric vehicles can play an important role in the integration of more wind power in the electricity grid, they are also generally more expensive than conventional vehicles using combustion engines that burn fossil fuels. Thus, if we want the share of electric vehicles to increase, the incentive structure should provide the right amount of support for making investment in an electric vehicle competitive with conventional vehicles. Until recently, the incentive structure provided a tax advantage to electric and hybrid vehicles, by having them be exempt from the registration fee. However, it was decided in 2015 to phase in the registration fee for these vehicles from 2016, so it is level with the registration fee for conventional vehicles in 2020 (Dansk Elbil Komité, 2015). The introduction of the registration fee on electric vehicles caused sales to drop quite dramatically from 1,588 vehicles in Q4 of 2015 to only 305 vehicles in the same quarter in 2016 (Dansk Elbil Alliance, 2017). Therefore, it seems appropriate to revise whether the introduction of the registration fee on electric and hybrid vehicles has appeared too early/rapidly, and that these vehicles are not yet competitive enough compared to their fossil counterparts. In April of 2017, the government and several other political parties came together to extend the phasing in of the registration fee on electric vehicles (Danish Ministry of Taxation, 2017c). The intention is to give a helping hand to the sales of electric cars.

Another issue with the registration fee on electric and hybrid vehicles is the fact that the fee is also applied on the cost of the vehicle’s battery. The effect of this is that it becomes expensive to increase capacity without increasing end-user investment cost severely. For example, the expected cost for an average electric vehicle in 2030 is estimated to be around 107,000 DKK plus 39,000 DKK for the battery, while the cost of a conventional gasoline vehicle is expected to cost 105,000 DKK. While the vehicle investment costs (without the battery) are roughly the same, the additional cost for the battery will result in an additional 58,500 DKK in registration fee for the electric vehicle.[11] Since there is a strong correlation between vehicle range, battery size and battery cost, the taxation of the battery is similar to applying a tax on the size of the fuel tank in a conventional vehicle. However, the latter tax does not exist, thereby favoring the conventional vehicle.

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[11] The battery cost is added to the value of the car and the registration fee is thereby payed on the total cost.

1.5.2 Taking advantage of excess heat

There is a large potential for improving overall energy efficiency in the energy system by taking advantage of excess heat from industry in the district heating sector. This is true because the use of excess heat can replace heat from other sources, and thereby reduce the overall primary energy consumption needed to supply the demand. There is an estimated 9-25 PJ of excess heat available today, depending on requirements for repayment period, which can be used in district heating grids either directly or through heat exchange in heat pumps (Viegand Maagøe, 2013). Furthermore, there is a lot of room for this number to grow if e.g. biorefineries become a larger part of the Danish energy system. However, the actual use of excess heat from industrial processes in district heating is very limited due to a tax on the sale of excess heat. This tax is making it too expensive for many district heating companies to purchase excess heat from industry and use it to supply heating to their customers. The main purpose of the excess heat tax, which is currently at 50 DKK/GJ, is to ensure that excess heat does not become a primary product for the industrial companies. The ability to sell excess heat could potentially give companies an incentive to lower their production of goods, or produce them at a lower energy efficiency, in order to increase revenues from the sale of excess heat. While this is a very legitimate concern, it is often argued that there is room for optimizing the excess heat tax rate in order to ensure a larger use of the excess heat potential in the heating sector (Lillevang, 2017) (Danish District Heating Association, 2016b).

The Danish Ministry of Taxation has recently published a report on the subject of excess heat taxation, which argues that the excess heat tax is in fact not the cause of the lack in excess heat utilization. Instead, they argue that the an increased amount of excess heating should be promoted by a decrease in the electricity for heating tax, which would make heat pumps more attractive. They also argue that all the exemptions are causing irregularities in the excess heat potential and that they should be removed (Danish Ministry of Taxation, 2017b).

The solution to these problems have been heavily debated for a long time and is subject to a continuous discussion. We hope to provide some clarity on how these technologies can better gain market share in the energy- and transport sector.

1.6 Introduction to the remaining chapters

The overview provided in this chapter has shown a number of things. First, it is now clear that Denmark has so far met its political targets for renewable energy implementation and GHG emission reduction. However, it is necessary to agree on new energy policies, which will ensure that GHG emission levels do not remain constant or increase towards 2030 and 2050. Second, it is shown that there is a strong need for a common strategy for the future energy system if we want to ensure a cost-efficient transition to an energy system independent of fossil fuels. Third, we have identified a number of issues with the existing incentive structure. These are limiting the private-economic attractiveness of specific development pathways, which otherwise make good sense in terms of socio-economics and energy efficiency.

In the remaining chapters of this report, we seek answers to the objectives stated in the introduction. We intend to answer the objectives with the modelling of 3 scenarios. The 3 scenarios will each answer one of the objectives. The first scenario used in this report is our *Frozen Policy scenario* which aims to show the development of the Danish energy system until 2050. Frozen Policy means business as usual and in this context implementing the current incentive structure as stated in the legislation. This scenario will enable us to answer the first objective; will we reach the remaining future targets under current energy policy?

The second scenario in this report is our recommended future energy system in 2050 which meets the political targets outlined in the beginning of this chapter. As this is our recommended scenario in 2050 we call it *R2050*. Using TIMES-DK we will model an energy system which reaches zero fossil fuel dependency in 2035 and remains fossil-free thereafter. The reason for moving the target forward in this simulation is to force the model to construct a long-term solution for 2050, i.e. a solution which will also be cost-efficient after 2050. In this scenario, all existing taxes (except for taxes on externalities) are removed from 2020[12], while existing subsidy schemes are removed after they expire. The reason for this is to give the model “free hands” to construct the cheapest energy system without the interference of policies on economic parameters.

Finally we intend to analyze the differences between our Frozen Policy scenario and our recommended scenario R2050 to identify irregularities. In this 3rd scenario we will start with the Frozen Policy scenario and implement changes to the existing incentive structure in order to ensure a steady development towards our R2050 scenario of no fossil fuel consumption in 2050. We call this scenario our Incentive Structure. The goal is to recreate the energy system in the long-term

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[12] The taxes are not completely removed, but are set equal to the minimum tax rates set forth by the EU (European Commission, 2003). The minimum tax rates are very small compared with existing taxes, so the effect of the taxes on the system development is drastically reduced.

R2050 scenario using only changes to the incentive structure. We will compare our results with the results of reports concerning the changes to the incentive structure.

In Chapter 2 of this report, we provide a more detailed description of the methodology for each of the objectives described above, including an overview of the function of the TIMES model generator and a comprehensive description of the energy system modelled in TIMES-DK.

In Chapter 3, we present the results for each of the scenarios and answers our objectives. We discuss the results compared to other sources and discuss these in terms of their resemblance of reality and the likelihood of reaching a certain development proposed by the model. We take into account the possibility of market conditions developing different from the base case assumptions, and discuss the impact of this on our proposed development strategy.

CHAPTER 2

Modelling of the Danish energy system in TIMES-DK

2.1 Overview

In this chapter, we describe in detail the TIMES-DK energy system model, which is used in this study for providing policy recommendations. TIMES-DK is a model of the Danish energy sector, which is based on the TIMES model generator. In this chapter, and this report in general, it is important to distinguish between TIMES and TIMES-DK. TIMES can be described as a so-called *model generator*, while TIMES-DK is an *instance* (a specific model) of its implementation. In short, TIMES is the "black box" model, which does not change from one implementation to the next. TIMES-DK is then a specific model representing a specific energy system, which uses the TIMES model generator to calculate its optimum set of variables.

Figure 2.1: Difference between TIMES and TIMES-DK. TIMES-DK uses TIMES as a "black box" for modelling.

In the following, we start by giving an introduction to TIMES and its function. Then, we describe the energy system modelled in TIMES-DK, where we especially focus on the input parameters provided for the model to use in simulations of the scenarios described in Chapter 1, i.e. the *Frozen Policy* scenario, the *R2050* scenario and the *Incentive Structure* scenario. In this context, we explain the assumptions made regarding future energy system development. We then proceed to describing the different scenarios modelled in regard to the objectives stated in the *Introduction*.

2.2 Introduction to the TIMES model generator

The TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), an international community which uses long-term energy scenarios to conduct in-depth energy and environmental analyses (IEA-ETSAP, n.d.).

TIMES is a partial equilibrium, bottom-up, economic model generator for local, national, multi-regional, or global energy systems, which provides a technology-rich basis for representing energy dynamics over a multi-period time horizon. It uses linear programming to produce a least-cost energy system, which is optimized according to a number of user constraints, over medium to long-term time horizons. In short, TIMES is used for "*the exploration of possible energy futures based on contrasted scenarios*" (Loulou, et al., 2016).

The TIMES model generator combines two approaches to modelling energy systems: a technical engineering approach and an economic approach. This means that the model seeks to minimize the overall cost of meeting all specified end-use energy service demands in the energy system while simultaneously complying with technical requirements and constraints provided, e.g. limits on interconnector capacity between countries or maximum district heating production from a certain technology. The model makes investment decisions for installation of new technology capacity and calculates the optimal operation of the installed technologies. The choice of technology is based on the analysis of the characteristics of alternative technologies, on the economics of the energy supply and on environmental criteria. The model also takes into account the optimal supply of primary energy and energy trade for each region.

Box 2.1 – The ups and downs of energy system models

Generally, there are two main types of models used in economic modeling of energy systems (and economic modeling in general). These are called *General Equilibrium* models (or *Top-Down* models) and *Partial Equilibrium* models (or *Bottom-Up* models). There are many variations of the two, and many models combine their functions to create hybrid models. A brief description of the function of core General Equilibrium models and Partial Equilibrium models is given below.

General Equilibrium models	Partial Equilibrium models
General Equilibrium models typically represent an entire economy and have the objective of finding the economic equilibrium *across all markets*. These models take into account the fact that individual markets affect each other and that the entire system is not necessarily optimized if the objective function only calculates the equilibria for individual markets. General Equilibrium models typically model a system on a highly aggregated level using only few variables, e.g. energy, capital and labor. Furthermore, General Equilibrium models include macroeconomic variables, such as wages, consumption and interest rates.	Partial Equilibrium models are typically very detailed and technology explicit. They typically focus on only a few sectors of an economy, such as the energy sector. The objective of a Partial Equilibrium model is to obtain the market equilibria in *individual markets* independently from prices and quantities in other markets. Thus, core Partial Equilibrium models do not take the effect of markets on each other in to account. In these models, a sector is typically made up of many well-defined technologies, which are linked together by their inputs and outputs. Compared with General Equilibrium models, the Partial Equilibrium models are often able to track a much wider variety of traded commodities. Furthermore, they are better at representing policies targeted at specific technologies or commodities.

The TIMES model type

TIMES can best be described as an advanced Partial Equilibrium model, which also encompasses some of the effects of the entire economy on the energy system. In TIMES, end-use demands can be elastic and sensitive to their own prices. This makes TIMES able to capture the impact of rising or falling energy prices on the demand in individual markets, but also in connected markets, since energy commodities in one market may originate from another, price-sensitive market. Thus, although the economic rationale of TIMES is that the total economic surplus is maximized when all individual markets are in equilibrium, the model also captures the main feedback from the economy on the energy system. Furthermore, since TIMES can model multi-regional energy systems, it also has the ability to consider the impacts of energy-related decisions on trade by implicitly constructing the production- and trade functions for each region.

2.2.1 TIMES in a scenario analysis context

TIMES is well suited for scenario analysis. In TIMES, a complete scenario consists of four types of inputs: 1) Energy service demand curves, 2) primary resource supply curves, 3) descriptions of a complete set of technologies, and 4) a policy setting. Each of these input types are described in the following.

2.2.1.1 Energy service demand curves

A TIMES model is built around end-use energy service demands, e.g. the demand for room lighting, space heating per square meter or passenger-kilometers for passenger transportation. The size of these demands depend on various drivers, such as population, number of households, GDP, etc. Projections for these drivers are specified exogenously. In addition, demand elasticities are specified exogenously. The model uses these specifications to calculate demand curves for each end-use demand, thereby making the demands responsive to their own prices.

2.2.1.2 Primary resource supply curves

The second input needed for a TIMES scenario is a set of supply curves for primary energy and material resources. The supply curves are modelled as step-functions, where each step represents a certain potential for a resource or material available at a particular cost. The potential can e.g. be expressed as a cumulative potential over the entire model time horizon, or as an annual potential (e.g. maximum annual straw potential within one region). The supply component also includes trading possibilities. In global models, the amounts and prices of the traded commodities can be determined endogenously. The supply curves for commodities other than primary energy and material resources are usually determined endogenously in the model, e.g. electricity prices and district heating prices are determined endogenously based on the cost parameters of the technologies producing these commodities.

2.2.1.3 Description of a complete set of technologies

A TIMES scenario requires a set of technical and economic parameters for the transformation of primary resources (the supply curves) into energy services (the demand curves). In TIMES, these are described in the form of *technologies* (or processes) that transform some *commodities* into others (fuels, materials, energy services and emissions). Capacities of specific technologies that exist at the beginning of the model horizon can be user imposed in the model, while others can be made available for the model to choose from when investing in new capacity in the remainder of the time horizon.

2.2.1.4 Policy setting

It is possible in TIMES to include practically any type of policy, for example a cap on emissions, a subsidy on specific technologies or a tax on fossil fuels. By comparing a reference scenario with a specific policy scenario, it is possible to see the impact of a specific policy on the energy system development.

2.2.2 The TIMES economy

The TIMES energy economy is made up of producers and consumers of commodities such as energy carriers, materials, energy services, and emissions. By default, TIMES assumes competitive markets for all commodities, unless the modeler voluntarily imposes regulatory or other constraints on some parts of the energy system. Thus, the modeler can introduce market imperfections, e.g. in the form of taxes, subsidies or constraints on emissions. The assumption that markets have perfect competition means that market imperfections, such as monopolies and lack of full information, are not taken into account in the model. It is possible to some extent to simulate the existence of a monopoly by adding a constraint in the model, which forces some specific technology to supply a certain share of the demand at specific times. However, the economic effects of market imperfections are not part of the core TIMES paradigm.

The TIMES model computes the quantities and prices of the various commodities such that they are in equilibrium, i.e. their prices and quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers. This equilibrium has the property that the total economic surplus *in each market* is maximized. However, the fact that TIMES is a partial equilibrium model means that the effects of markets on each other is only partially accounted for via the demand elasticities, as described in Box 2.1. Since TIMES does not model an entire economy or calculate a general equilibrium across all markets, some effects are not included in the surplus maximization. For example, effects on employment and welfare are not taken into account in this partial equilibrium model framework. In addition, the economic distortions caused by imposing taxes and subsidies in markets are not taken into account in a TIMES model. This means that the economic deadweight loss is not part of the model optimization. Similar, the ripple-effects throughout the entire economy caused by changing a market equilibrium through a tax or subsidy is not included in the model optimization (economic distortion loss).

It is clear that in the context of energy system modelling, there is a trade-off between capturing macroeconomic costs and benefits, and being able to model detailed, technology-explicit energy systems and their development. In this regard, it can be argued that the macroeconomic effects are not large enough to have a significant impact on the energy system development, which is the main objective of TIMES energy system modelling. If one seeks to investigate the complete socio-economic costs and benefits of a certain development pathway, it may be most accurate to obtain the development in a technology-explicit, partial equilibrium model, and subsequently use the resulting economic drivers in a general equilibrium model in order to capture the full effect of the specific development pathway on the economy.

The TIMES model has *perfect foresight*, meaning that all investment decisions are made for each period with full knowledge of future events. This property results in an overall minimization of cost over the entire time horizon. Under this assumption, each individual or company in the modelled energy system is assumed to have knowledge of future events, such as changes in fuel prices and future technology investment costs. Similar to the assumption that markets have perfect competition and all agents have full knowledge, this is a limitation of the model which to some extent limits the model's accuracy in depicting a real-world development. In this regard, the "forecast" made by the model may not accurately imitate the development that would occur in the real world under the same framework conditions. However, the model describes the *best* (least-cost) development under those conditions, i.e. the decisions that companies and individuals should make if they had full knowledge of future events.

In summary, the result of a TIMES model run is a supply-demand equilibrium for each commodity that maximizes the *net total surplus* (i.e. the sum of producers' and consumers' surpluses) under the imposed constraints. The official TIMES documentation uses the following description: "*A TIMES run configures the energy system of a set of regions, over a certain time horizon, in such a way as to minimize the net total cost of the system, while satisfying a number of constraints*" (Loulou, et al., 2016).

2.2.3 Time horizon in TIMES

TIMES is built with the purpose of simulating long time horizons. The time horizon can be divided into a user-chosen number of time-periods, each of which can be of a different length. In addition to these time-periods, each individual period may be divided into *time-slices* of different levels of detail. Examples of time-slice levels are seasons, weeks or portions of the day/night. An example of time-slices is shown in Figure 2.2.

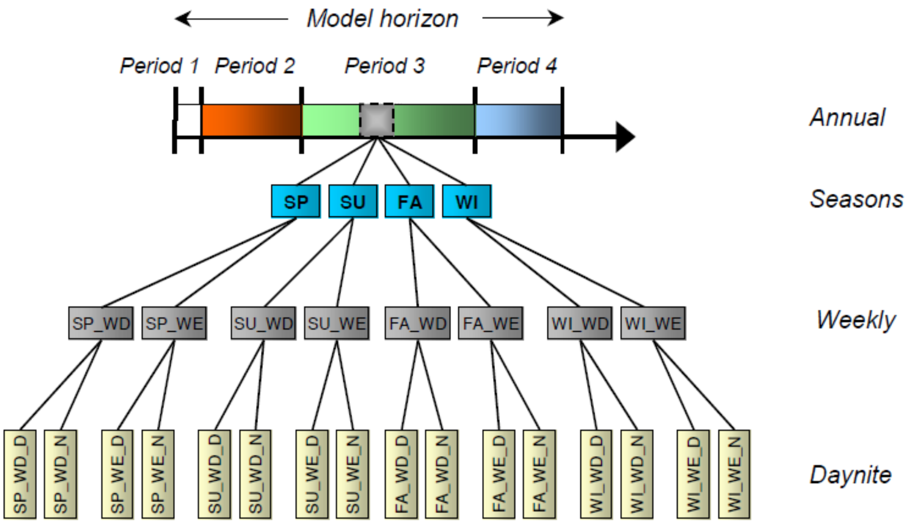

Figure 2.2: Example of time-slices in the TIMES model. The figure is kindly borrowed from (IEA-ETSAP, n.d.).

Time-slices are especially important when the mode and cost of production of an energy carrier are significantly different at different times of the year. An example of this is photovoltaic solar panels, which have significantly different production patterns during the day and night, but also between summer and winter. Another example is when commodities are difficult or expensive to store (e.g. electricity) so that matching the production and consumption is an issue for the model to resolve. In these cases and many others, it is very relevant to track the production and consumption over shorter time-slices.

In the following section, we describe a specific instance of a TIMES model, namely the TIMES-DK model. The TIMES-DK model is built to simulate the Danish energy sector, given currently installed capacities and the existing policy framework.

For a full description of the TIMES model generator, we refer to the official documentation (IEA-ETSAP, n.d.).

2.3 TIMES-DK – A Danish energy system model

TIMES-DK is an instance of the TIMES model generator, which is developed and maintained in a collaboration between DTU Management Engineering and the Danish Energy Agency. This means that TIMES-DK is in fact a TIMES model, which is tailored so it simulates the Danish energy system. The TIMES-DK model used in this study has been slightly changed and updated compared with the TIMES-DK version downloaded on February 25, 2017.[13] This section provides an overview of the energy system modelled in this updated version of TIMES-DK. This includes a description of the following elements in the model:

- The time horizon
- The geographical system boundary
- A description of the four scenario inputs required for a complete scenario, i.e.:
    - Energy service demand curves
    - Primary energy supply curves
    - A complete set of technologies
    - A policy setting

The overview also includes a description of important constraints used in modelling the Danish energy system. All major updates and changes to TIMES-DK made in the process of this project are described in Appendix 03, and the updated model files can be found in Appendix 01.

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[13] As the TIMES-DK model is on a GitHub server there are no version number. The download date is the identification.

2.3.1 Time horizon

The time horizon modelled in this study is from 2010 to 2050. The time horizon is divided into aggregated periods, which generally have a length of 5 years, with the exception of the first three periods. All periods are shown in Table 2.1, as well as their so-called *milestone year*, which is the year used in reporting of results, etc. The milestone year is the middle year of each period.

Period no.	Start	Milestone year	End	Length
1	2010	**2010**	2010	1
2	2011	**2012**	2013	3
3	2014	**2015**	2017	4
4	2018	**2020**	2022	5
5	2023	**2025**	2027	5
6	2028	**2030**	2032	5
7	2032	**2035**	2037	5
8	2038	**2040**	2042	5
9	2043	**2045**	2047	5
10	2048	**2050**	2052	5

Table 2.1: Time horizon in TIMES-DK. To minimize modelling time milestone years are used.

Input parameters can be defined for any year in the time horizon, including non-milestone years. Many parameters are specified on a more detailed time-slice level than annual in order to account for fluctuations in e.g. production patterns of wind turbines. The TIMES-DK model operates with 4 time-slice levels, namely annual, seasonal, working day/non-working day and the DayNite level. The DayNite level consists of 4 different groups of hours over the year, as illustrated in Table 2.2.

A	B	C	D
Wind high, electricity demand low	Electricity demand high, wind low	No solar PV	Remaining hours

Table 2.2: Overview of the DayNite level used in TIMES-DK.

When using the most detailed time-slice level, it is possible to specify model parameters in 32 different time-slices.[14] Each of these 32 time-slices include a different fraction of the year, e.g. the model has one specific time-slice, which represents the number of hours on non-working days during summer, which have a high electricity demand but a low wind availability. The use of detailed time-slices is primarily used for defining production potentials for all intermittent, renewable energy sources, as well as the calculation of electricity prices. Furthermore, prices for import and export of electricity and end-use demands are specified on a DayNite time-slice level.

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[14] There is a total of 32 time-slices, since there is 1 annual level split into 4 seasons, each of which have 2 groups (working day/non-working day) with 4 DayNite groups. This gives 1*4*2*4 = 32 time-slices.

2.3.2 System boundary

As mentioned previously in Section 2.3, a TIMES model can include systems up to a global level. TIMES-DK does not model such a large system, but focuses specifically on Denmark. This means that only Denmark is modelled endogenously. Denmark is modelled as two regions, namely West Denmark (DKW) and East Denmark (DKE). Demand curves are specified individually for each region, as well as existing technology capacities at the beginning of the model horizon, etc. Each region is not divided into smaller areas in the model. This means that e.g. district heating networks are modelled as one large network in each region, and wind power production potential is assumed constant throughout an entire region (i.e. no differentiation between geographical locations based on e.g. wind velocity), etc. While this is a relatively low geographical resolution, it is considered sufficient for the type of analysis made in this study, which primarily investigates energy system development on a long-term and aggregated level.

Neighboring countries are only included insofar as there is an electricity interconnector between Denmark and the specific country. Interconnectors included in the model are shown in Figure 2.3 and listed in Table 2.3 including the capacities assumed in the model. The model includes all existing interconnectors to Norway, Sweden and Germany, as well as the Great Belt Connection between DKW and DKE. In addition, the model includes all planned interconnectors that have been finally decided, i.e. new capacity between DKW and Germany, as well as the COBRAcable to the Netherlands. The Viking Link cable between DKW and the UK is not included in the model, since final investment decision has not yet been made for this interconnector. This also means that the planned West Coast Connection from DKW to Germany is not included, since the installation of this interconnector depends on the Viking Link being installed (Energinet.dk, 2016b).

*Figure 2.3: Illustration of the interconnectors used in TIMES-DK.
Original picture (modified here) kindly borrowed from Energinet.dk.*

Interconnector	Name	Import capacity	Export capacity	Available from
DKW-DKE	Great Belt	600	590	Full period
DKW-NO	Skagerrak	1,632	1,632	Full period
DKW-SE	Konti-Scan	680	740	Full period
DKW-DE	DKW-DE	1,500	1,640	Full period
	DKW-DE	1,000	860	2021
DKE-SE	Øresund	1,300	1,700	Full period
DKE-DE	Kontek	600	585	Full period
	Kriegers Flak	400	400	2019
DKW-NL	COBRAcable	700	700	2020

Table 2.3: Details for interconnectors used in TIMES-DK.

Connected countries are not actually simulated in the model, but are only included in terms of exogenously defined electricity prices for the model horizon. This makes it possible for the model to calculate the amount of exported and imported electricity for each model period. Electricity prices for neighboring countries are based on electricity market data for 2011 from Energinet.dk and calculated forward using background data from the DEA's *Baseline Projection* from 2015 (Energinet.dk, 2015b) (Danish Energy Agency, 2015a).

2.3.3 Energy service demand

As mentioned above, a TIMES model is built around end-use energy service demands and primary energy supply. In TIMES-DK, energy service demands are specified for the residential sector and the transport sector. For each of these, the demands are not specified in terms of demand for e.g. electricity, heating or fuel input, but rather as demands for the services provided by technologies within each sector. For the industrial sector, the demands are specified in terms of demand for energy commodities. The demands specified for each sector are described in the following.

2.3.3.1 Residential sector

For the residential sector, the demand for heating and electricity is not directly specified. Instead, it is specified in terms of square-meters, which is then used by the model to calculate the need for space heating. For electricity, the demand is specified as the demand for specific groups of appliances, e.g. the average number of computers, refrigerators and washing machines per household multiplied by the number of households. This is paired with exogenously defined energy consumption projections (energy efficiencies) for each type of appliance in order for the model to calculate the demand for electricity for household appliances.

The appliance categories included in the model are shown in Figure 2.4 together with the assumed development in electricity demand and the aggregated development in demand for residential appliances. The increase in number of appliances is primarily driven by a large increase in the "Miscellaneous" category. This category includes all other appliances than specified in the remaining categories, including for example vacuum cleaners, electric gardening tools, hairdryers, etc.[15] Thus, it is assumed that the number of miscellaneous electric appliances will increase throughout the model horizon, which is a fair assumption given the attractiveness of electricity as an energy carrier and expected economic growth (European Environment Agency, 2012). The number of appliances demanded in the remaining categories is more or less constant throughout the model horizon.

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[15] For a comprehensive list of appliances included in the "Miscellaneous" category, see *ElmodelBolig Statistik* by the DEA on http://www.electric-demand.dk/

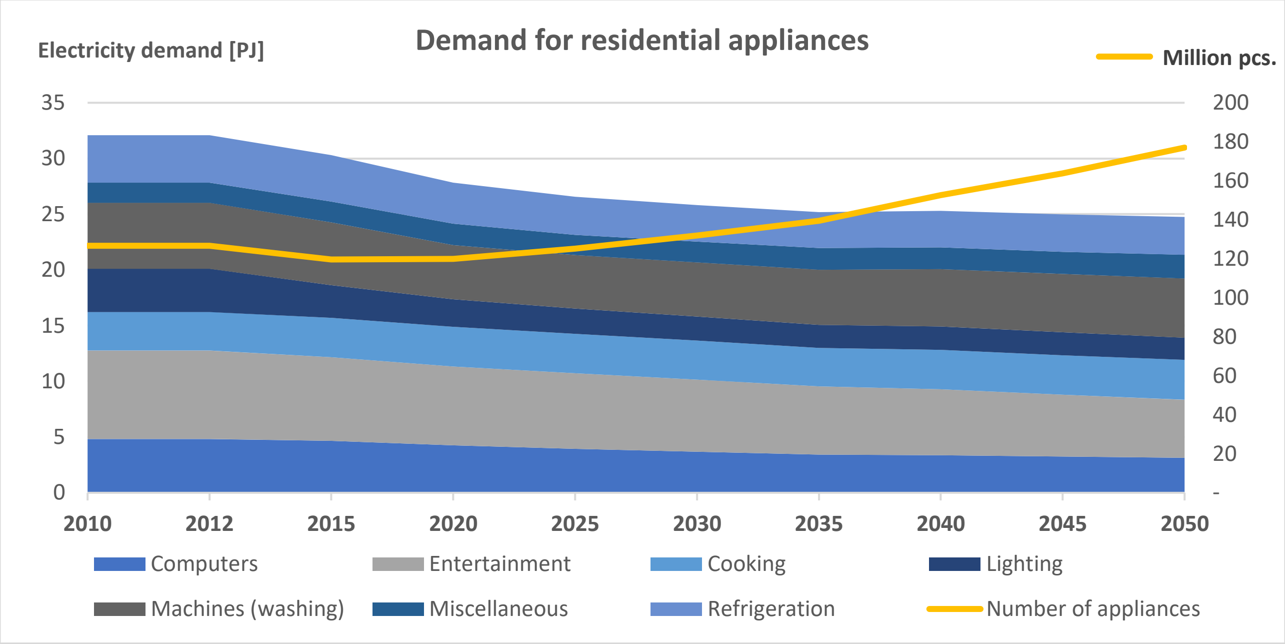

Figure 2.4: The electricity demand for residential appliances is decreasing even though the number of appliances is increasing.

While the number of appliances is assumed to increase, the opposite is true for the total electricity demand for residential appliances that follows from the use of the appliances. It should be noted that the electricity demand shown here is an estimated demand based on the number of appliances (as per Figure 2.4 above) and the efficiency of each type of appliance in each milestone year. While this is an appropriate estimate of the electricity demand, the demand shown in Figure 2.4 might not be the actual demand used by the model, as this depends on the replacement rate of each type of appliance in each type of building and region. Since some appliances have lifetimes different than the length of each period (in most cases 5 years), the annual average efficiency in the simulations may be different from efficiencies used in Figure 2.4.

The simultaneous increase in number of appliances and decrease in electricity consumption is caused by the assumption that all appliances are assumed to increase in efficiency over time. Machines and cooking equipment have the smallest increase, while “Miscellaneous” has the largest increase. This is based on the assumption that new appliances coming into households in the future will generally be much more efficient than today.

The demand for space heating in the residential sector is based on a projection of the demand for housing in terms of square-meters. This demand is split between DKE and DKW and divided into housing in district heating areas and areas with individual heating. The housing demands are further divided into single-family housing and multi-family housing.

The housing demand projections are based on projections by the DREAM[16] group, which project the demand for different types of housing (single-family and multi-family) for each region (DREAM, 2017). The split between district heating area housing and individual heating is based on DTU Energy Atlas (based on BBR[17] extract from 2014) and the Energy Producers Count by the DEA (Danish Energy Agency, 2016b).

The assumed development of existing buildings and new buildings is shown below in Figure 2.5. The decrease in existing buildings is based on annual demolition rates as estimated by the DEA for the Danish Government (Danish Government, 2014). The development of new buildings is calculated as the difference between housing demand and remaining existing buildings after demolition.

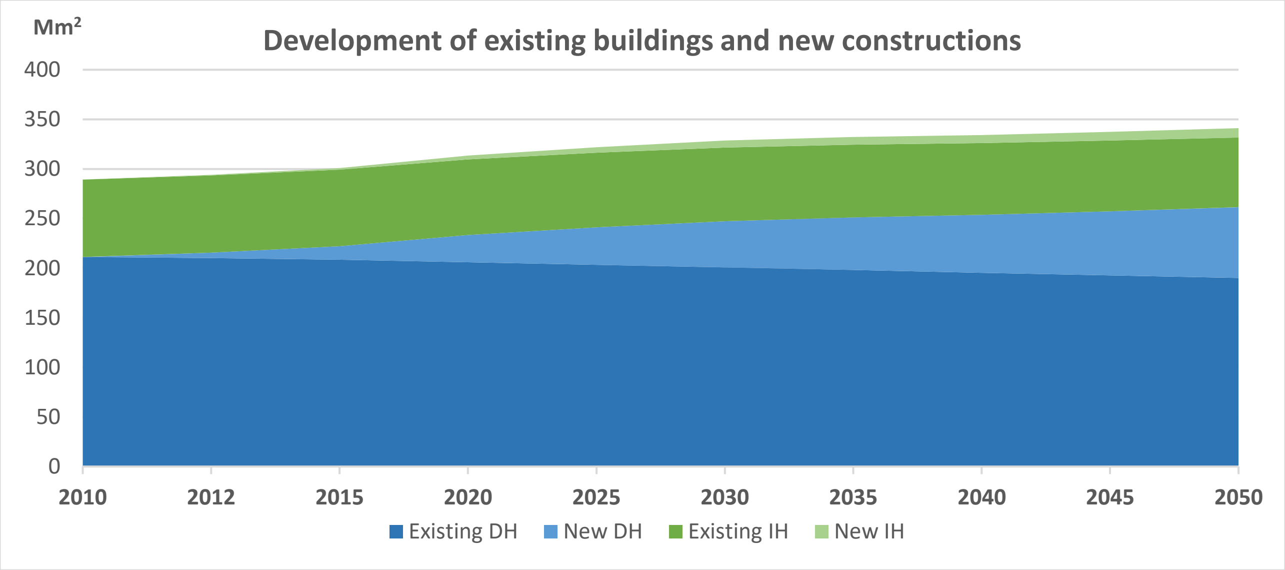

Figure 2.5: Development of the buildings in TIMES-DK. The amount of new housing in the District heating (DH) area is increasing far more the new housing in individual heating (IH) area.

The model meets the housing demand by use of certain technologies, which in the model convert heat energy into square-meters. Thus, these technologies represent the heating needed to supply a square-meter with heating for different types of households. This is modelled as a specified efficiency in Mm^2/PJ for each technology.

The efficiency of new houses is assumed to increase until 2020 and remain constant thereafter. Thus, it is assumed that new buildings built after 2020 will not be more efficient than they are in 2020. The efficiency of houses existing at the beginning of the time horizon can also increase in the

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[16] DREAM is an abbreviation for "Danish Rational Economic Agents Model".

[17] BBR is an abbreviation for "*Bygnings- og Boligregistret*" (Building- and housing registry).

model as a result of energy improvements. Increasing the efficiency of existing buildings has a cost parameter attached, meaning that the model can decide for itself if it is better to make buildings more efficient, or if it is better (for the system) to produce more heating.

Heat savings in existing houses are modeled by defining additional technologies, which produce a certain amount of heating without using any fuel input (i.e. heat savings are modelled as heat generation technology). This means that part of the demand is covered by “heat saving technologies”. This effectively incorporates heat saving potentials into the model. Figure 2.6 illustrates the concept.

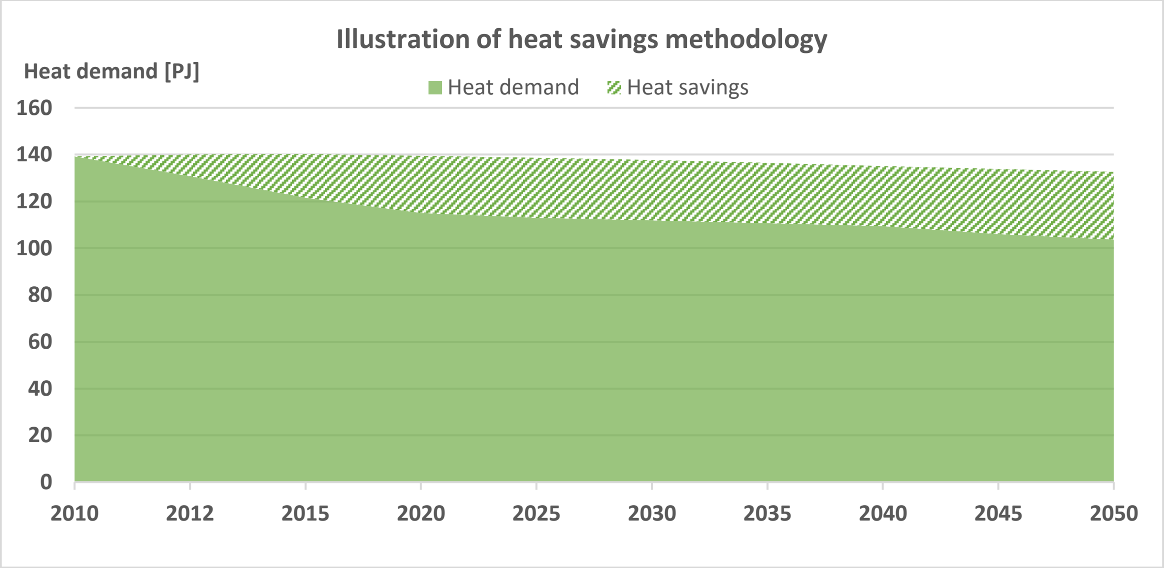

Figure 2.6: The net heating demand in the residential sectors is decreasing. Note that the heat savings “production” is illustrative, and can vary between 0 and 93 PJ. The combined area shows the projected heat demand.

The sum of the two areas in the figure show the total demand for heating in the residential sector. In this figure, the bottom area represents the actual heating produced in the model, while the top area represents the heating produced from “heat saving technologies”. This means that the top area represents the heat savings achieved throughout the model horizon. Note that the figure is only illustrative, and that the model may choose freely to invest less in heat savings, and simply produce more heating (i.e. increase the size of the bottom area).

2.3.3.2 Industrial demand

The energy demands in the industrial sector are specified in terms of different types of energy demands for different industrial sectors. The categories used for industrial sectors are shown below in Table 2.4 (leftmost column) together with the assumed energy demands for different purposes in 2014. The same data is illustrated in Figure 2.7. The industrial demand data are based on the VMAS surveys of energy services and energy matrices from Statistics Denmark (Technical University of Denmark & The Danish Energy Agency, 2017).

Demand in 2014 [PJ]	Heat Medium Temp. up to 150C	Heat High Temp. over 150C	Heat Room Heat	Light	Electric Motors	Haulage Tractors, Trucks, Fishing boats, Forest machines	Haulage Forklifts
Agriculture	11.8	0.2	0.4	1.8	4.9	16.1	0.1
Food	12.1	0.5	1.7	0.8	8.3	-	0.1
Chemical	4.2	0.5	0.7	0.4	4.3	-	-
Glass & Concrete	7.0	5.2	0.3	0.2	2.5	-	0.1
Metal	1.4	2.3	3.9	1.3	5.1	-	0.1
Other	2.8	0.2	1.5	0.7	3.0	-	0.1
Motor vehicles	0.1	-	1.1	0.6	0.6	-	-
Sales	0.6	-	9.2	6.2	4.9	-	-
Private Service	0.9	-	12.6	5.3	4.0	-	-
Public Service	1.2	-	15.5	5.7	3.6	-	-
Construction	5.7	0.2	0.1	0.2	0.8	-	0.0
Other Utilities	0.1	-	1.5	1.0	0.8	-	0.0

Table 2.4: Energy demand in the industrial sector by sector and purpose.

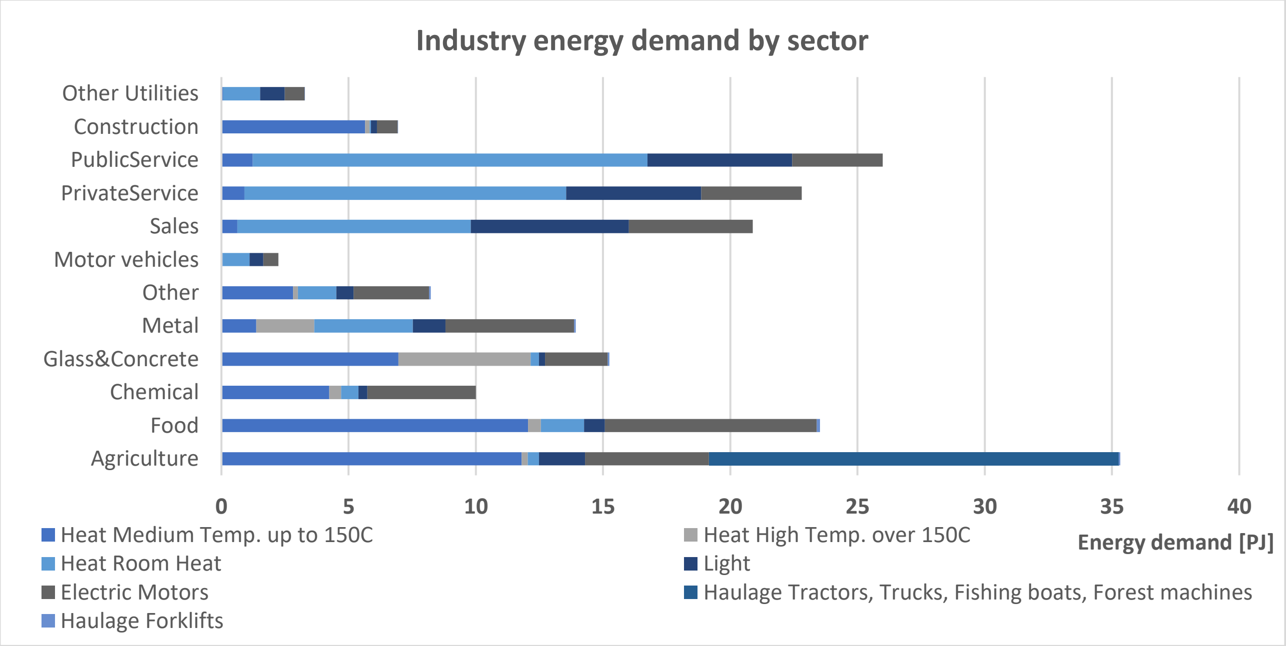

Figure 2.7: Energy demand in the industrial sector visualized by sector.

The industrial energy demands are expected to grow throughout the model horizon, as shown in Figure 2.8 below. The demand projections are based on the Ministry of Finance's Convergence Program for the Danish economy (Technical University of Denmark & The Danish Energy Agency, 2017). The projections are made with a focus on the economic development until 2020, and the projection is mostly a mathematical extrapolation with relative flat growth rates afterwards. The projection takes the following into account: 1) the North Sea oil extraction outlook, 2) development in workforce, including raising the pension age every five years, 3) development in labor productivity in services and manufacturing, and 4) that development in the growth of the public sector is fixed by policy.

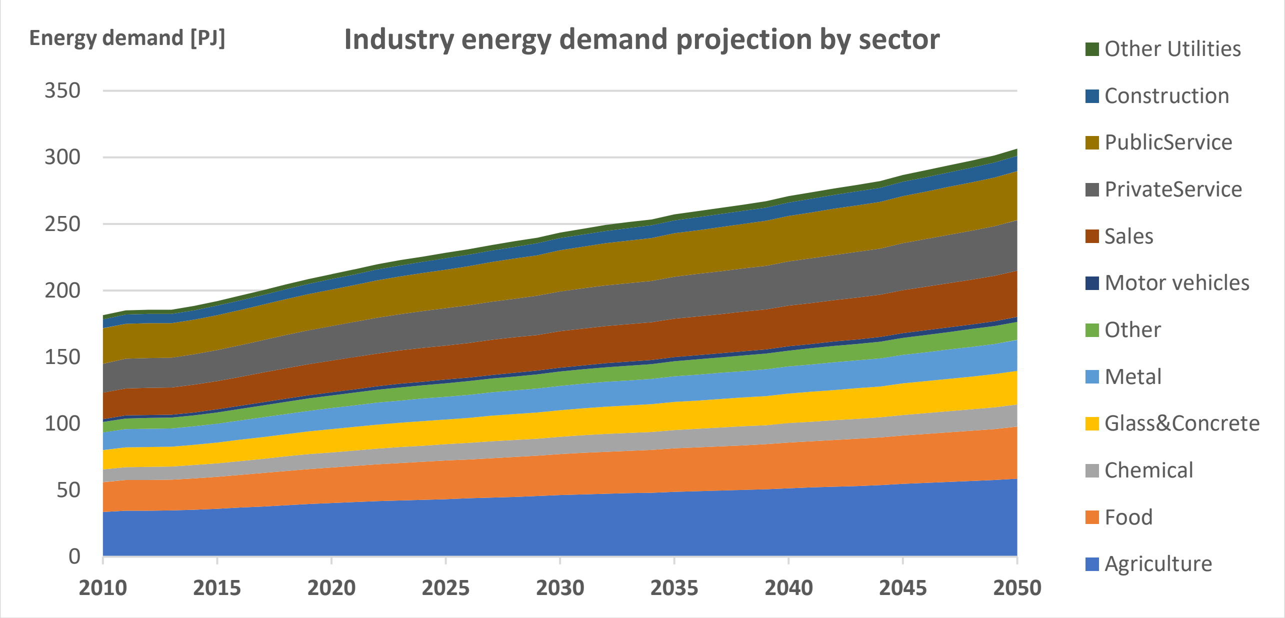

Figure 2.8: The energy demand used in TIMES-DK is expected to increase across all sectors.

The industrial demand increases consistently throughout all sub-sectors towards 2050 with the largest absolute increases in the agriculture and food industries. While many of the different types of demands can be met using a multitude of supply units, there are certain sectoral demands which require very specific supply functions. These include for example machinery in agriculture and construction, which only operate on diesel. On the other hand, medium temperature heating can be supplied from many different fuel types, e.g. fuel oil, wood pellets, electricity, etc.

2.3.3.3 Transport demand

The energy service demands in the transport sector are specified in terms of millions of passenger-kilometers (Mpass-km) for passenger transport, and millions of ton-kilometers (Mton-km) for freight of goods. The demands are provided for passenger and freight transport and divided into different vehicle types. The different types are listed in Table 2.5.

Passenger transport	Freight transport
Walking	Trucks
Bicycles	Vans
Cars	Trains
Motorbikes	Ships
Mopeds	Airplanes
Buses	
Trains	
Ships	
Airplanes	

Table 2.5: Overview of the transportation possibilities in TIMES-DK split in passenger- and freight demand.

The model has a specified demand for transport from each transport type for the entire model horizon. For example, this means that the model has to supply a certain demand for passenger-kilometers driven by cars by providing the model with sufficient cars to meet this demand. The demand for passenger transport in 2015 is shown in Figure 2.9 for different transport types.

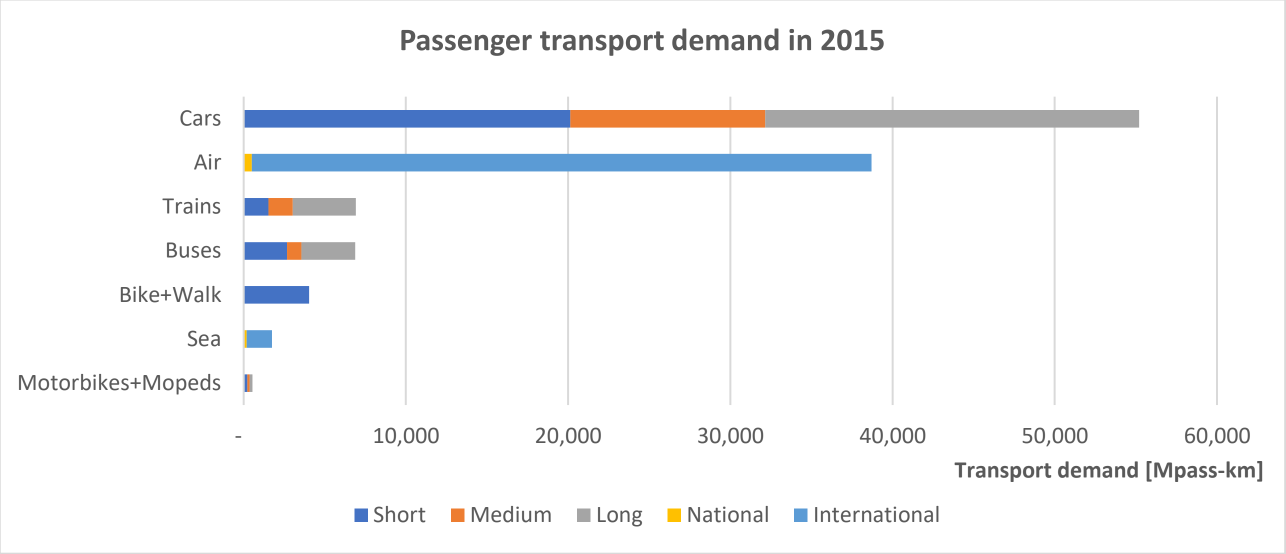

Figure 2.9: Passenger demand in 2015 per transportation type and distance.

The passenger transport demands are generally divided into short, medium and long distance demands for all land-based transport, while air and sea transport is split between national and international demands. The historical transport demands are based on data from The Danish Energy Statistics, while projected future demand is based on data estimated by the DEA (Technical University of Denmark & The Danish Energy Agency, 2017). The passenger transport demand projection is shown in Figure 2.10.

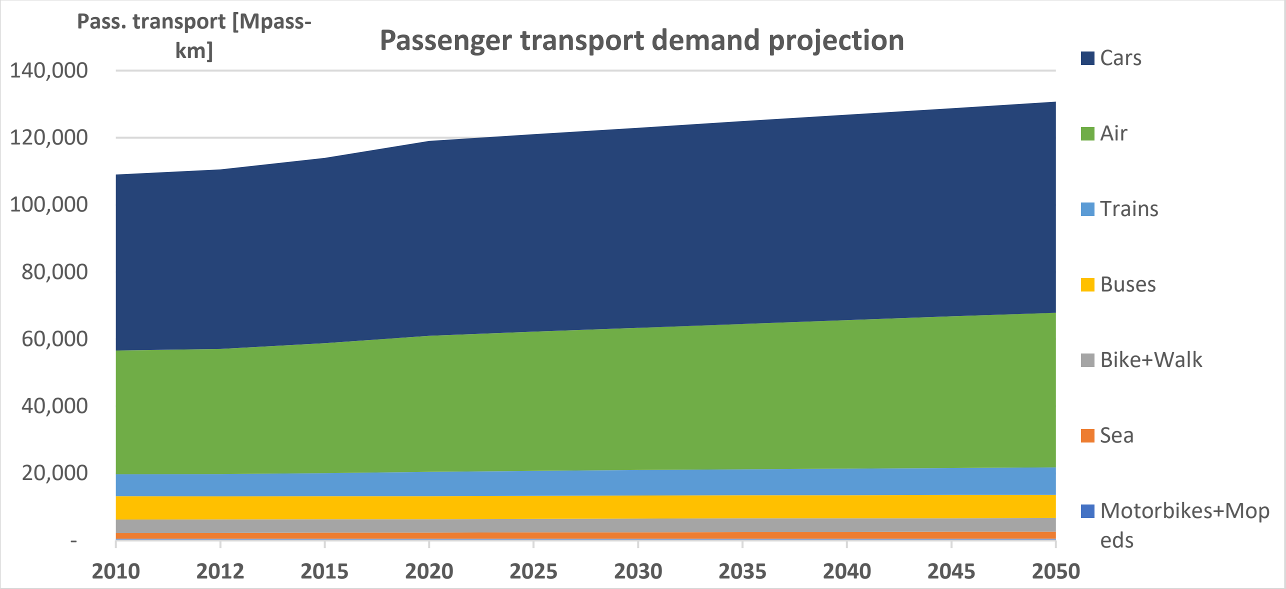

Figure 2.10: Expected development of passenger transport demand used in TIMES-DK.

The projected passenger transport demand shows an overall increase in transportation, primarily driven by increases in demand for air transport and car transportation. Thus, it is assumed in the model that the people in Denmark will generally travel more by air and drive more in cars than today.

The demand for freight transport is based on data from The Danish Energy Statistics (Statistics Denmark, 2017b). The freight demands are also divided into short, medium and long distance, as well as national and international transport. The demand projection for freight transport is shown in Figure 2.11. For illustrative purposes, the split between different categories of distances is not shown.

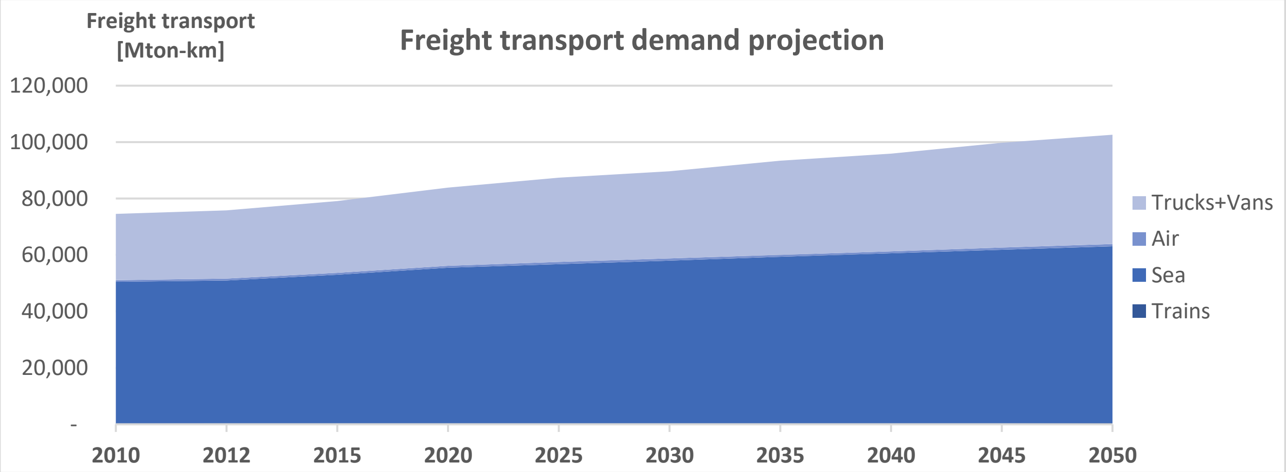

Figure 2.11: Expected development of freight transport used in TIMES-DK.

The freight demand projection is assumed to have a clear increase over the model horizon, almost entirely driven by increases in freight transported by sea and trucks/vans. This demand increase corresponds to an expected increase in domestic demand for goods, as well as an increase in expected export of goods.

2.3.4 Primary energy and resource supply

The second input needed for a TIMES scenario is a set of supply curves for primary energy and material resources. In TIMES-DK, primary energy commodities can be supplied from a number of sources. First, some commodities can be supplied to the model by means of *mining* technologies. These represent domestic production of a primary energy commodity. Only the extraction of crude oil and gas is included as mining technologies[18], while domestic production of other products, such as straw and wood chips, are made available through so-called *import* technologies. Import technologies represent the second source of energy commodities, namely import from commodity markets. These markets can be both national and international, meaning that the label *import technology* should not be understood too literally. Crude oil and natural gas are both available from mining technologies and import technologies.

Most primary energy commodities in TIMES-DK are generally assumed to be imported from national or international markets. If a commodity is imported from an international market, it is assumed to have unlimited potential. Commodities from national markets are modelled the same way as international markets, except for an additional constraint on maximum potential of the commodity. Some commodities are assumed to originate partly from domestic producers (national market) and partly from international markets. Examples of commodities that are available in TIMES-DK through international trading are coal, wood pellets and heavy fuel oil (HFO). For such commodities, the price is specified exogenously based on the International Energy Agency's (IEA) *World Energy Outlook 2016* and converted to Danish CIF[19] import prices (Danish Energy Agency, 2017c). Thus, it is assumed that Denmark is always a price-taker for these commodities, i.e. Denmark is not able to affect the price in the international market. This assumption is fairly realistic, especially for coal and HFO, where the consumption in Denmark is very small compared with the total volumes traded in the market. It is more likely that Denmark is able to affect the market price for industrial grade wood pellets, especially in the short- to medium term, by increasing or decreasing consumption. According to Hawkins Wright, Denmark accounted for 12 % of global industrial wood pellet demand in 2015 (Hawkins Wright, 2015).

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[18] For technical modelling reasons, the "production" of ambient heat is also modelled as a mining technology.

[19] Cost, Insurance and Freight (CIF) prices include the costs of the goods delivered + insurance costs + freight costs to the port of destination.

The prices of commodities supplied from national markets are also specified exogenously and are based on DEA projections (Danish Energy Agency, 2017c).

2.3.4.1 Fuel price assumptions

As mentioned above, fuel prices are based on IEA's *World Energy Outlook 2016* and converted to Danish CIF imported prices by the DEA. The most important prices used in scenarios are shown in Figure 2.12, while all fuel price data is given in Appendix 01.

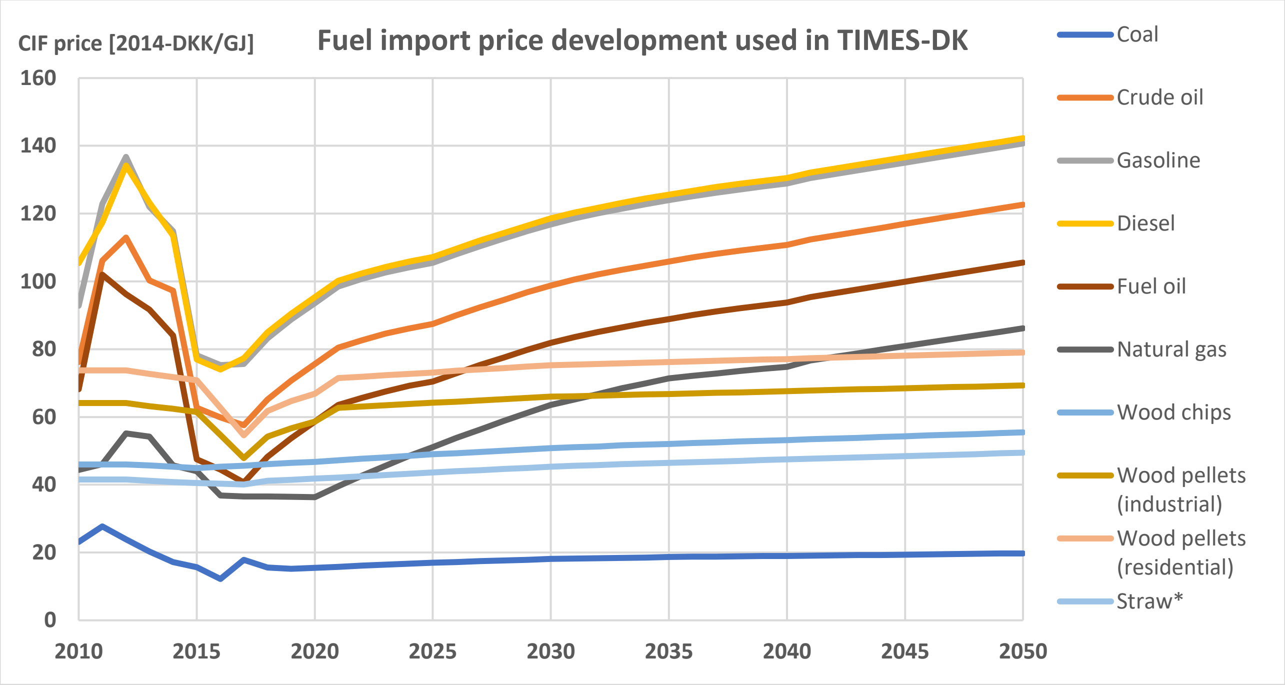

Figure 2.12: Expected fuel price development of imported fuels.
**Note that straw is not an import price, but is the price of straw delivery from within Denmark.*

Prices for 2010 to 2015 are historical and based on data from Statistics Denmark, while 2017 to 2040 are price projections from the DEA. 2016 is estimated as an average of 2015 and 2017 values, while 2041 to 2050 are extrapolated with the trend from 2031 to 2040.

2.3.4.2 National resource potential

Commodities that are assumed to be supplied solely from national markets are limited to a certain maximum potential in order to align the model with estimated national potentials. Commodities restricted to national supply are bio-products and waste, and their assumed national potentials are shown in Table 2.6. Note that wood chips are limited to 80 PJ, which is twice the national potential according to the DEA (Danish Energy Agency, 2014). This commodity potential is doubled in order to allow for some import of wood chips from the international market.

National commodity potentials [PJ]	2010	2050
Straw	68(1)	118(1)
Manure	14.5(2)	13.8(2)
Wood chips	80(1)	80(1)
Sugar beets	10(3)	15(3)
Rapeseed	10(3)	15(3)
Organic waste	1.9(3)	4.2(3)
Waste	32.2(3)	49.2(3)

Table 2.6: Overview of national biomass resource potential used in TIMES-DK.
(1) Assumption is 148 PJ from DEA minus sugar beets and rapeseed potential (Danish Energy Agency, 2014)
(2) Source: (Agrotech, 2013)
(3) Source: (Technical University of Denmark & The Danish Energy Agency, 2017)

The limited bio-potentials in turn limit the potential for domestic biofuel production. The production of biofuels from bio-products is further described in Section 2.3.5.7. It is assumed in the model that biogas is not imported, but liquid biofuels are available for import (e.g. biodiesel or bio-kerosene).

The entire waste potential is assumed to be used in the model. This is modelled by forcing the model to use all waste available each year. This is done because we want to make sure waste is used for energy rather than simply dumped in landfills.

2.3.5 Technology assumptions in the model

TIMES-DK includes a long list of technologies, which transform the primary energy commodities into other energy commodities, which are necessary to meet the end-use demands specified above. The technologies can be divided in two categories. First, there are a number of *existing* technologies, i.e. technologies which represent those technologies that exist at the beginning of the model horizon. Second, there are a number of *new* technologies. These are technologies that the model can choose from when making investment decisions, i.e. when building new capacity. The assumptions regarding existing capacity and new technologies are described in the following for each sector, i.e. electricity and heating, residential, industrial and transport. In addition, there are certain *supplementary* technologies, which are described subsequently.

2.3.5.1 Existing technologies in the electricity and heating sectors

As mentioned above in Section 2.3.1, the TIMES-DK model simulates the period from 2010 to 2050. At the beginning of the time horizon, there is an existing mix of technology capacities in all sectors. These are specified exogenously for the model, thereby providing the model with a starting point. Since we are now in 2017, the existing technology base is updated so the model includes all capacity installed today. Furthermore, it includes expected installations for the remainder of 2017 and planned capacity until 2022. This means that ultimo 2016, the model includes installed electricity and heating capacities as specified in the Energy Producers Count, the Wind Data Registry and data for solar PV (Danish Energy Agency, 2016b) (Danish Energy Agency, 2017b) (Energinet.dk, 2017). Expected new capacities for the remainder of 2017 are as specified by the DEA in the latest *Baseline Projection* (Danish Energy Agency, 2017a).

Those capacity installations, which are planned until 2022, are also exogenously imposed in the model, meaning that these capacities are forced into the model. The planned capacities are defined based on the latest DEA *Baseline Projection*, and include installation of the offshore wind farms *Horns Rev 3* and *Kriegers Flak*, as well as the near-shore wind turbines, which have planned start of operation ultimo 2019 (Energinet.dk, 2016c). Furthermore, it includes installation of solar PV and onshore wind equal to the expected capacity increase estimated by the DEA. The planned capacities also include a number of thermal plants, such as the *BIO4* project being built by HOFOR, as specified in the background report for the *Baseline Projection* (Danish Energy Agency, 2017a). In extension of this, it is assumed that *Funen Power Station* and *North Jutland Power Station* both extend their lifetime and continue with coal as main fuel.

We take into account the recent public statement from DONG Energy A/S, saying that the company will stop using coal from the beginning of 2023. In this context, we assume that their remaining non-bio-converted plants, *Esbjerg Power Station* and *Asnæs Power Station*, will both be converted to use wood chips instead of coal by the end of 2022, as stated as a likely scenario on their website (DONG Energy, 2017).

2.3.5.2 New technologies available in the electricity and heating sectors

Throughout the model horizon, TIMES-DK can decide to install new capacity to meet the specified end-use demand. In order for the model to make these decisions, it has a large database of technology types to choose from. The primary technology types available are shown in Table 2.7. The technology parameters change over time, since technologies are expected to mature over time. This is modelled as new technologies throughout the model horizon, e.g. the model has a new type of offshore wind turbine available every 5 years.

Technology	Type of plant	Available fuel inputs
Pulverized fuel CHP	CHP	Coal, wood pellets, natural gas$^{(1)}$
Gas turbine single cycle	CHP	Natural gas$^{(1)}$
Gas turbine combined cycle	CHP	Natural gas$^{(1)}$
Waste-to-energy CHP	CHP	Waste
Biomass CHP	CHP	Wood chips, straw
Onshore wind turbine	Power	-
Offshore wind turbine	Power	-
Solar photovoltaic cells	Power	-
Wave power	Power	-
Large scale electric heat pump	Heating	Electricity
Absorption heat pump	Heating	Flue gas
Electric boiler	Heating	Electricity
Biomass boiler	Heating	Wood pellets, wood chips, straw
Natural gas boiler	Heating	Natural gas$^{(1)}$
Geothermal heating w. absorption HP	Heating	Steam
Geothermal heating w. electric HP	Heating	Electricity
Solar heating	Heating	-
Waste-to-energy boiler	Heating	Waste

Table 2.7: Overview of new technologies available in the electricity- and heating sector.
(1) Natural gas includes synthetic natural gas

All cost and performance data for technologies in the electricity and heating sectors are based on the most recent DEA *Technology Catalogue* (Danish Energy Agency, 2016c). This catalogue includes expected values for all important technology parameters until 2050, such as minimum capacity, lifetime, construction time, efficiency, investment cost, variable- and fixed operation and maintenance costs, etc.

2.3.5.2.1 Renewable energy potential

The model includes certain limits on the potential for renewable energy capacity, which are shown in Table 2.8. These limits are based on estimates from various sources, as indicated in the table. The possible maximum capacity of a technology is limited by natural constraints as well as constraints on technology development.

Renewable potential [MW]	DKW	DKE
Onshore wind	3,600	700
Offshore wind	47,500	2,500
Solar PV	5,400	3,600
Solar heating	9,782	5,650
Wave power	3,175	-
Geothermal	437	192

Table 2.8: Overview of renewable capacity potentials used in the TIMES-DK.
Source: (Technical University of Denmark & The Danish Energy Agency, 2017)

The most important limitations in the table are the limits for onshore wind and solar PV, since these technologies are becoming increasingly favorable in terms of cost. Thus, it is very likely that the limit will be reached for these technologies, also if the limit is greatly increased. The limit on onshore wind capacity is set to a total of 4.3 GW across Denmark. This limit is based on an analysis by Energinet.dk, which estimate that there is a total potential in Denmark of 12 GW, but that it is necessary to buy private-owned property and provide compensation to neighbors when capacity exceeds 4 GW (Energinet.dk, 2015a). Due to this and the complications regarding site approval and neighbor complaints, it is assumed that the maximum capacity in the base case scenarios will not exceed the capacity installed today plus expected capacity until 2022. The impact of allowing a larger onshore wind capacity is investigated in Section 3.5.1.3 of Chapter 3.

The limit on solar PV is set to a total of 9 GW across Denmark. This limit is based on an analysis by PA Energy Ltd., which estimate a total potential of around 18-20 GW if 100 % of all south-facing rooftops are used for solar PV in Denmark (PA Energy Ltd., 2016). In our scenarios, we thus assume that the maximum solar development potential is 50 % of their estimated limit.

2.3.5.2.2 Maximum annual rate of capacity installation

In addition to the renewable potentials described above, there is a constraint in TIMES-DK on how much renewable capacity can be built each year. The maximum annual build rates are shown in Table 2.9. The maximum build rates are set to model a certain limit on resources (manpower, machinery, etc.) available to construct new capacity.

Maximum annual build rate [MW]	DKW	DKE
Onshore wind	200	200
Offshore wind	600	200
Solar PV	200	200
Solar heating for DH	80	165
Wave power	200	200
Geothermal	200	200
Industrial heat pumps	80	165
Residential heat pumps	50	30

Table 2.9: Overview of the build rates used in TIMES-DK to ensure a steady installation of renewable energy capacity per year. Source: (Technical University of Denmark & The Danish Energy Agency, 2017)

The build rates limit the possibility for a sudden spike in installed capacity over the model horizon, thereby forcing the model to phase in capacity over time, e.g. if it wants to have a certain capacity of a technology in 2050. Other technology types than shown in Table 2.9Table 2.7: Overview of new technologies available in the electricity- and heating sector. are not limited, because they are not economically attractive enough for the model to create sudden spikes in capacity.

2.3.5.3 Existing technologies in the residential sector

The existing stock of technologies in the residential sector can be divided into two categories of technologies. First, there are heating technologies for supplying the residential heat demand. Second, there are electricity consuming appliances, which are specified in terms of the number of appliances existing at the beginning of the model horizon. The mix of existing heating technologies are based on data from the *DTU Energy Atlas*, the *Heating Model* and *Danish Energy Statistics* (Technical University of Denmark & The Danish Energy Agency, 2017). Data for the existing stock of electric appliances comes from the Danish Energy Statistics (Danish Energy Agency, 2015b).

The stock of existing heating capacity in the residential sector is shown in Figure 2.13 and the existing stock of electric appliances are shown in Figure 2.14.

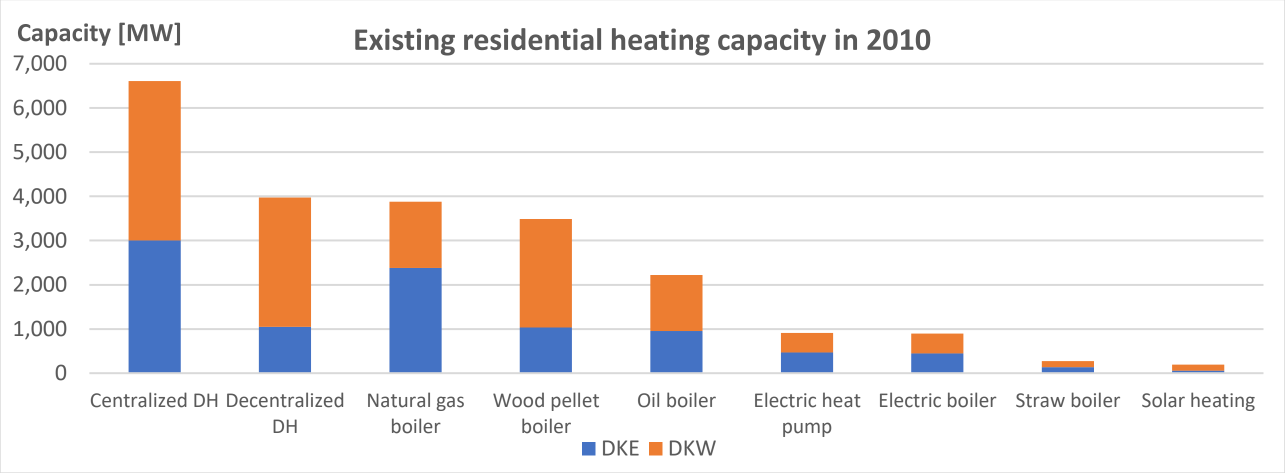

Figure 2.13: Existing heating capacities in the residential sector at the start of the model time horizon.

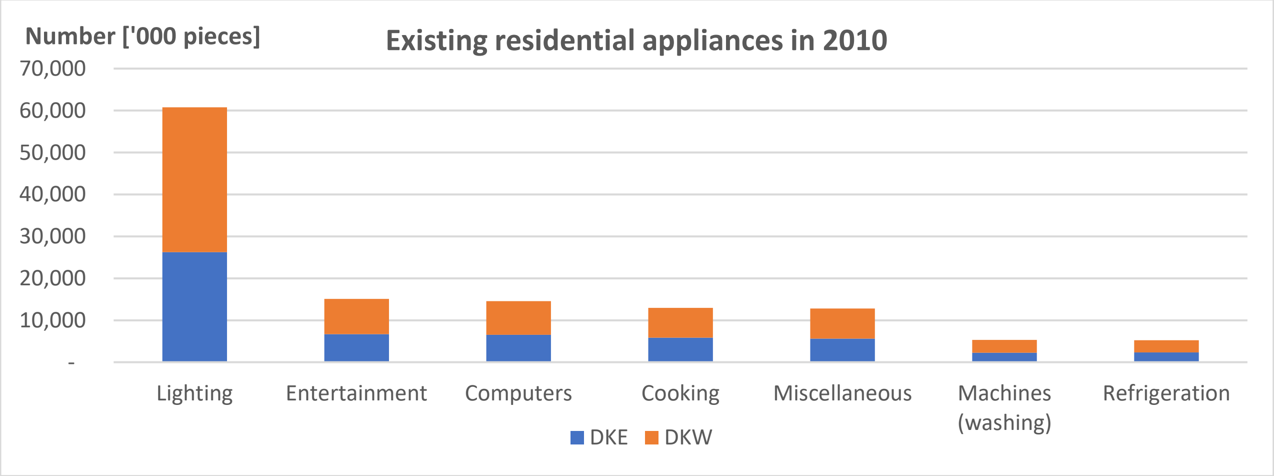

Figure 2.14: Existing number of residential appliances at the start of the model time horizon.

2.3.5.4 New technologies available in the residential sector

The model only has one type of technology available to choose from when making new investments in electric appliances. This means that there is essentially only one type of computer available to meet the demand for computers. Similarly, there is only one type of lighting available to supply the demand for light. However, the technologies are vintage over the time horizon, meaning that they become more efficient over time.

In regards to residential heating, the model has a few more options to choose from when making investment decisions. For residential heating, the model can choose between all technology types described by the DEA in their *Technology Catalogue for Individual Heating and Energy Transport* when deciding to replace some of the existing stock (Danish Energy Agency, 2013). The cost and operation parameters for these technologies are specified based on data from this catalogue. Similar to the electricity and heating sector, the cost and operation parameters for residential heating technologies also develop over time as technologies mature.

2.3.5.5 Technologies in the industrial sector

The industrial sector is modelled with a relatively high number of energy demands and technologies. The sector has 12 different sub-sectors, each of which can have up to 7 different types of energy end-use demands. These sub-sectors and end-use demands were shown above in Table 2.4.

Some of the industrial demands can be met by simply using electricity from the grid or using the available district heating. Other demands need technologies installed in the industrial sector specifically, e.g. the demand for high temperature heat can only be supplied by an on-site boiler. Whenever industry needs on-site technologies for production of heating or a specific service (e.g. industrial transport), the model will have at least one technology type available to supply the end-use demands. In most cases, there are multiple technologies available, which can supply an end-use demand in a specific sector. For example, there are 5 types of technologies, which can supply the glass and concrete sector with medium temperature heat.[20]

The technologies defined for the industrial sector for providing heat at different temperatures are primarily based on data from the technology catalogues for energy plants and individual heating plants by the DEA (Danish Energy Agency, 2016c) (Danish Energy Agency, 2013).

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[20] These are boilers using different fuels, namely natural gas, coal, diesel, electricity and wood pellets.

2.3.5.6 Technologies in the transport sector

As described in Section 2.3.3.3, the transport sector has specific demands for each type of vehicle, e.g. cars, trains, airplanes and ships. The model can meet these demands for passenger transport and freight transport by using technologies from an extensive technology catalogue. This means that each aggregated category of vehicle (e.g. cars) has multiple technology types. For example, the *Cars* category consists of diesel cars, gasoline cars, electric cars, hybrid cars, natural gas cars, fuel cell cars, etc. Similar, there are diesel- and electric trains. Airplanes can be fueled by kerosene (bio- and conventional) and aviation gasoline, while ships are fueled by diesel blends and heavy fuel oil.

The number of vehicles, trains, airplanes, ships, etc. that exist at the beginning of the horizon is shown in Table 2.10 divided by fuel input.

Number of vehicles in 2010 [‘000 vehicles]		**Gasoline**	**Diesel**	**Electric**	**Kerosene**	**HFO**	**LPG**
Freight	Airplanes	-	-	-	-	-	-
	Trains	-	0.06	0.04	-	-	-
	Ships	-	-	-	-	1.3	-
	Trucks	-	32	-	-	-	-
	Vans	-	461	-	-	-	-
Passenger	Airplanes	-	-	-	1.07	-	-
	Buses	-	15	-	-	-	-
	Cars	1,674	468	0.26	-	-	0.01
	Motorbikes	205	-	-	-	-	-
	Trains	-	0.33	0.28	-	-	-
	Ships	-	-	-	-	0.24	-

Table 2.10: Overview of the existing amount of vehicles in the transportation sector at start of model time horizon.

The technologies available for the model to choose from when making new investments in the transport sector are based on data and parameters from the DEA’s *Alternative Propulsion Model* (Danish Energy Agency, 2016a). Similar to the remaining sectors, the cost and performance parameters for the transport sector develop over time as technologies mature.

2.3.5.7 Supplementary technologies

In addition to the technologies in the four sectors described above, i.e. electricity and heating, residential, industry and transport, there are a number of *supplementary* technologies in the model. These technologies include conventional oil refineries, biogas plants, biorefineries and hydrogen production plants. There can be multiple plant types within each category. For example, biogas plants include biogas production from mono-digestion of pig slurry and co-digestion of straw or sugar beets. Biorefineries include production of biodiesel, bio-kerosene and bioethanol from different biological sources, e.g. wood chips, corn and straw. Lastly, hydrogen can be produced by means of coal gasification, biomass gasification or alkaline electrolyzers. Note that this is not a full list of supplementary technologies. For a full overview, we refer to the model files available in Appendix 01. The cost and performance data for these plants is primarily based on data from the

DEA's *Technology Data for Advanced Bioenergy Fuels* report (FORCE Technology, 2013). There are many other sources of information behind the data used in the model. These are stated where they apply in Appendix 01.

2.3.6 Policy settings and constraints

The last constituent of a complete TIMES scenario is a policy setting. The ability to apply practically any desired policy in the model is one of the great advantages of the TIMES model setup. In the TIMES-DK model, we use the policy setting to analyze the effects of different policies on the energy system development. We use the ability to apply policies to test different policies and provide policy recommendations. However, there are some policy settings, which remain constant in all scenarios in this study. These include assumptions related to the EU ETS, as well as phasing out of the PSO tariff between 2017 and 2022. The EU ETS assumptions are described in the following. Subsequently, we introduce the methodology used regarding policies and constraints for answering our primary objectives.

2.3.6.1 EU ETS assumptions

The EU ETS is included in the model, i.e. the cost of emission allowances are applied to the industry, electricity and heating sectors where applicable. The EU ETS prices are specified exogenously and are based on values from the DEA (Danish Energy Agency, 2017c). Prices are shown in Figure 2.15. The future price for emission allowances in the EU ETS market are of course difficult to estimate and thus very uncertain. This is taken into account in Chapter 3, where sensitivity analysis is performed on EU ETS prices, fuel prices and other parameters.

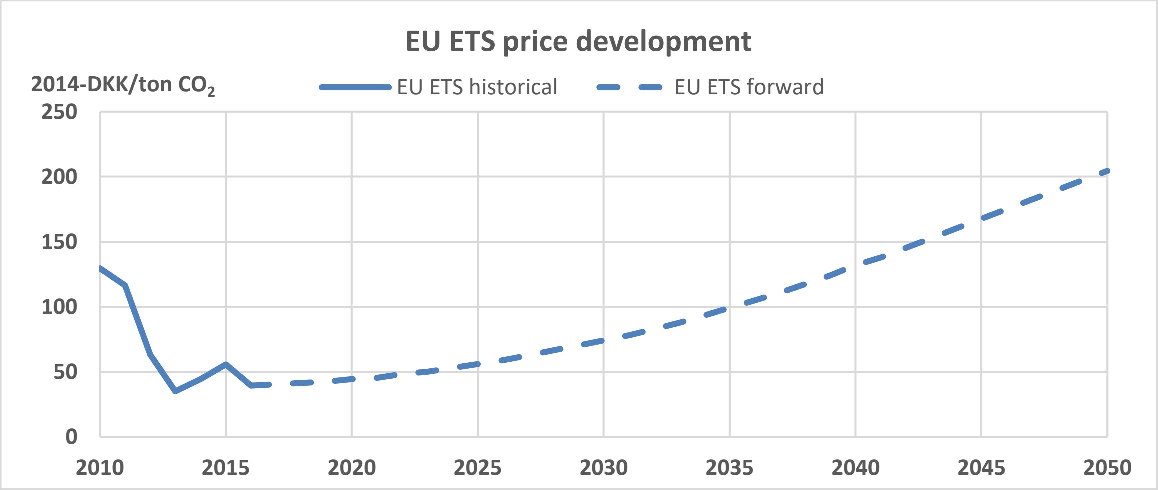

Figure 2.15: Projection for the EU ETS prices used in TIMES-DK.

The EU ETS prices are historical for 2010 to 2016 and DEA price projections for 2017 to 2040. The price is extrapolated with the trend from 2017 to 2040 for the years 2041 to 2050.

2.3.6.2 Frozen policy scenario

The *Frozen policy* scenario is made with the purpose of investigating if the current regulatory incentive structure is likely to ensure compliance with the GHG emission reduction target for 2050. In this scenario, the existing legislation is included for as long as it applies. This means that all taxes are included throughout the model horizon (i.e. until 2050), while subsidies are being removed at different times in the model horizon, as stated in the applicable legislation. This means that current subsidy schemes are not prolonged after their current expiration date. The scenario is similar in setup to the *Baseline Projection* by the DEA. Figure 2.16 below outlines the assumptions regarding policies and capacity installation included in the model.

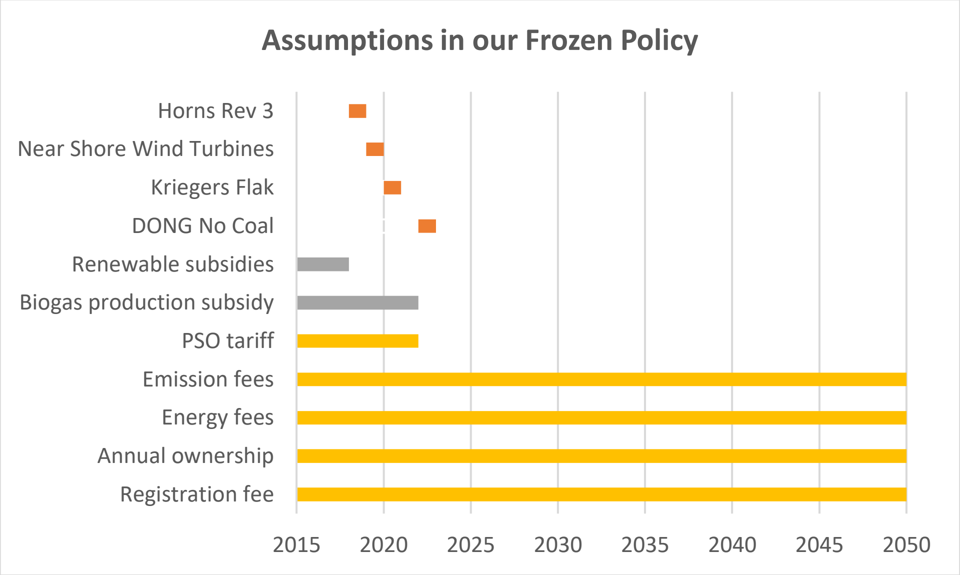

Figure 2.16: Overview of assumptions used in our Frozen Policy scenario.

In this scenario, the model is allowed to operate freely, i.e. there are no constraints on GHG emissions. Therefore, the scenario represents a good indicator for the future energy system development if the regulatory framework remains unchanged. The results from this scenario will therefore show a likely path for future CO_2 emission levels under current policy.

2.3.6.3 R2050 – A recommended 2050 energy system

In the *R2050 scenario*, we use the model to outline a cost-efficient and sustainable energy system for 2050, which meets the political targets for GHG emission reduction. This means that we use the model to define a mix of technologies and energy commodities, which will be relatively cheap to implement and is a sustainable, long-term solution for keeping GHG emission levels at a minimum post 2050.

In this scenario, all existing taxes (except for taxes on externalities) are removed from 2020[21], while existing subsidy schemes are removed after they expire. The reason for this is to give the model “free hands” to construct a least-cost energy system without the interference of government intervention on the costs and revenues of specific technologies. The difference in incentive structure from the *Frozen Policy* scenario is therefore that the taxes are also removed.

The *R2050* scenario is subject to a constraint on CO_2 emissions, which forces the model to construct an energy system without fossil fuels. The constraint reduces the emission of fossil CO_2 to zero from 2035 onwards.[22] The reason for constraining the emissions to zero already in 2035 is to force the model to construct an energy system in 2050, which will also be cost-efficient in the long-term after 2050. Since we are not able to simulate the model past 2050, this is a good approximation of an energy system, which is also cheap to maintain in the long-term. This method was invented as a result of a scenario, where the model is only constrained on CO_2 emissions according to the policy targets, i.e. 40 % reduction in 2030 compared with 1990 level and zero emissions in 2050. This scenario allows the model to construct a last-minute, short-term energy system in 2050, i.e. a sudden change just before 2050, to ensure compliance with the constraint. However, since this is not a sustainable energy system, the method of moving the zero emission constraint forward to 2035 has been introduced. The *R2050* scenario is described in further detail in Section 3.3 of Chapter 3.

2.3.6.4 Guidelines for policy changes

In the *Incentive Structure* scenario, we aim to recreate the 2050 energy system provided by the *R2050* scenario by use of an updated incentive structure, thereby showing how to go from the *Frozen Policy* scenario to the *R2050* scenario. In the *Incentive Structure* scenario, we remove the constraints on emissions, which are used in the *R2050* scenario, and introduce a new set of energy policies, which results in an energy system in 2050, which is approximately equal to the recommended *R2050* energy system. This scenario represents a likely energy system development if the incentive structure is changed according to our recommendations.

The updated incentive structure is found by analyzing the differences between the *Frozen Policy* scenario and the *R2050* scenario, and using those differences to estimate the changes to the *existing* incentive structure that are necessary to achieve the *R2050* energy system. This process is repeated iteratively to ensure that the energy system development driven by the incentive structure is as close as possible to the recommended energy system in 2050.

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[21] The taxes are not completely removed, but are set equal to the minimum tax rates set forth by the EU (European Commission, 2003). The minimum tax rates are very small compared with existing taxes, so the effect of the taxes on the system development is drastically reduced.

[22] Emissions of biogenic CO_2 and CO_2 from combustion of waste is still allowed past 2035.

2.4 Improvement potentials for TIMES-DK

In this section, we describe some of the improvement potentials for TIMES-DK identified in the process of conducting this project. In this regard, we provide our suggestions for future improvements that might further improve the model's resemblance of reality.

2.4.1 More detailed geographical resolution

The TIMES-DK model currently models two regions, namely DKW and DKE. Modeling a larger number of regions would make it possible to more accurately differentiate costs and resource potentials across local areas. For example, having two regions creates a total of four isolated district heating grids when combined with the split between centralized and decentralized district heating. A more detailed geographical resolution would make it possible to better depict local-only resources, such as geothermal heating potentials or sea water for sea water heat pumps (if these are included in the model). Furthermore, it would make it possible to better differentiate costs and resource potentials for wind energy.

2.4.2 Chronological and more detailed time-slicing

When using the most detailed time-slice level in TIMES-DK, there are a total of 32 time-slices, which combined represent one year. These time-slices are aggregated groups of annual hours, which are similar in terms of electricity demand and renewable energy (solar and wind) potential. This grouping of hours into aggregated time-slices means that the time-slices are not chronological. If the model was changed to use chronological time-slices, it would be easier to represent energy storage across different time-slices. Furthermore, a more detailed time-slice levels (e.g. hourly time-slices) would provide the possibility for a more accurate matching of supply and demand, especially in the electricity sector.

2.4.3 Technology improvements

In practice, implementing new technology capacity in the energy system requires both energy and material resources. However, the effects of increased demand for technology capacity on the demand for energy is not included in TIMES-DK. This issue means that the model is not using a cradle-to-grave approach. Rather, the current model represents an energy system where the production and construction of new capacity simply appears without increasing demand temporarily. Adding this to the model can potentially impact the computation of market equilibria.

Another suggestion for technology improvements is to include the option of investment in additional interconnector capacity to neighboring countries, i.e. to allow the model to decide to invest in additional capacity for import and export of electricity. When given exogenously specified electricity prices for other countries, this would allow the model to choose to install additional interconnector capacity rather than additional production capacity. Of course, adding this possibility to the model would require the specification of constraints, which limit the potential import and export to other countries in each time-slice. This is so the model does not simply consider the connected country a “black hole” where infinite amounts of electricity can be exported to or imported from.

2.4.4 Representation of existing regulatory framework

There are a few areas in the model, where representing the existing regulatory incentive structure correctly is complicated or not entirely possible. First, due to the nature of CHPs (i.e. the production of two products from combustion of one commodity) it is difficult to add a tax or subsidy on a specific fraction of the fuel input, e.g. the fraction allocated to heat production. This is especially the case when adding a subsidy on electricity production from CHPs, which can use both subsidized and non-subsidized fuels for electricity production. The method used in this study is to add the subsidy to the consumption of the subsidized fuel and use the specified electrical efficiency of the plant to convert a legally defined subsidy on electricity output to a subsidy on fuel input. However, since some CHPs can operate with some flexibility on the ratio of electricity to heat production, the resulting subsidy paid to the CHP only approximates the subsidy that should have been paid, if the subsidy parameter could be defined for the electricity output.

Second, the model is not modelled in sufficient detail in regards to excess heat from industrial processes, since it is currently not possible for industry to use some (or all) of their excess heat internally. Since the regulation distinguishes between excess heat used internally and externally, a better representation of this would allow for a more precise application of taxes on excess heat.

Lastly, the division of energy plants and industry into the ETS- and non-ETS sectors is currently very simple and remains constant throughout the model horizon. If the number of regions in the model was increased, as described previously, it might be possible to more accurately model the split between ETS and non-ETS.

2.4.5 Demands and markets

A market related suggestion is to create separate markets for importing e.g. wood chips from national and international markets, respectively. This will make it possible to specify different prices for national and international commodities.

A final suggestion for improving the TIMES-DK model is to include demand elasticities in the model. As previously described, one of the advantages of a TIMES model is that commodity demands are sensitive to their own prices. However, currently the TIMES-DK model simply specifies firm demands, which must be met in the optimization without elasticity.

Chapter 2

CHAPTER 3

Presentation of scenario results and guidelines for energy system development and policy changes

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Chapter 3

3.1 Overview

In this chapter, we describe the results of our 3 objectives outlined in the introduction. The first scenario is the *Frozen Policy* scenario, which shows the development of the Danish energy system if the regulatory incentive structure remains unchanged. We discuss the results for our first objective, namely to investigate if the current incentive structure is likely to ensure that we reach the 2050 target.

Second, we describe our recommended scenario for the Danish energy system in 2050. We call this scenario *R2050*. Using TIMES-DK, we develop an energy system for 2050, which is cost-efficient and sustainable in the long-term.

Third, we discuss our recommended policy changes, which we estimate will guide Denmark in the direction of the *R2050* scenario and meet the 2050 target. As the modelling of energy systems in the future is subject to a great deal of uncertainty, we will try to cover some of the most dominant factors in a sensitivity analysis.

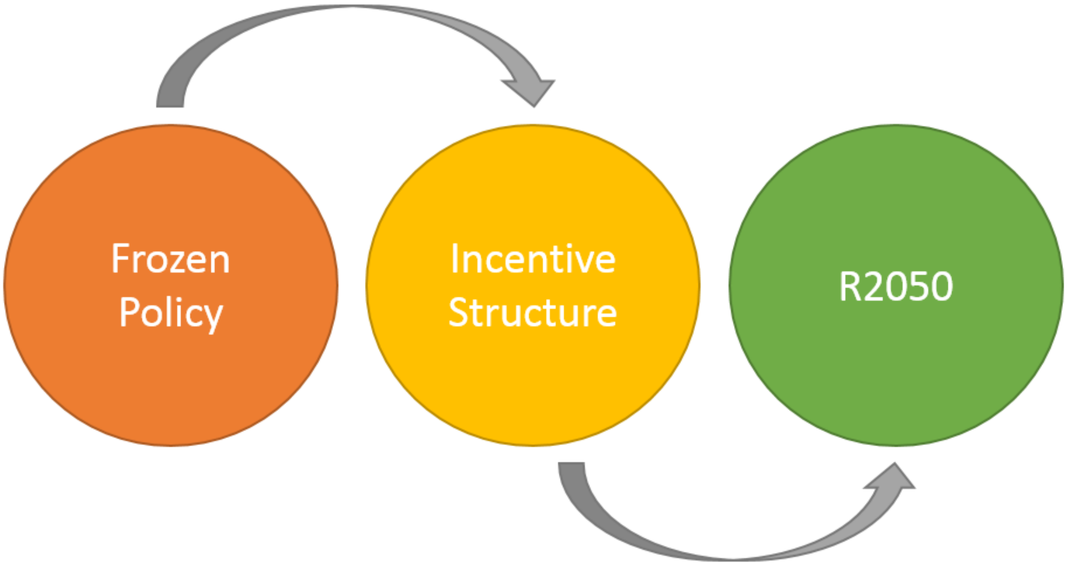

Figure 3.1: Our objective is to get from our Frozen Policy scenario to our recommended R2050 scenario, using only our Incentive Structure.

3.2 Frozen policy scenario

The first objective of this report is to investigate if the current regulatory incentive structure is likely to ensure compliance with the GHG emission reduction target for 2050. Each year the DEA publishes their annual *Baseline Projection*, which projects the development of the Danish energy system in the short- to medium term under a frozen policy (business-as-usual) scenario. This projection, which is based on a somewhat similar modelling framework to TIMES-DK, is generally one of the best estimates of how the Danish energy system will develop in the short- to medium term. However, their most recent projection includes only the expected development until 2030, and as such does not say anything about the long-term development until 2050. It is clear that these modeled projections are very uncertain even in the short- and medium term, and any attempt to project a development until 2050 should only be seen as a likely *direction* for the energy system, and not as a precise projection of energy system development.

Thus, to provide an indication of the direction of the energy system under frozen policy, and the likelihood of target compliance, we have used TIMES-DK to model a *Frozen policy* scenario until 2050. This scenario both tells the story of where the energy system is going, but also provides valuable input for the third and final objective of this report, namely to provide recommendations for policy changes, which will ensure compliance with GHG targets both in the short- and long term.

The *Frozen policy* scenario is modeled with similar assumptions as the DEA *Baseline Projection*, and includes all planned constructions of energy plants, such as new offshore wind farms and planned bio-conversions of CHP units. Furthermore, our *Frozen policy* scenario includes the recent statement from DONG Energy saying that they will phase out coal by the beginning of 2023. Therefore, our scenario is most similar to the alternative scenario described in the *Baseline Projection* (Danish Energy Agency, 2017a).

The *Frozen policy* scenario is mainly characterized by the fact that it is a *policy* scenario, where the existing legislation is included for as long as it applies. This means that all taxes are included throughout the model horizon (i.e. until 2050), while subsidies are being removed at different times in the model horizon, as stated in the applicable legislation, as described in Section 2.3.6.2. This means that current subsidy schemes are not prolonged after their current expiration date. In this scenario, the model is allowed to operate freely, i.e. there are no constraints on GHG emissions. Therefore, the scenario represents a good indicator for the future energy system development if the regulatory framework remains unchanged.

The following sections provide a detailed overview of the projected energy system development in the *Frozen policy* scenario. We begin by discussing the projected development in each sector of the energy system, and proceed to provide a conclusion to the first objective, namely if the current incentive structure will guide the Danish energy system towards the 2050 target.

3.2.1 Electricity sector

The Danish electricity sector is already well underway in the transition to renewable energy, primarily driven by increases in electricity production from wind turbines. Based on the results of our *Frozen policy* scenario, this trajectory is expected to continue until 2025 to a level of 71 % wind energy in electricity production. After 2025, the wind energy share is expected to decrease slightly, but increase again in 2050 to a level of 75 %. As will be shown later, the stagnation and slight decrease in the medium term is a result of a lack in electrification in other sectors combined with existing wind capacity being phased out at end-of-life.

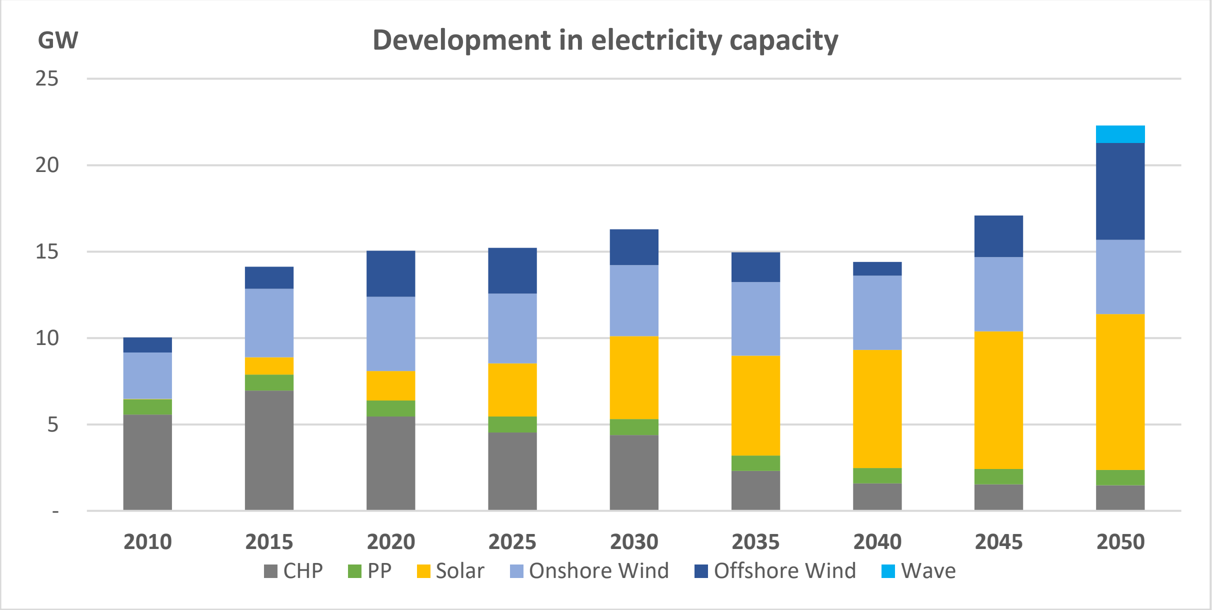

Figure 3.2: The development of electricity capacity in our Frozen Policy scenario.

In fact, no new offshore wind capacity is expected to be put in operation between 2020 and 2045, meaning that the last installed wind farms in that period are Horns Rev 3, Kriegers Flak and 350 MW of near-shore wind turbines. Onshore wind capacity remains at its maximum potential of 4.3 GW in the second half of the time horizon. The sudden increase in offshore wind capacity (and production) in 2045 and 2050 is a result of more electrification at the end of the time horizon as especially large-scale electric heat pumps become competitive with other sources of district heating production. The capacity of solar PV increases steadily to reach the assumed maximum potential of 9 GW in 2050.[23] There remains a small amount of power-only capacity, which are fossil power plants, which are built at the beginning of the time horizon and remain available until 2050.

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[23] Recall from Chapter 2 that 9 GW of solar PV is approximately equal to 50 % of all south-facing rooftops in Denmark.

However, they are barely used for electricity production, as shown in Figure 3.2, which shows the development in the electricity production, and includes the renewable energy share in the electricity production.

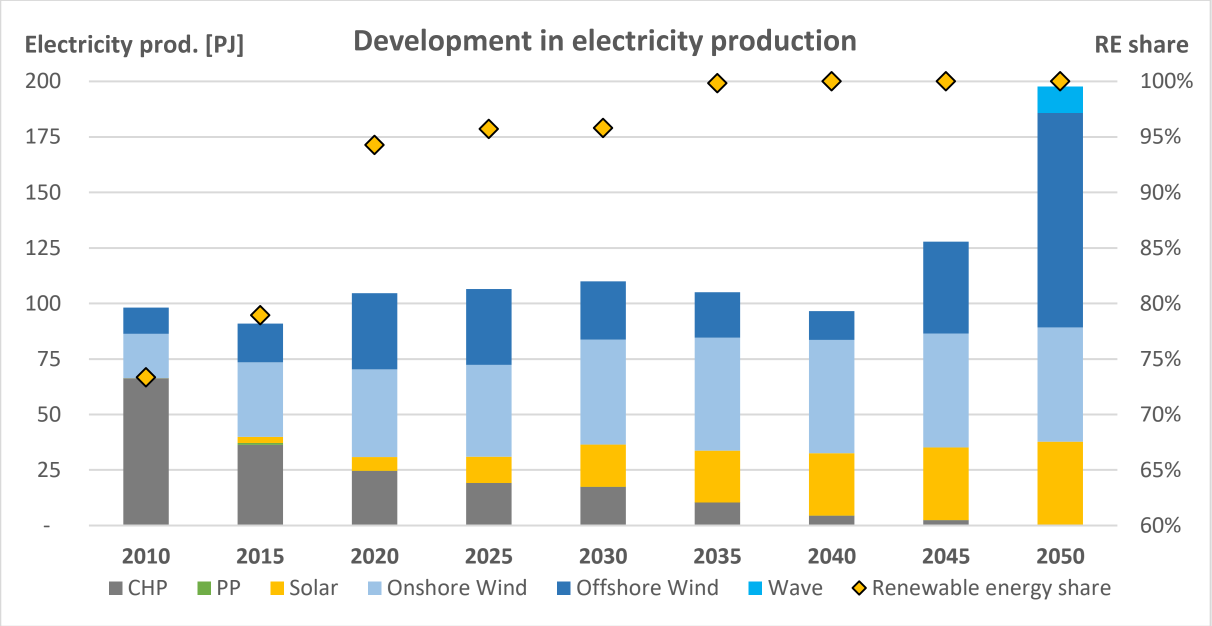

Figure 3.3: The development of electricity production in our Frozen Policy scenario.

The share of renewable energy in the electricity production is expected to increase significantly in the short-term until 2020, primarily driven by the installation of additional offshore wind capacity. In our projection, the renewable share reaches 100 % in 2035 and remains constant thereafter. The electricity production from CHPs is expected to continue to decrease throughout the time horizon and be almost entirely gone by 2050. This decrease is a result of the increasingly lower marginal cost of especially wind power and solar PV.

We estimate that Denmark will meet the expectation of 50 % wind in electricity production in 2020 as proclaimed in the *Energy Agreement of March 2012* (Ministry of Climate, Energy and Building, 2012). The projection shown in Figure 3.3 estimates this share to be 70 % in 2020. It should also be noted that wave power is expected to become competitive with offshore wind turbines after 2045, resulting in an expected installation of 1 GW by 2050. The model reaches its assumed annual maximum build rate for wave power of 200 MW per year from 2046 to 2050, as described in Section 2.3.5.2.2.

3.2.2 District heating sector

The district heating sector is expected to have an increasingly larger share of renewable energy, with the projection showing a large increase already in 2020, as shown in Figure 3.4. In this figure, all waste and excess heat is considered renewable, regardless of the fuel type used in the process. Electric heat pumps are here considered partly renewable and the share is dependent on the renewable energy share of electricity in the particular year (i.e. they are 100 % renewable from 2035 onwards, as shown above in Figure 3.3).

It is important to note here that it is unlikely that such a large increase will actually occur in the short-term. The reason the model can achieve this can be partly contributed to the fact that TIMES-DK currently only models two regions and partly to the fact that the investment cost of all existing technologies in the model are assumed to be sunk costs. It is therefore more cost-efficient for the model to invest in new technology, while leaving the existing capacity available but unused.

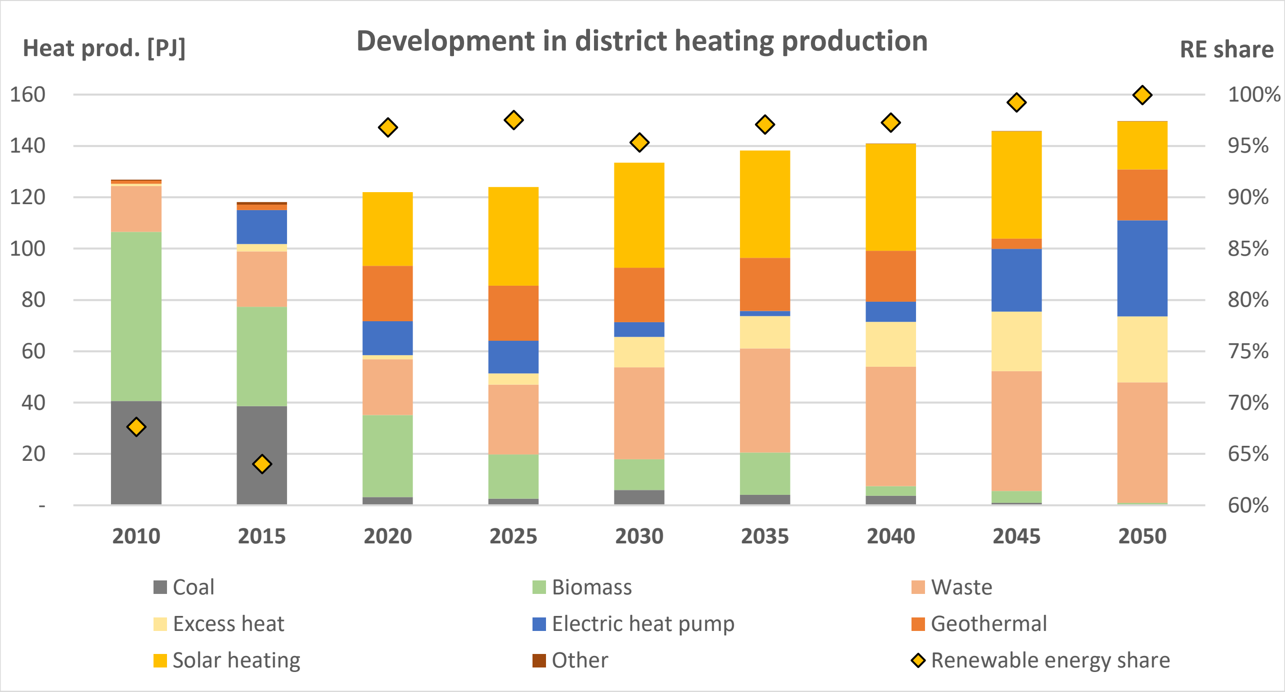

Figure 3.4: The development of heat produced in the district heating sector.

The development in the district heating production has multiple facets. The projection removes most coal from 2020 onwards, while biomass is slowly phased out. The phase-out of biomass is mainly caused by the removal of the current subsidy on electricity production from biomass in 2018, which causes biomass CHPs to stop operation. It is shown on Figure 3.6 below, that the share of biomass will peak in 2020 by 64 PJ heat production if the subsidy scheme is prolonged.

The decrease in coal and biomass is replaced with a large share of solar heating, which remain a dominant source of district heating until 2045, after which it decreases. Furthermore, we expect an increase in district heating from combustion of waste, since the amount of waste available is expected to increase, and electricity production from waste combustion becomes less competitive. Thus, more of the available waste is used for heat-only production. Also, due to an expected increase in biofuel production for the transport sector, an increasing share of the district heating demand is expected to be supplied with excess heat from these processes. Large-scale heat pumps have a share in the market throughout the time horizon, but see a large increase in 2045 and 2050. This is primarily because they are expected to become more competitive, also under the current tax scheme. Lastly, there is a certain amount of geothermal heating (all using absorption heat pumps) throughout most of the horizon.

In summary, the electricity and heating sectors are both likely to continue the upwards trajectory for renewable energy share under our *Frozen policy* scenario. While coal is being phased out, renewable energy sources such as wind, solar PV and wave power are being phased in. The combined development in fuel consumption in the electricity- and heating sectors is shown in Figure 3.5.

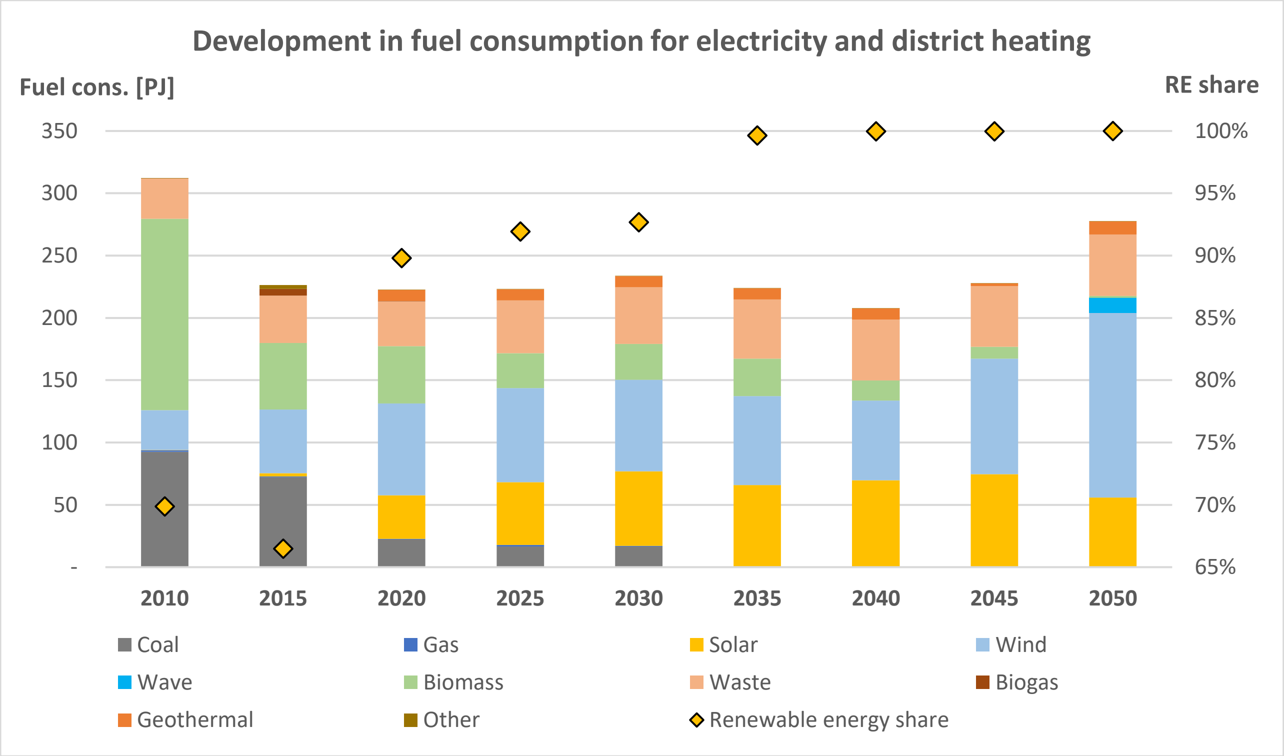

Figure 3.5: Development of fuel consumption for electricity- and district heating production.

We estimate that by 2050, the only sources used for electricity and district heating production will be intermittent renewables, i.e. wind, solar and wave, combined with geothermal energy and waste incineration for district heating production. We mentioned in Chapter 1 that the district heating sector is likely to increase its share of biomass in the short-term. However, an important condition for such a development is a prolonged subsidy on the use of biomass for electricity. In our *Frozen Policy* scenario, this subsidy is removed in 2018, causing the biomass share to decrease and remain low. Thus, our *Frozen Policy* scenario shows that intermittent renewable energy sources will be more competitive than import of wood pellets under the assumed market conditions. The impact of a prolonged subsidy on biomass is shown below in Figure 3.6, which is similar to the *Frozen Policy* scenario in all other aspects.

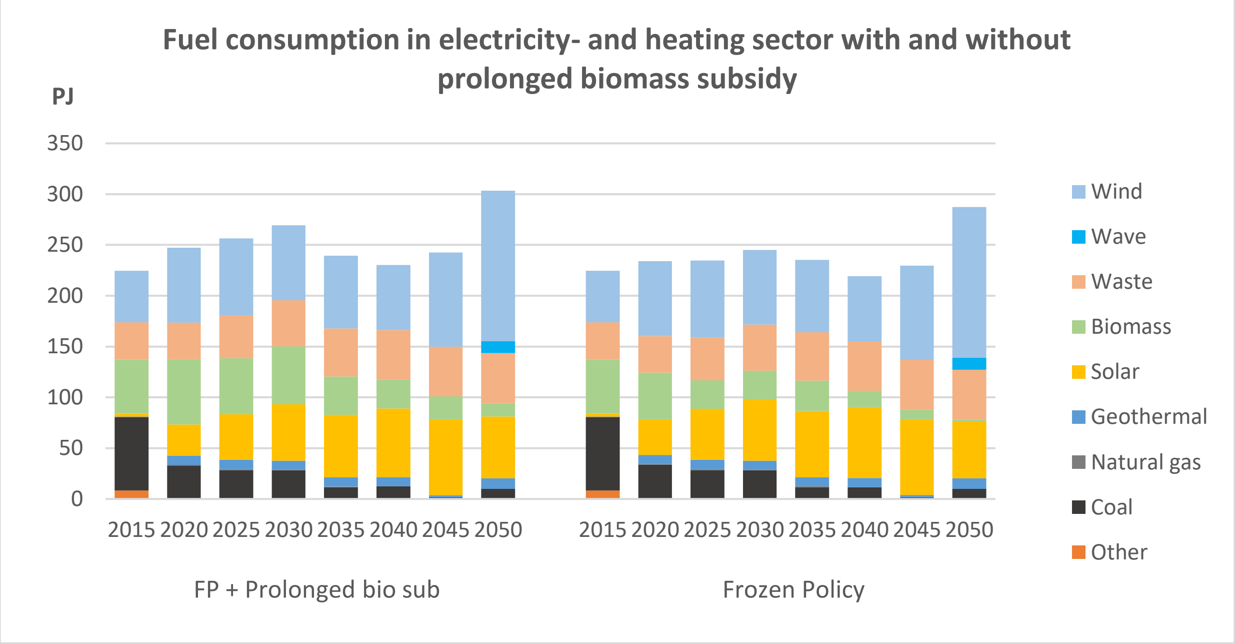

Figure 3.6: The effect of prolonging the current biomass subsidy on fuel consumption in the electricity sector.

It is clear from the figure that the biomass share in electricity- and heating will be more likely to remain high in the medium term if the subsidy scheme is extended. Thus, the analysis shows that continuing the current subsidy scheme until 2050 will increase the attractiveness of biomass as a transitional fuel. Prolonging the biomass subsidy until 2050 will benefit the business cases for existing electricity producers using biomass. However, the subsidy will affect the net tax revenue and increase overall system costs as solar PV is cheaper for the overall energy system, which affects the increased electrification needed in 2050.

3.2.3 Industrial sector

The fuel consumption in the industrial sector is expected to increase following the increase in demand, as was shown in Section 2.3.3.2 in Chapter 2. However, the transition towards renewable energy is very slow in the industrial sector, which generally rely about 50 % on consumption of fuels locally and 50 % on consumption of grid electricity and district heating. The share of renewable fuels in local fuel consumption is expected to increase towards 2050, but have a remaining fossil fuel share of 25 % in 2050 as seen on Figure 3.7.

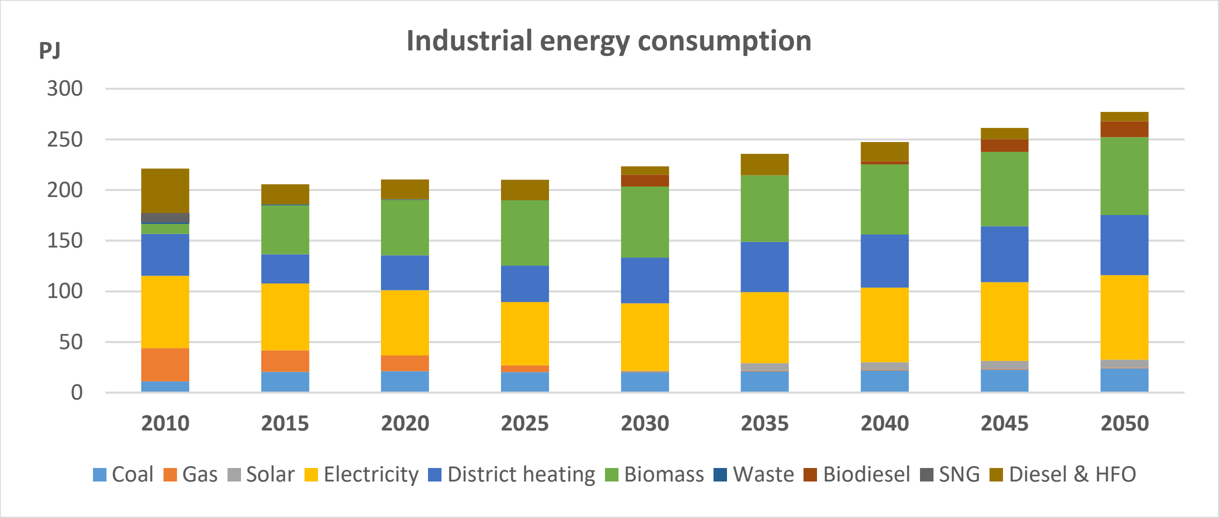

Figure 3.7: Development of the energy consumption in the industrial sector.

The most notable element in the expected development in the industry sector is that biomass is expected to increase by about 60 % in 2050 compared to 2015, replacing primarily natural gas and accounting for some of the increased demand in 2050. However, coal is expected to contribute with roughly the same amount of fuel input in 2050 as in 2015. The main reason why the industrial sector is not expected to have the same degree of change as the electricity- and heating sector is that all process energy in Denmark is reimbursed for almost all energy fees, resulting in an effective tax rate on energy equal to the EU minimum tax rates.[24] Therefore, industries that currently use fossil fuels are lacking an incentive to move away from the cheap fossil fuels, because of the current incentive structure. The reason for the lack of strong signals in the incentive structure in the industry is to allow the industry to be competitive on international markets. However, the expected development indicates a need for an incentive structure in the industry, which provides a stronger incentive to replace fossil fuels with renewable alternatives. This is true if we want to ensure that this sector also complies with GHG reduction targets.

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[24] Except for gasoline, which a taxed by the full tax according to the Danish legislation.

3.2.4 Residential sector

The demand for energy in the residential sector is expected to decrease over the model horizon, as was shown in Section 2.3.3.1 of Chapter 2. This is true for both the residential electricity demand and the demand for space heating, primarily due to the replacement of old buildings with new ones. Since all residential appliances use electricity, this section will only focus on the development in the supply of space heating for the residential demand. This development is shown in Figure 3.8.

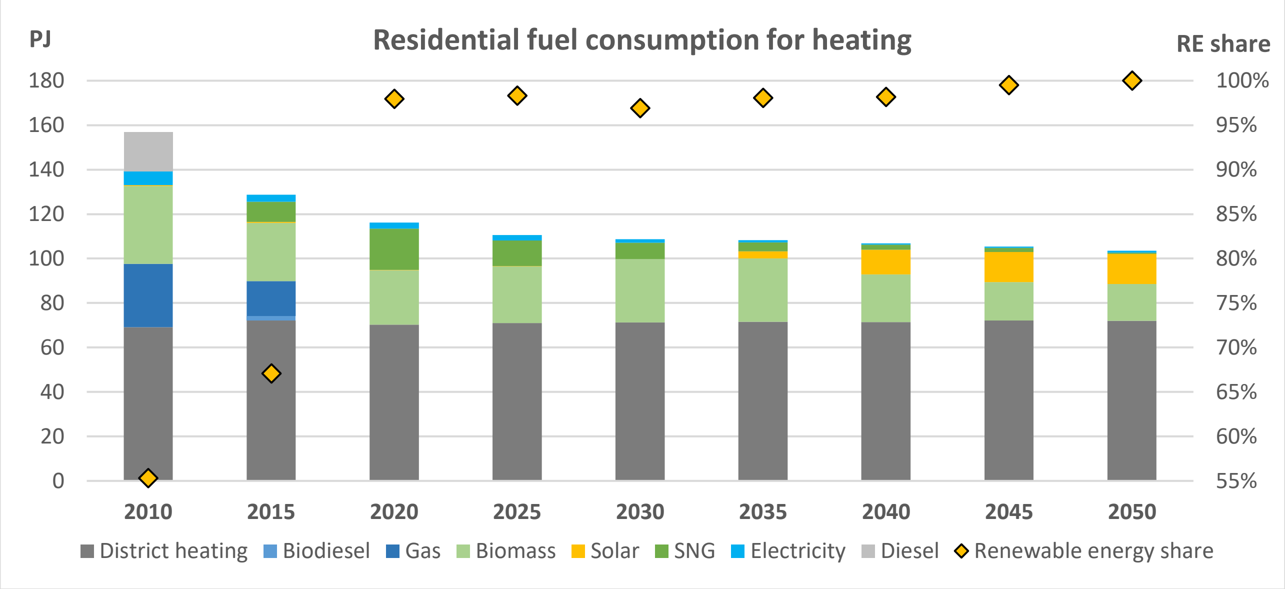

Figure 3.8: Development of fuel consumption in the residential heating sector.

The share of district heating is expected to increase from 56 % in 2015 to 70 % in 2050. The remaining 30 % of the heat demand in 2050 is supplied by individual heating technologies. The individual heating will mostly be wood pellet boilers, solar heating and a small amount of synthetic natural gas. The small share of electric heat pumps will be almost completely phased out by 2040, primarily due to the high cost of electricity for residential heating (i.e. including taxes and transport costs). Overall, the residential heating sector is expected to have a renewable energy share of almost 100 % in 2050, with a large increase expected between 2015 and 2020, primarily driven by the phasing out of natural gas in residential heating. While it is not likely that natural gas will be completely phased out of residential heating by 2020, the model here provide an insight into the most optimal development for the energy system as a whole under the specified assumptions for market- and framework conditions.

3.2.5 Transport sector

The transport sector is the sector most dominated by fossil fuels today in the Danish energy system with fossil fuels still covering 95 % of the energy consumption in the sector today (Danish Energy Agency, 2017a). Change in the transport sector is generally slow due to the transport demand being strongly dependent on tried, tested and cheap vehicles. We estimate that the renewable energy share in the transport sector will remain low until 2050, as shown in Figure 3.9.

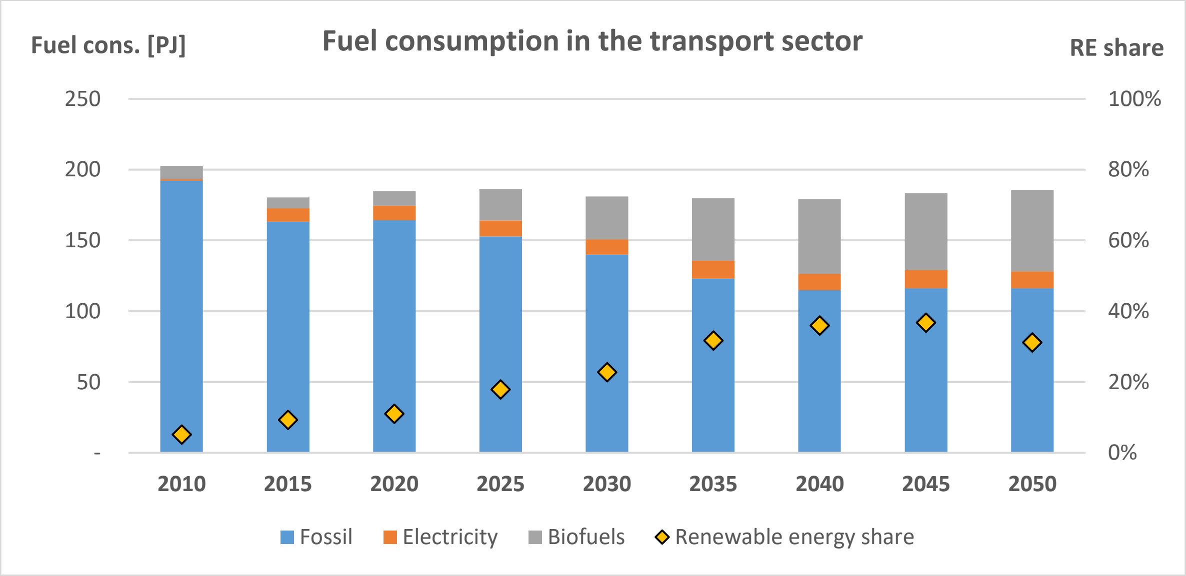

Figure 3.9: Development of the fuel consumption in the transportation sector.

We estimate that there will only be a small amount of electrification in the transport sector, while the share of biofuels is expected to increase from 4 % in 2015 to 31 % in 2050. Note that the figures here include the entire transport sector, i.e. land, sea and air transport. Some vehicle types in the transport sector are not able to be replaced with non-combustion vehicles, e.g. aviation and shipping. Thus, the only available renewable alternative to fossil fuels for these vehicles is biofuels. While biofuels are gaining a larger market share in the projection, they are still not able to compete fully with conventional, fossil fuels.

When zooming in on the development in personal cars over the time horizon, we see an increasing share of natural gas cars towards 2050, which is replacing diesel and gasoline cars. This is shown in Figure 3.10. Furthermore, the share of electric vehicles is expected to be almost non-existing under the current regulatory framework.

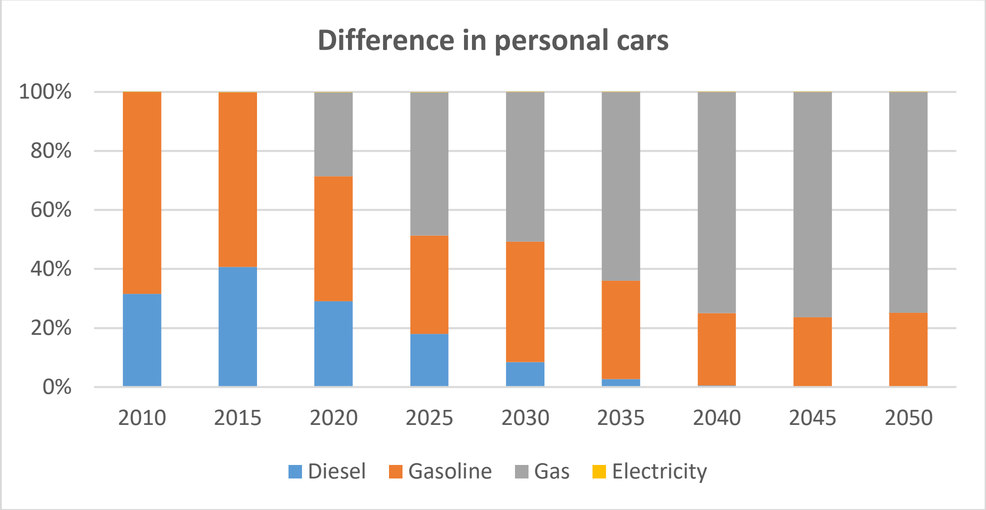

Figure 3.10: Development of capacity distribution of personal vehicles.

The relatively small amount of electricity consumption in the transport sector combined can primarily be attributed to the development in rail transport as seen on Figure 3.11. The share of electric trains in both passenger transport and freight is expected to increase steadily and be fully electric in 2040.

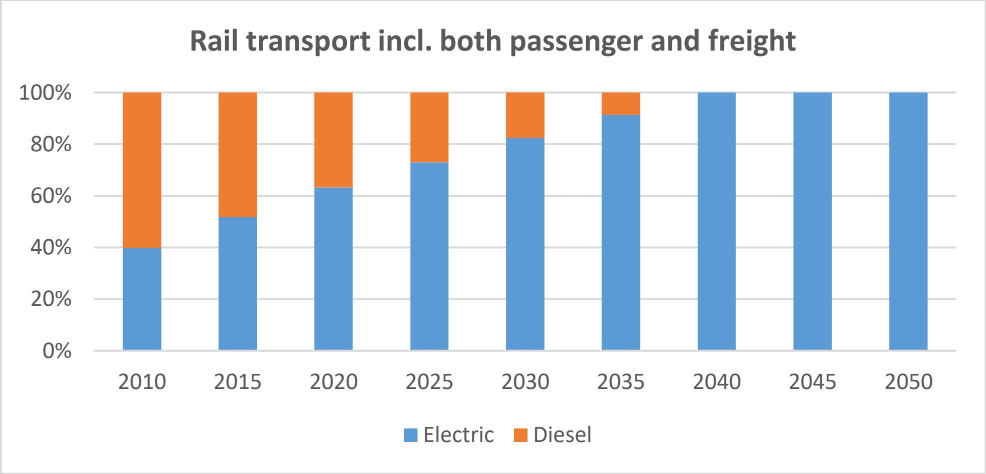

Figure 3.11: Development of capacity distribution of rail transportation

It is clear that there is a need for political initiatives if the transport sector is to transition completely too renewable energy. However, we estimate that the transport sector will meet the target of 10 % renewable energy by 2020, and will achieve a renewable energy share of 11 %.

3.2.6 Net revenue from taxes and subsidies

In 2015, 23 % of the total Danish tax revenue came from taxes related to the energy sector, e.g. energy fees, emission fees and the registration fee on cars (Danish Ministry of Taxation, 2017a).[25] Since this is a large share of the total annual tax revenue, any significant changes in the incentive structure may have a substantial impact on the Danish national budget. Thus, an evaluation of future revenue streams from the energy and transport sectors should therefore be included in considerations regarding policy changes. Figure 3.12 presents the estimated future net revenue from taxes and subsidies under the *Frozen policy* scenario.

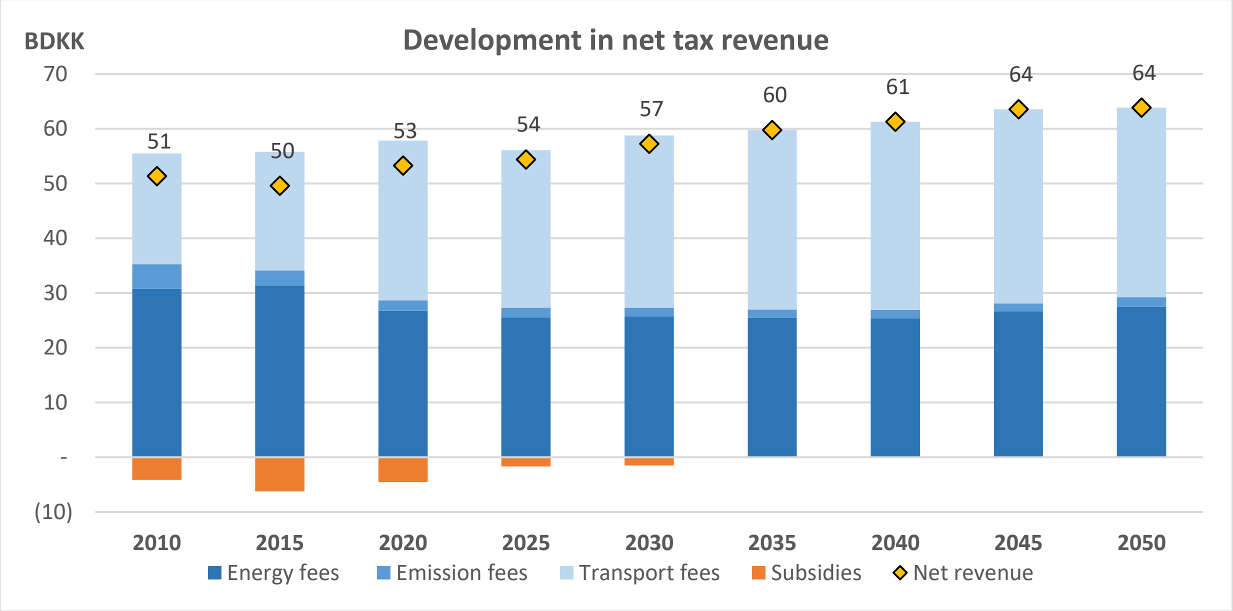

Figure 3.12: Development in the net tax revenue in our Frozen Policy scenario.

The tax revenue from energy fees and emission fees is expected to decrease for the first half of the time horizon and increase slightly towards the end of the horizon. The latter is primarily driven by an increased tax revenue from electricity fees, which is caused by an increased consumption of electricity at the end of the horizon. The net tax revenue is generally increasing throughout the time horizon, which can be contributed partly to the phasing out of subsidies and partly to an increase in the tax revenue from the fees on transport, i.e. registration fee, weight fee and the fee on fuel efficiency. Thus, the development in the *Frozen policy* scenario is estimated to have a net increased tax revenue over the model horizon.

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[25] Our calculation includes all energy fees (34 BDKK), CO2-, SO2- and NOx emission fees (4.5 BDKK) and registration-, annual ownership- and road utilization fee (29 BDKK).

3.2.7 Projection for CO_2 emissions

The Danish national target of becoming a so-called *low emission society* in 2050 can be interpreted in many ways. Similar, the progress toward that goal can be measured in many ways, e.g. by the level of GHG emissions, CO_2 emissions or by the share of renewable energy in the energy system. The estimated projection of CO_2 emissions from the energy system development in the *Frozen Policy* scenario is shown in Figure 3.13. Since TIMES-DK most likely does not include all sources of CO_2 emissions, we have added an adjusted CO_2 emission to the figure, which is equivalent to the resulting emission from TIMES-DK multiplied by a correction factor of 1.4. This correction factor is calculated based on the difference between the emission from TIMES-DK in 2015 and the actual measured CO_2 emission according to (Joint Research Center, 2016). Note that this method only approximates the actual emission that would occur in the specific energy system, since TIMES-DK does not model the exact same energy system in 2015 as actually existed.

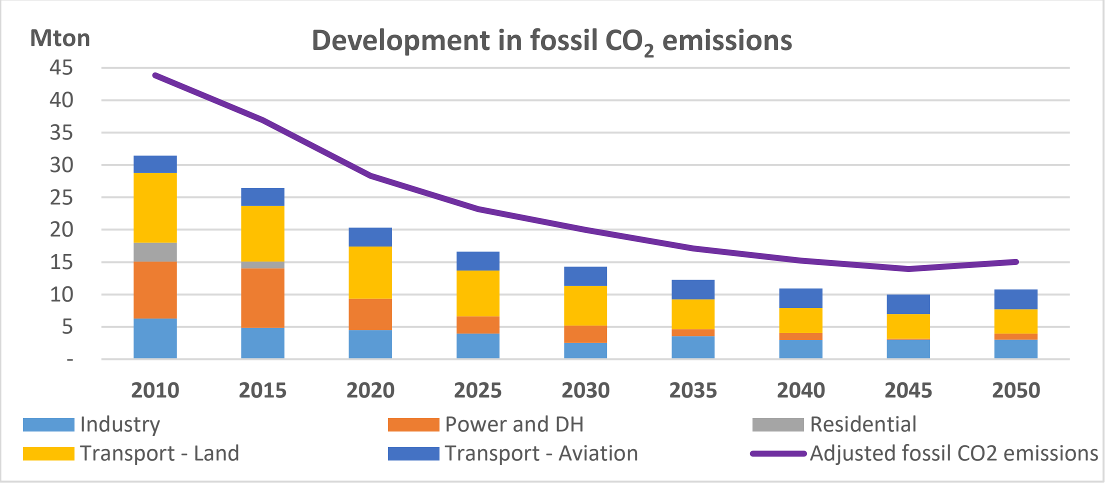

Figure 3.13: Development in total CO_2 emissions.

The emission of CO_2 from fossil fuels is generally assumed to decrease throughout the model period, however with a slight increase from 2045 to 2050. This increase is driven by a temporary decrease in coal used in a geothermal plant with absorption heat pump in 2045, which increases again in 2050. The CO_2 emission level is expected to drop by 59 % from 2015 to 2050. However, there is still some fossil fuels left in the energy system. The industrial sector remains at an almost constant level throughout the horizon. Emissions from land-based transport is expected to decline towards 2050, while the emissions from aviation see a slight increase due to increased demand for air transport and high prices of bio-kerosene. The transport sector combined is responsible for around 63 % of the total fossil emission in 2050. On the positive side, the power and district heating sectors are expected to be almost fossil-free in 2050.

Figure 3.14 shows the expected development in gross energy consumption, including import and export of electricity.

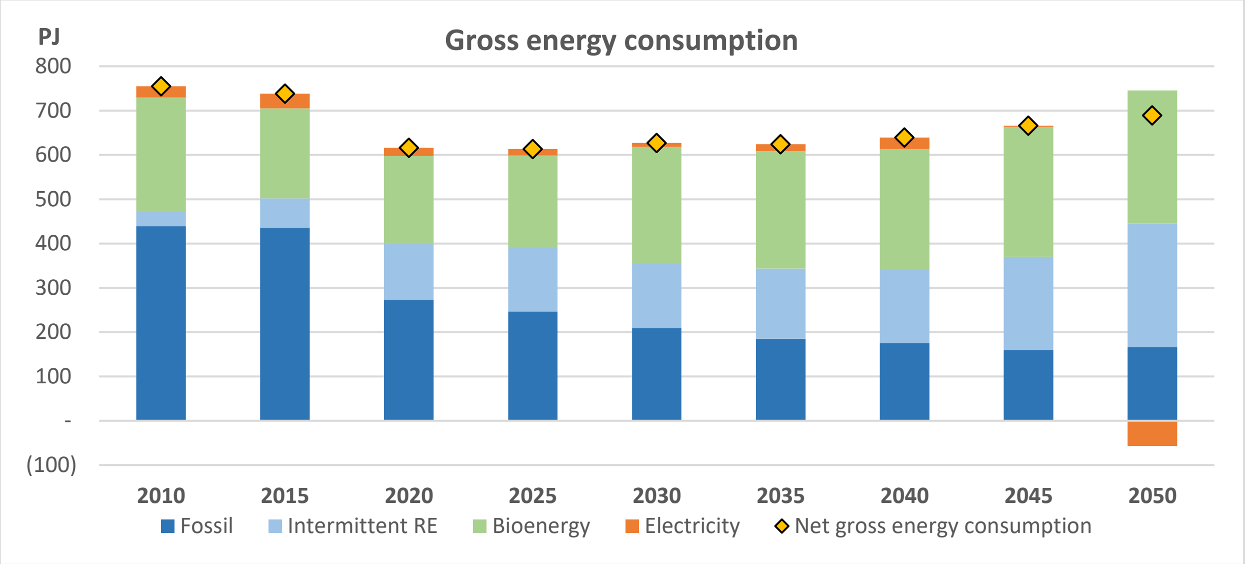

Figure 3.14: Development in gross energy consumption.

The figure shows that the amount of bioenergy and intermittent renewable energy is increasing as fossil fuels decrease, which is in line with developments shown previously. In total, the amount of renewables is expected to increase significantly towards 2050, and biomass will account for more than a third of the gross energy consumption. Furthermore, we estimate that the share of renewables in gross energy consumption (excluding imported and exported electricity) to be 53 %, which is well above the target of 30 % renewable energy in 2020.

3.2.8 Summary of Frozen policy scenario

The main objective of the *Frozen policy* scenario was to investigate if the current regulatory incentive structure is likely to ensure compliance with the GHG emission reduction targets for 2030 and 2050. The results given in the sections above show that it is unlikely that the Danish energy system will be successful in transitioning to a low emission society by 2050 if policies remain unchanged. However, some of the targets are expected to be achieved with the existing incentive structure, i.e. the target for 30 % renewable energy in the combined system by 2020 and the target of 10 % renewable energy in transport in 2020.

If the transition to a fossil-free society in 2050 is to be reached, it is necessary to make changes to the existing incentive structure. Among the immediate needs is a need for supporting renewable vehicles in the transport sector, since this sector is lacking behind the most. We estimate that 63 % of the fuel used in transport in 2050 will still be from fossil fuels, unless changes are made to the current incentive structure. The industry will slowly become more renewable, however fossil fuels are expected to account for 12 % of the industrial fuel consumption in 2050. The electricity and heating sectors are expected to be based 100 % on renewable energy in 2050, also under the current incentive structure.

3.3 A recommended future Danish energy system

The second objective of this report is to propose a future energy system for 2050, which meets the energy policy targets. As previously mentioned, the DEA has outlined four scenarios for the future energy system that all meet the target of a low emission society in 2050. Based on these scenarios, it was discussed in Chapter 1 that there is an urgent need for deciding on a common strategy for the energy system development if we want to reduce the number of investments, which are limiting beneficial synergies in the energy system. With answering this objective, we aim to provide an updated scenario for a future energy system, which is both cost-efficient and renewable.

In our recommended *R2050* scenario, we use the TIMES-DK model to outline a cost-efficient and sustainable energy system for 2050, which meets the political target of a low emission society. This means that we use the model to define a specific mix of technologies and energy commodities, which we believe should be the foundation of a sustainable 2050 energy system.

The initial method used for determining a least-cost, renewable energy system was to constraint the level of CO_2 emissions according to the policy targets. In this *Policy Target* scenario, we forced the model to emit a maximum emission of fossil CO_2 in 2030 equal to 60 % of the emissions in 1990 (i.e. a 40 % reduction), and to have zero fossil emissions in 2050.[26] However, since the model's objective is to minimize the overall cost of the system over the entire time horizon, the model opts to use fossil fuels, which have a low cost, for as long as possible. This means that the energy system development resulting from this scenario shows a very sudden change to renewables at the end of the time-horizon in the end-use sectors (i.e. residential, industry and transport). An example of this sudden change is shown in Figure 3.15 below, which shows the development in the transport sector.

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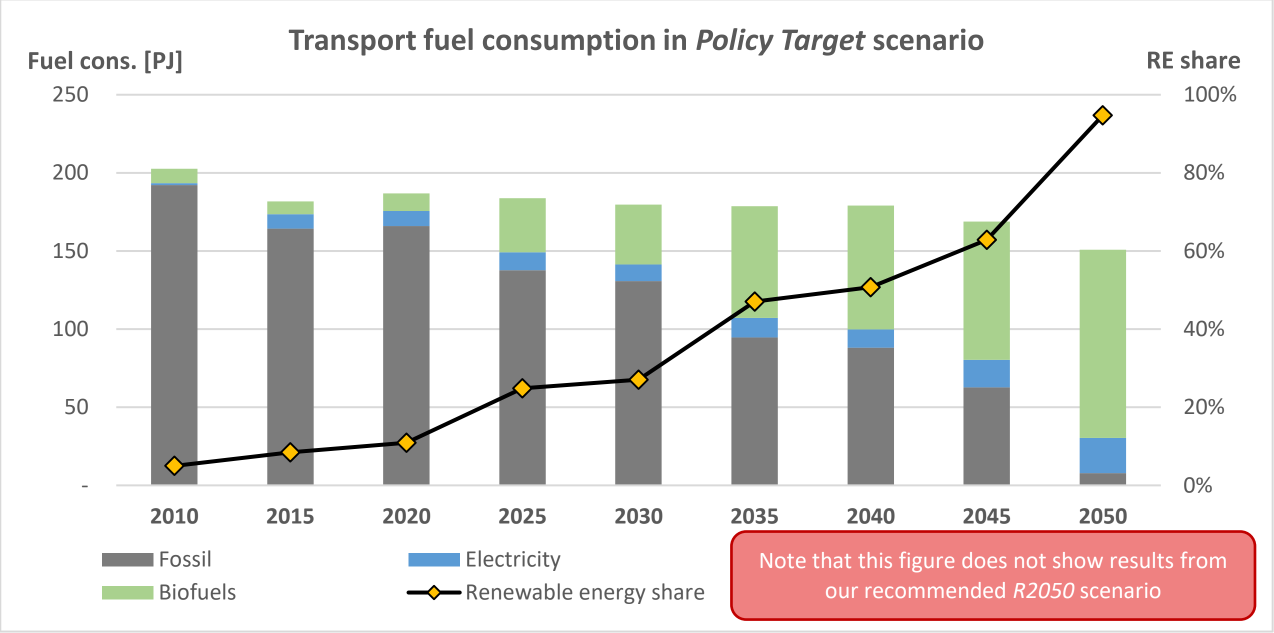
[26] The level of CO_2 emissions in 1990 was 53 Mton according to the JRC (Joint Research Center, 2016). Since TIMES-DK does not include all emissions of CO_2, we used a correction factor of 0.72 to adjust the constraint so that only those emissions included in the model are included in the target used in the model. We exclude other greenhouse gases from the simulations. Furthermore, the constraint on emissions used in the model includes interpolation between the maximum level in 2030 and the zero level in 2050.



Note that this figure does not show results from our recommended *R2050* scenario

Figure 3.15: Development in the transport fuel consumption towards 2050 in a scenario with existing policy targets

The sudden change is made possible by simply increasing import of biofuels to replace the fossil fuels, which are used in the energy system until just before 2050. This can occur since many technologies can use both a fossil fuel and a biological alternative. While this is a possible way of reaching the targets, and the cheapest one for the system as well, it is a very shortsighted solution, which is chosen by the model simply because it stops the simulation in 2050. Had the model been able to simulate for a longer period, and thereby have to remain fossil-free for a longer period, it is most likely that the method used by the model for complying with the 2050 target would be different from simply relying on import of biofuels. Therefore, we have used a different approach to determine a low-cost *and sustainable* energy system in 2050.

In the *R2050* scenario, we have used a constraint which forces the model to construct an energy system without fossil fuels from 2035 onwards, and hence reduce the emission of fossil CO_2 to zero from 2035. The development in emissions of CO_2 in this scenario is shown in Figure 3.16, where it can be seen that all emissions are gone from 2035 onwards.[27]

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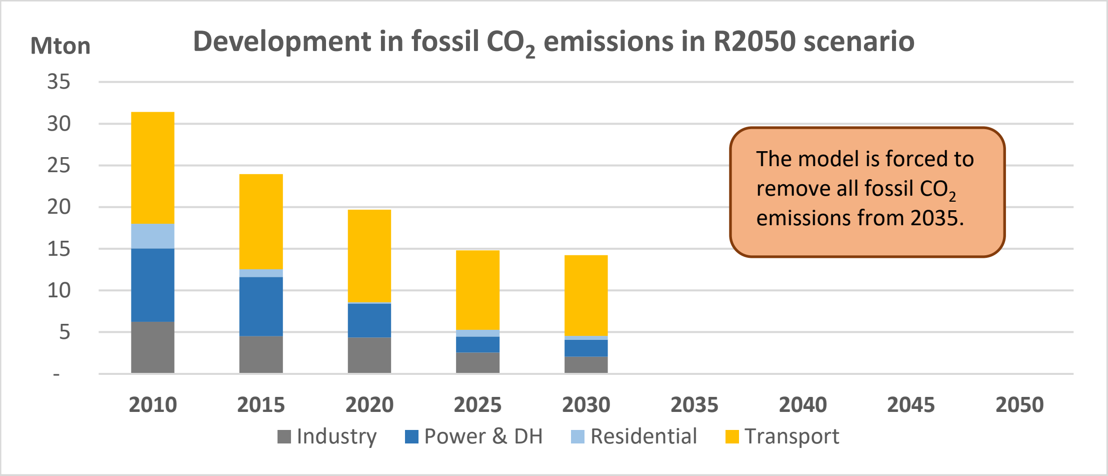
[27] Note that emissions from bioenergy and waste is not included in this figure. Furthermore, emissions from the use of heavy fuel oil in ships is not included, since these cannot operate on a renewable alternative in TIMES-DK. However, the emission from these is minor (0.6 Mton per year from 2035 to 2050) compared with remaining fossil emissions.



The model is forced to remove all fossil CO_2 emissions from 2035.

Figure 3.16: Development of CO_2 emission in the R2050 scenario with a restriction on emissions from 2035

Setting the constraint already in 2035, as opposed to 2050 where the target applies, makes it possible to construct a long-term, sustainable energy system in 2050, since the model has been forced to invest in new, renewable capacity to maintain a renewable energy system over a longer period. Our recommended 2050 energy system is presented in the following sections.

3.3.1 Overview of R2050 energy system

Based on analysis of our *R2050* scenario, we recommend that the energy system in 2050 should be characterized by a large degree of electrification throughout all sectors, as well as the use of biofuels. Figure 3.17 and Table 3.1 show the energy flows in 2050 for all sectors.

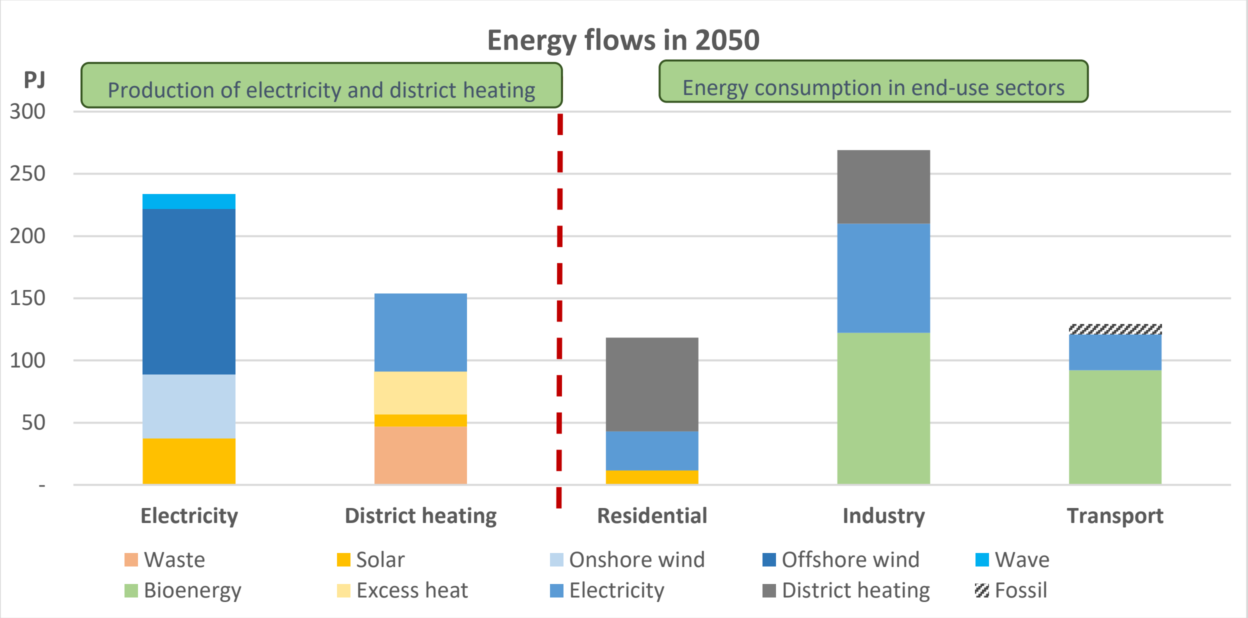


Figure 3.17: Energy flows in the R2050 scenario specified for the 5 sectors

PJ	Production of energy		Consumption of energy		
	Electricity sector	**District heating sector**	**Residential sector**	**Industrial sector**	**Transport sector**
Fossil	-	-	-	-	8
Waste	0.1	47	-	-	-
Solar	37	10	12	-	-
Onshore wind	51	-	-	-	-
Offshore wind	133	-	-	-	-
Wave	12	-	-	-	-
Bioenergy	-	-	-	122	92
Excess heat	-	34	-	-	-
Electricity	-	63	31	88	29
District heating	-	-	76	59	-

Table 3.1: Energy flows in the R2050 scenario specified for the 5 sectors

We recommend that the energy system in 2050 is characterized by the following in each sector:

- The electricity should be produced from intermittent renewable energy, i.e. wind, solar and wave power. There should still be some thermal capacity left in the system, which can deliver peak electricity production and act as reserve capacity.

- The district heating sector should be based on large-scale electric heat pumps, waste combustion and solar heating. In addition, excess heat from industry and from production of biofuels should be used in district heating.

- Residential heating should primarily come from district heating combined with electric heat pumps and solar heating in non-district heating areas.

- The industry should use bioenergy for those processes, which require high and medium temperature heat, and for machinery and vehicles, which require a combustion engine. The remaining energy demands in the industry should be supplied with district heating and using electricity from the grid.

- The transport sector should be fueled by biofuels and electricity. Rail transport should be electrified, while personal cars should be hybrid vehicles, which use both electricity and bioethanol. Truck transport should use biodiesel, while aviation should be completely fueled by bio-kerosene. Shipping may still use some fossil fuel oil if no alternative can be used, but should change to a renewable alternative if possible.

The large degree of electrification will lower the gross energy consumption compared to today's level, since technologies using electricity are generally more efficient. The gross energy consumption in 2015 (as estimated by TIMES-DK) is 738 PJ, while it is 617 PJ in 2050 in our recommended scenario. The main values of the *R2050* scenario is summarized in Table 3.2.

PJ	Intermittent renewables	Bioenergy	Electricity import/export	Fossil fuels	Gross energy consumption
2015	70	199	34	436	739
2050	306	355	-56	12(1)	617

Table 3.2: A summary of main values in PJ energy consumed in the R2050 scenario with 2015 as a reference year. (1) Fossil fuels are entirely consumed by the ships

In the following sections, we discuss the details of our recommended scenario and subsequently compare it to the DEA scenarios and to a similar scenario by The Danish Society of Engineers (IDA).

3.3.1.1 Intermittent renewables should increase dramatically

We recommend that the electricity production capacity in 2050 is almost entirely intermittent renewables, primarily onshore- and offshore wind turbines. In addition, there should be some thermal capacity left in the system to supply peak demand and act as reserve capacity. We have not included synchronous condensers in the model; however, these may be necessary to ensure stability in the electricity grid in the *R2050* energy system, since the thermal capacity is small and is not intended for baseload production.

MW	CHP	Thermal PP	Onshore wind	Offshore wind	Solar PV	Wave
Actual 2015	7,740	1,436	3,745	1,271	780	-
R2050	1,480	883	4,300	7,730	9,000	1,000

Table 3.3: Energy capacities of the energy scenario R2050 compared to actual values in 2015

The capacities of CHPs and thermal power plants are existing plants, which are assumed to remain operational in 2050. The onshore wind capacity and solar PV capacity are at their respective maximum capacity potentials, as assumed in the model and described in Section 2.3.5.2.1. Thus, as shown in Table 3.3, we recommend that Denmark increase the capacities of onshore wind, offshore wind, solar PV and wave power towards 2050. Offshore wind and solar PV should see the largest increase. The capacity of CHPs and thermal power plants should see a substantial decrease, as these technologies become less competitive.

3.3.1.2 Domestic production of biofuels provides large system benefits

In order to reach a low emission society in a cost-efficient way, it will be very beneficial if domestic biofuel production capacity is constructed. Biofuels, such as bio-kerosene, biodiesel and biogas, can serve as direct replacements for fossil fuels in many technologies. For example, fossil kerosene can be replaced with bio-kerosene, while diesel for heavy truck transport and industrial processes can be replaced with biodiesel. Furthermore, an increased domestic production of biofuels will increase the amount of excess heat, which can be used in the district heating sector. This increases the overall energy efficiency in Denmark, since the excess heat can replace other sources of heating.

Therefore, we recommend that the 2050 energy system includes domestic production of biogas, biodiesel, bioethanol, bio-kerosene and bio-naphtha. Figure 3.18 illustrates the recommended use of primary bioenergy for production of biofuels in biorefineries.

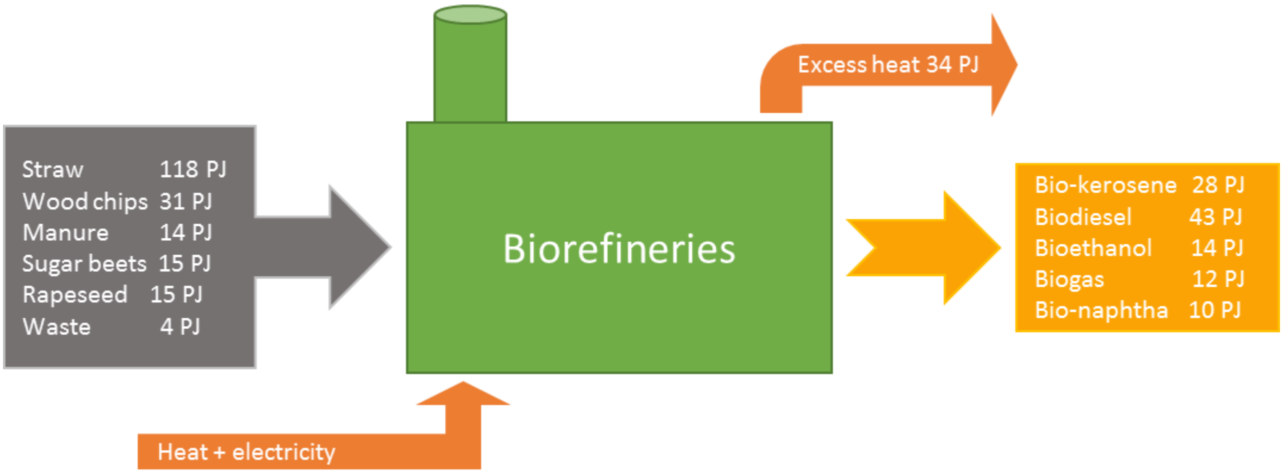


Figure 3.18: Illustration of the R2050 biorefineries fuel consumption and production of biofuels in 2050

We recommend that the entire potential of straw is used for production of bio-kerosene, since this is required for fossil-free aviation, and it simultaneously produces a large amount of biodiesel, bio-naphtha and excess heat. Furthermore, we recommend that 31 PJ of wood chips potential (close to the national potential of 40 PJ) is used for production of bioethanol, which is entirely used by hybrid electric/ethanol vehicles. The entire national potential of sugar beets and manure should be used in combination with 4 PJ of waste for production of biogas, while the national rapeseed potential should be used for biodiesel production.

3.3.1.3 Hybrid cars and electric trains should dominate personal transportation

We recommend that all cars for personal transport should be hybrid vehicles, which uses both electricity and bioethanol. Our estimates show that the use of both electricity and biofuels in hybrid cars will be less expensive for the combined system than converting all personal cars to pure electricity. This is primarily because the model decides to invest in biofuel production capacity in Denmark, which provides system benefits by adding large amounts of excess heat to the system, which can be used in district heating. Thus, the combination of domestic biofuel production, heating demand and demand for passenger transport means that it is better to use hybrid cars than electric cars. The share of hybrid cars and other types of vehicles in different parts of the transport sector are shown in Figure 3.19. It should be noted that the figure describes the types of vehicles, hence the term “Diesel” means vehicles which have a diesel engine that can use both fossil- and biodiesel. In this scenario, all fuels are biofuels, except for a small amount of fuel oil for shipping.

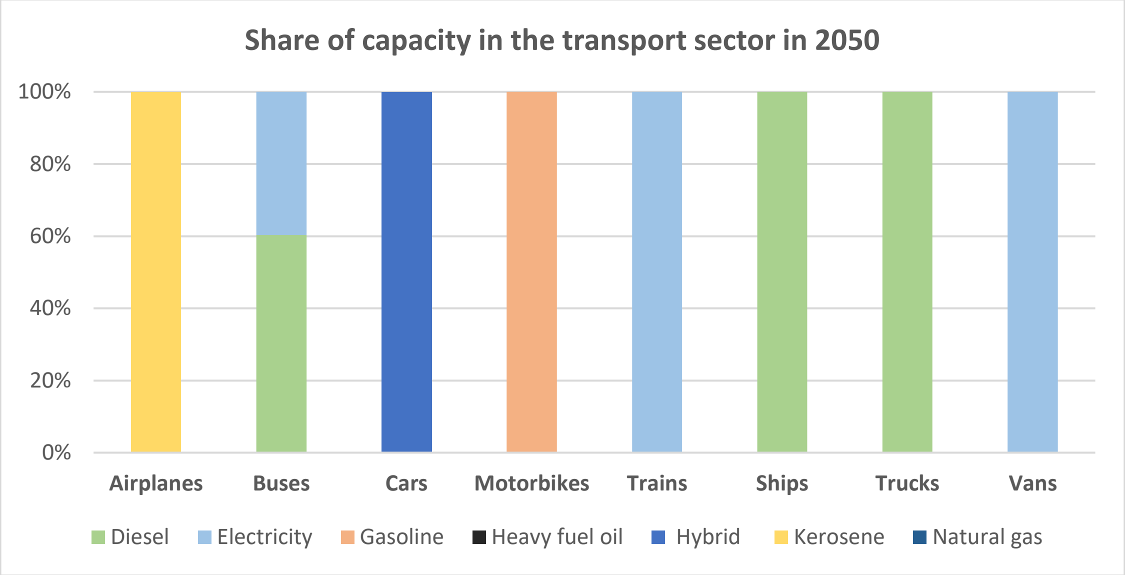


Figure 3.19: Share of capacity in the transport sector in 2050 visualized by the vehicles engine types in reference to its fuel consumption

We recommend that all rail transport (freight and passenger transport) be electrified by 2050. Train transport is relatively inexpensive to convert to electricity, so the opportunity of increasing electricity consumption here should be taken. Since it was shown in the *Frozen Policy* scenario that train transport is expected to be fully converted from diesel to electricity in 2035 under current policy, it should be entirely feasible to achieve full electrification of trains by 2050.

While renewable alternatives to fossil kerosene are currently very expensive, it is necessary that all airplanes are fueled by bio-kerosene in 2050 if we are to meet the 2050 target. Part of the necessary bio-kerosene should come from domestic production as described above, while the rest will have to be imported due to limits on national bioenergy potentials.

Trucks generally require an internal combustion engine for long-haul transport, unless electrified roads or battery-powered trucks are implemented. These are not included in the model and are therefore not considered. However, the model can use either diesel engines or natural gas engines for truck transport. It is estimated that trucks should have diesel engines using biodiesel, primarily based on the direct cost of investment and operation, but also due to the system benefits of biodiesel production versus biogas production. The former has the advantage that biodiesel is necessary for some technologies in the industry and is used in ships. In addition, the production of biodiesel is more efficient than biogas production and produces excess heat, which can be used in district heating. Furthermore, biodiesel is a bi-product from bio-kerosene production, which is domestically produced in this scenario, since it is less expensive than import of bio-kerosene.

3.3.1.4 Electrification in heating outperforms increases in building efficiency

As mentioned in Section 2.3.3.1 in Chapter 2, the TIMES-DK model includes the possibility for making improvements in energy efficiency of the existing building stock. The model includes a combined heat savings potential of 93 PJ, which is divided into three groups of 30-32 PJ, which have increasing costs. Thus, the model will always choose to use the entire potential from the first group before moving on to the next group. The difference in price represents the additional costs that efficiency improvements will require once the “low hanging fruits” have been used.

We estimate based on the *R2050* scenario that it is better for the system as a whole to limit building efficiency improvements to a total heat saving of 21 PJ, meaning that 9 PJ from the cheapest group of energy savings should not be used. Similar, the potential from the second and third group should not be used either. This is illustrated in Figure 3.20.

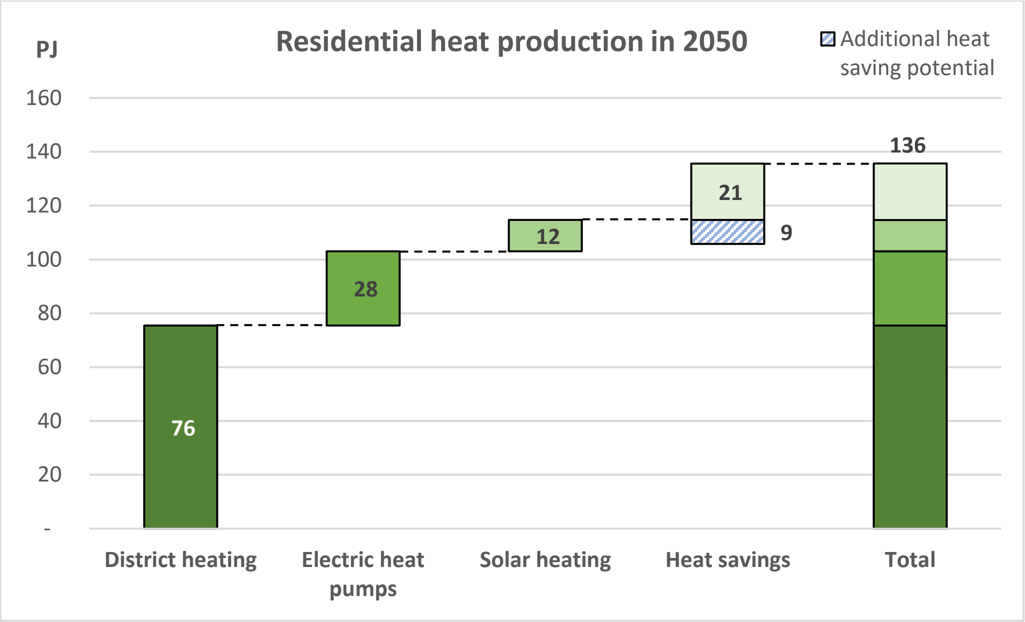


Figure 3.20: Visualization of the residential heat production and the additional heat savings potentials. Note that the heat savings showed only include the potential from the cheapest group of heat savings.

Thus, it is estimated that a point of too much efficiency improvement exists. This is because the cost of producing the additional heat is lower than the cost of the remaining efficiency improvements in the first group. Note that the cost of efficiency improvements varies between building types in the model, and that the remaining 9 PJ of heat savings are mostly buildings in centralized district heating areas, which have access to low-cost district heating primarily coming from large-scale electric heat pumps, excess heat and waste combustion.

3.3.1.5 Woody biomass should become a primary fuel for industrial processes

The industrial sector should rely on district heating, electricity and woody biomass (wood pellets and wood chips). The latter should replace the fossil fuels that are currently used for providing heat at high temperatures. We estimate that the industry should use approximately 49 PJ of wood pellets and 47 PJ of wood chips per year in 2050.

3.3.2 Comparison with other energy scenarios

In this section we compare the results of the *R2050* scenario to the energy scenarios by the DEA as well as a 2050 scenario made by The Danish Society of Engineers. The DEA's energy scenarios use the following parameters when describing the overall framework of an energy system: Bioenergy consumption, degree of self-sufficiency and gross energy consumption. Table 3.4 presents these parameters for the DEA scenarios, the IDA scenario and the *R2050* scenario.

	Unit	Wind	Bio	Bio+	Hydrogen	IDA	R2050
Bioenergy consumption	PJ	255	443	710	192	235	355
Self-sufficiency	%	104 %	79 %	58 %	116 %	No data	89 %(1)
Gross energy consumption	PJ	575	609	823	562	576	617

Table 3.4: Comparison between the energy scenarios created by the DEA and IDA and the R2050 scenario.
(1) If fossil fuels are used in calculating the self-sufficiency, the value will increase to 99 %.

The values for total bioenergy consumption show that the *R2050* scenario is located between the *Wind* and *Bio* scenarios from the DEA, and about 50 % higher than the IDA scenario. The *R2050* scenario is also located between *Wind* and *Bio* in terms of self-sufficiency, which is closely linked to the bioenergy consumption, since a higher consumption of bioenergy requires more import of bioenergy. Thus, since the *R2050* scenario has a net import of bioenergy equal to 90 PJ, the self-sufficiency is less than 100 %.[28] The *R2050* scenario generally has a higher gross energy consumption than the other scenarios, which is primarily due to an assumed higher industrial demand in the R2050 scenario.

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[28] The national bioenergy potential is estimated by the DEA to be 265 PJ (Danish Energy Agency, 2014).

3.3.2.1 Electricity and heating sectors

The *R2050* scenario differs quite significantly in terms of electricity production capacity, even compared to those scenarios, which are otherwise similar. This is shown in Figure 3.21.

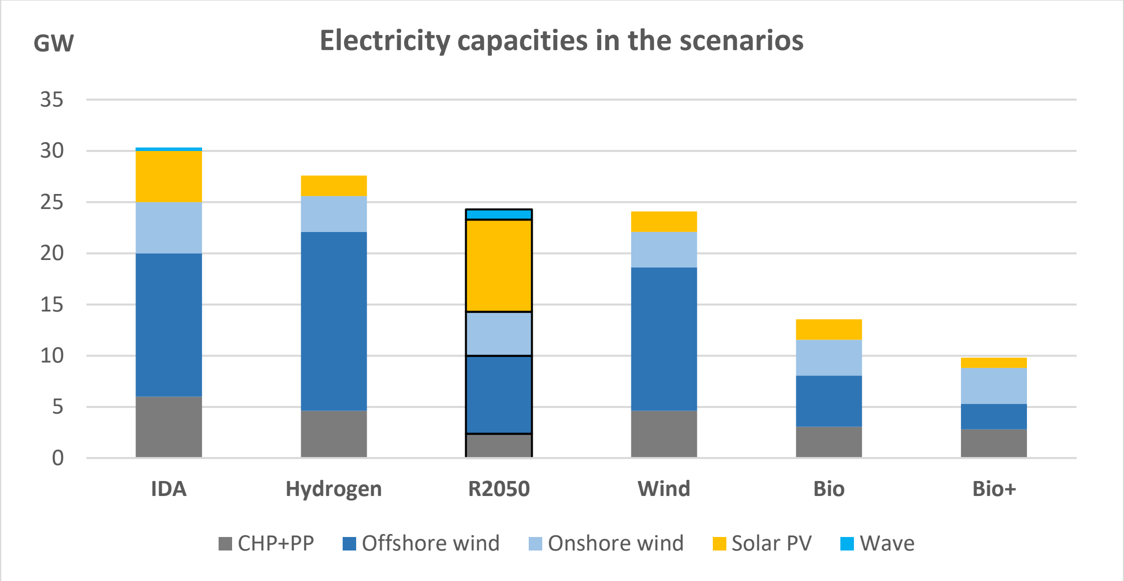

Figure 3.21: Comparison of capacities in the electric sector for scenarios created by DEA, IDA and R2050

Although similar to the *Wind* scenario in terms of total installed capacity, the distribution between different technologies is quite different in the *R2050* scenario. The primary difference is a much larger capacity of solar PV in the *R2050* scenario. The reason for the large solar capacity in the *R2050* is that solar PV is expected to become very competitive in the electricity market according to the most recent technology catalogue from the DEA (Danish Energy Agency, 2016c). Furthermore, the *R2050* scenario includes a maximum limit on solar capacity of 9 GW, which is reached by the model in 2050. This is a strong indicator of the future competitiveness of solar PV. Another special element in the *R2050* scenario is the existence of 1 GW of wave power. The only other scenario including wave power in 2050 is the IDA scenario, which believe that 0.3 GW should be installed in 2050.

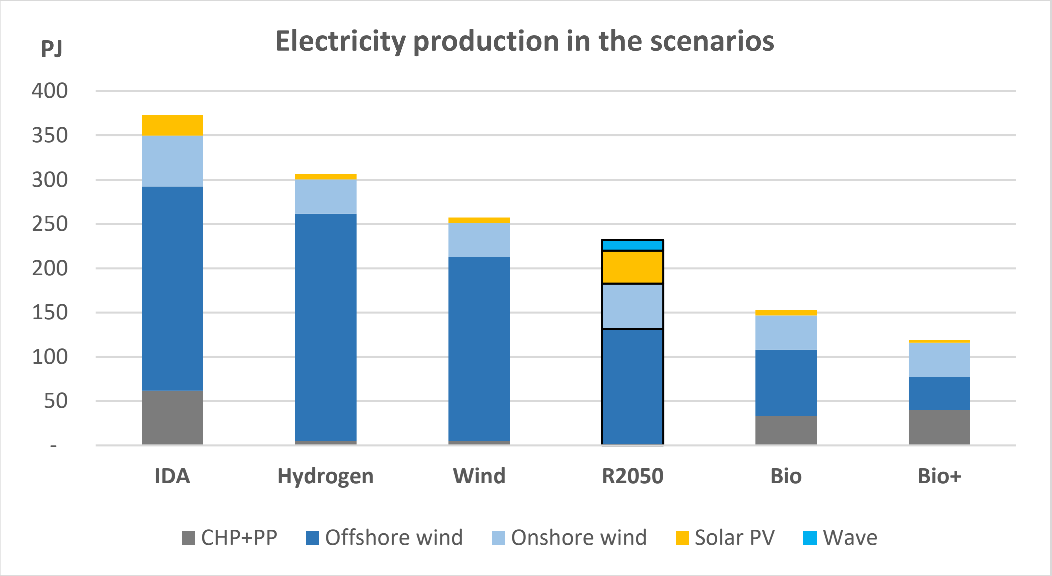

Figure 3.22: Comparison of electricity production by fuel type for scenarios created by DEA, IDA and R2050

Figure 3.22 above shows the production of electricity in each of the scenarios. It is clear that the amount of electricity production from onshore wind turbines is almost identical across all scenarios. This is because electricity from onshore wind turbines already today is highly competitive with other technologies. It is clear that the scenarios relying to a larger extent on bioenergy have a lower electricity production. This is because of a smaller degree of electrification throughout the energy system.

3.3.2.2 Transport sector

As previously discussed, the transport sector is currently very reliant on fossil fuels and is difficult to transition to renewable energy sources. However, each of the scenarios described here have provided a possible combination of fuel sources for transportation in 2050, which are based on 100 % renewable energy. These are shown in Figure 3.23.

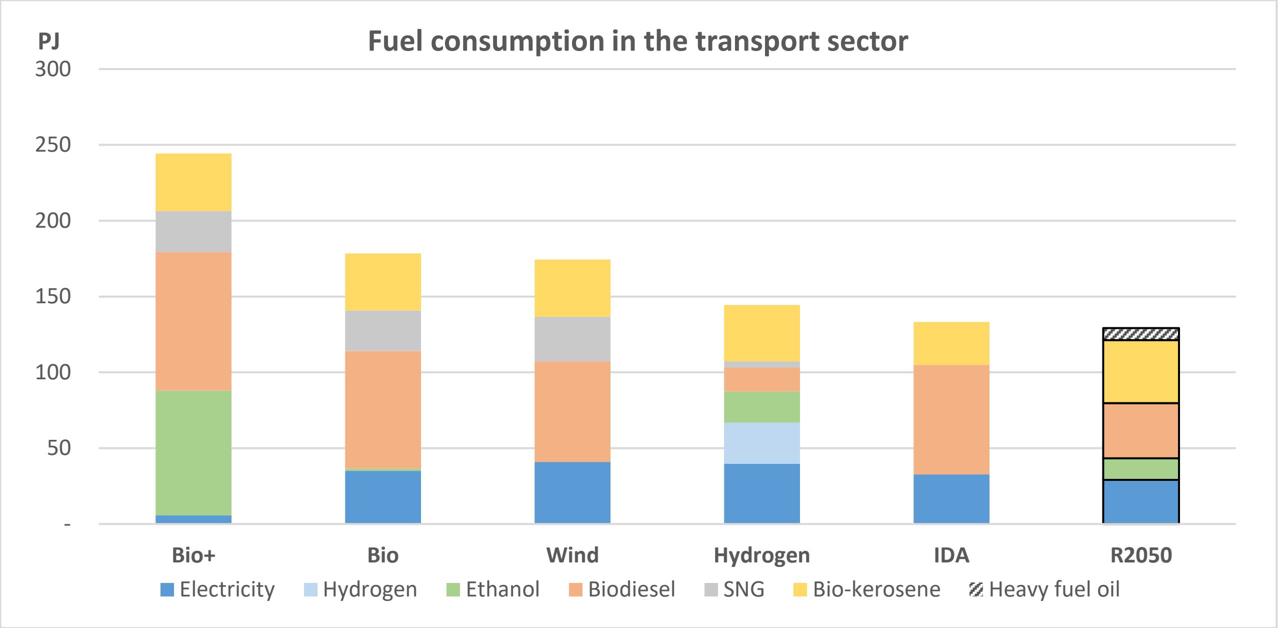

Figure 3.23: Comparison of fuel consumption in the transport sector for scenarios created by DEA, IDA and R2050

The DEA scenarios generally have the highest total consumption in transport, with the *Bio+* scenario by far consuming the most energy. The remaining scenarios have a more efficient transport sector due to the larger amount of electric vehicles, which are more efficient than cars using biofuels. Since the *Bio+* scenario is largely dependent on bioenergy and has very limited electrification throughout the system, the transport sector is also reliant on bioenergy.

The *R2050* scenario has the lowest total fuel consumption compared with the other scenarios. A plausible explanation for this difference can be that the transport sector modeled in the *R2050* sector does not include fuel consumed by industrial machinery, e.g. tractors for agriculture, since this is included in the industrial sector in TIMES-DK. The consumption of biodiesel for industrial processes in the *R2050* scenario is approximately 25 PJ, which, if added on top of the *R2050* column in Figure 3.23, will make the scenario more comparable with the remaining scenarios. Furthermore, one of the main differences between the *R2050* scenario and the *Bio* and *Wind* scenarios is the amount of biodiesel used in transport. This could indicate that the low total fuel consumption in the *R2050* scenario is a result of different assumptions regarding where to include biodiesel for industrial machinery.

Besides the difference in the total fuel consumption, there are notable differences between the *R2050* scenario and the other scenarios. First, the *Bio*, *Wind* and *Hydrogen* scenarios use between 35-41 PJ of electricity in transport, while the *R2050* scenario uses 29 PJ. A large part of the explanation is that the *R2050* scenario uses hybrid cars, which use both electricity and ethanol, while the DEA scenarios use electric cars. Second, in most of the DEA scenarios, the primary fuels for public buses and freight trucks are biodiesel and synthetic natural gas. However, the *R2050* scenario uses biodiesel exclusively for freight trucks, since biodiesel is produced domestically both as a primary product but also as a bi-product from bio-kerosene production. As previously described, the use of biodiesel in freight transport therefore provides system benefits.

Transport by rail, sea and air is very similar across all scenarios, with all aviation being fueled by bio-kerosene and rail being primarily electrified. The DEA scenarios have some biodiesel in rail transport, while the *R2050* scenario is 100 % electric trains.

There are generally four types of transport, which differ significantly between the DEA scenarios and the *R2050* scenario. These are freight trucks, public buses, vans and personal cars. Transport by ship is fueled by biodiesel and synthetic natural gas in the DEA scenarios, while the *R2050* scenario uses biodiesel and some heavy fuel oil. Heavy fuel oil is left in the system, because the processes defined in TIMES-DK cannot operate without a share of heavy fuel oil. However, we recommend a shift to biofuels as they become able to operate without fossil fuels.

3.4 Guidelines for policy changes

In the previous section, we presented our recommended future energy system for 2050, which is the result of our *R2050* scenario. In this section, we proceed to provide guidelines for policy changes, which in theory will be able to realize an energy system in 2050, which is very close to our recommended *R2050* scenario. In short, the method for identifying the appropriate policy changes is to test changes to the existing incentive structure (taxes and subsidies) in TIMES-DK, by allowing the model to construct an energy system development based on a new policy setting (i.e. the modeling method is similar to the method used in the *Frozen policy* scenario). While the *R2050* energy system was constructed by forcing the model to become fossil-free in 2035, the energy system resulting from the *Incentive Structure* scenario is constructed based on the incentives provided in the policy settings, meaning that there are no constraints on emissions in this scenario. With this method we can investigate if our suggested policy changes are likely to guide the Danish energy system towards a low emission society in 2050.

In the process of optimizing the existing incentive structure, the objective is to recreate our recommended *R2050* scenario. The method used for identifying necessary changes was to compare the 2050 energy system from the *Frozen policy* scenario with the 2050 energy system from the *R2050* scenario. By comparing these energy systems, we could identify the commodities or technologies that will need to be changed to achieve the *R2050* energy system.

The exercise is simplified by a few general rules, which apply to most of our recommended policy changes. These are illustrated below in Figure 3.24.

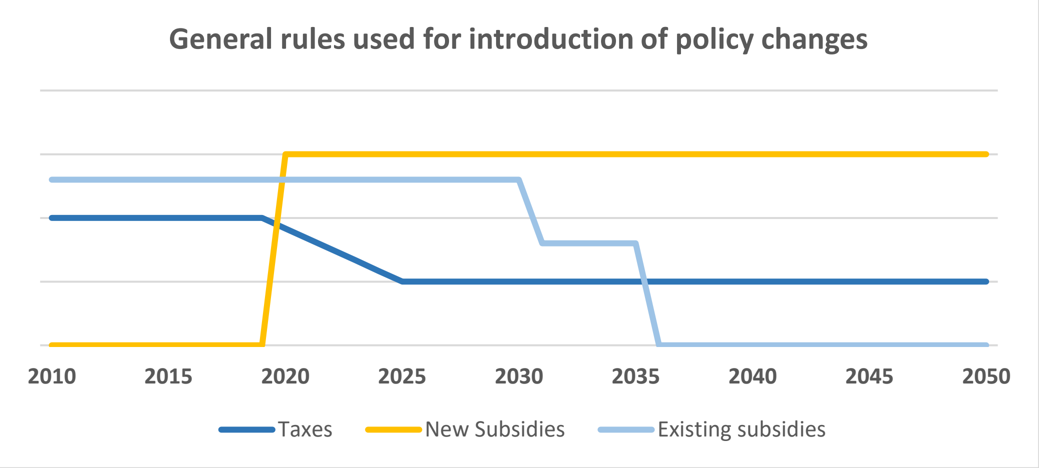

Figure 3.24: Visualization of implementation of the incentive structure scenario

First, we have kept all existing taxes at their current rate until ultimo 2019. New taxes or changes to existing taxes are phased in between 2020 and 2024, and are fully implemented primo 2025. This leaves a comfortable amount of time between today and 2020 for politicians to make the suggested changes to the incentive structure. In addition, the primary reason for phasing in adjusted tax rates and new tax rates is to allow industry (and individuals) enough time to re-adjust their positions according to the new incentive structure. Second, similar to the current legislation, we will keep the tax rate constant in real terms until 2050, which will provide a more stable environment for companies to make investment decisions. Third, since most existing subsidy schemes will be expired before 2020, any recommended subsidies in our incentive structure will be implemented with full effect from 2020, i.e. there is no phasing in of subsidy schemes. Subsidies are generally also kept constant in real terms throughout the model horizon.[29] By fully implementing subsidies from 2020 (and avoiding phasing them in), we help promote an early introduction of the technologies and commodities, which are necessary for achieving an energy system similar to the *R2050* scenario. It should be noted that the level of subsidies should be lowered as the subsidized technologies become competitive on market terms; however, in this report they are kept at a constant level in real prices for simplicity.

The *Frozen policy* scenario reaches approximately 84 % renewable energy in gross energy consumption in 2050. A comparison of the results from the *Frozen policy* scenario and the *R2050* scenario shows clearly that the largest change needed is in the transport sector, since this is expected to be lacking most behind in 2050 under the current regulatory framework. Thus, similar to the DEA energy scenarios, the process of identifying our recommended policy changes starts by achieving the right mix of fuel consumption in the transport sector. After the transport sector, we first move on to the industrial sector (including biorefineries), then the heating sector, and lastly we investigate the policy changes needed in the electricity sector. However, since all sectors in the energy system are linked to each other, it has been necessary to evaluate the impact of all tested policy changes on all sectors. Thus, the recommended policy changes are a result of an iterative process, in which all parameters changed have been rigorously tested by increasing and decreasing the applicable taxes and subsidies in order to find the most optimal value for the energy system as a whole. In the following sections, we first discuss the differences between the energy system in the *Frozen* policy scenario and the *R2050* scenario, and subsequently explain the process in more detail by focusing on each sector individually.

3.4.1.1 Comparison of Frozen policy and R2050

Figure 3.25 compares the 2050 energy systems in the *Frozen policy* and the *R2050* scenario. This comparison is used as the foundation for identifying those areas of the energy system, where there

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[29] All subsidies in our recommended incentive structure are kept constant throughout the model horizon, except for a prolonged subsidy scheme for offshore wind power, which is phased out between 2030 and 2036.

is a large need for policy changes if the future development should be in the direction of our recommended *R2050* energy system.[30]

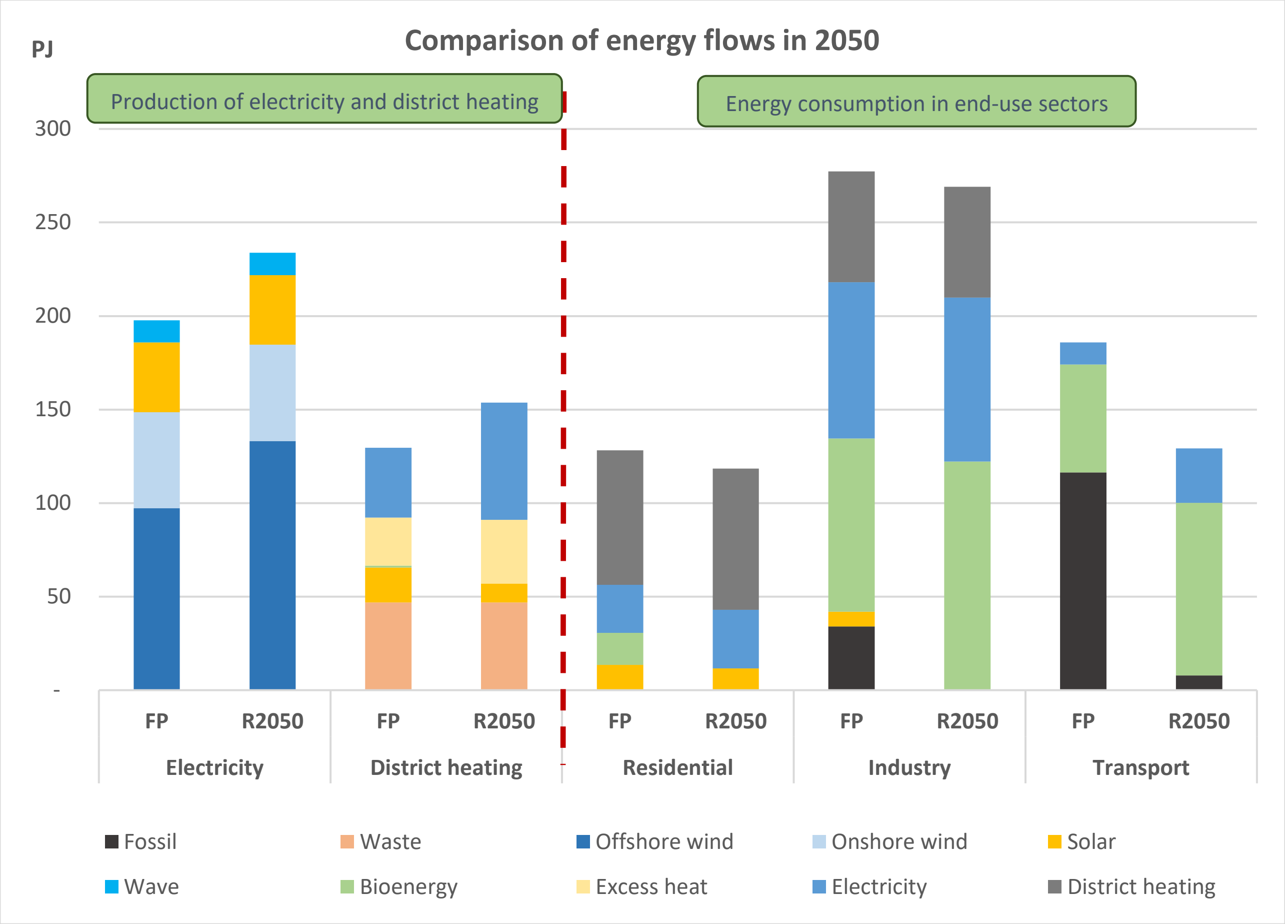

Figure 3.25 Comparison of energy flows in the Frozen Policy and R2050 scenarios by sectors

For example, it is clear from the figure that the development expected under frozen policy in the transport sector is far from the recommended development. This indicates a strong need for special attention on the transport sector. Similar, there are differences in the other sectors, e.g. the district heating sector should have a larger share of electric heat pumps. In the following, we describe the recommended policy changes and the process of identifying them. The resulting changes in the energy system development from implementation of these policy changes are shown for all policy changes combined in Section 3.4.3.

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[30] A less aggregated overview than the figure shows has been used in identifying areas requiring policy changes. This is provided in Appendix 08.

3.4.1.2 Transport sector

As shown above in Figure 3.25, comparing the *Frozen policy* scenario with the *R2050* scenario shows that a lot of additional electricity consumption in the transport sector is needed compared to expectations under frozen policy. This change can be achieved by changing the registration fee for electric- and hybrid vehicles, which both use electricity as their main fuel. As mentioned in Section 1.4.1.1.3, the registration fee is both a fiscal tax and a tax for reducing resource consumption. In the current legislation, the registration fee on electric vehicles is being phased in to be applied on the total value of the vehicle, including the cost of the batteries, so that it is fully implemented in 2022.[31] The inclusion of the battery cost in the calculation of the registration fee for electric- and hybrid vehicles is similar to applying a tax on the size of the fuel tank in conventional vehicles. Therefore, the first recommended incentive structure change is to exclude the cost of the batteries in electric- and hybrid vehicles from the calculation of the registration fee. This recommendation is in line with a recent recommendation from the Danish Council on Climate Change (Danish Council on Climate Change, 2016). The change has the intended effect of increasing electricity consumption in personal passenger transport in TIMES-DK. The increased electricity consumption is almost entirely the result of more hybrid cars in the system.

The change in the registration fee only partially moves the resulting energy system closer to the *R2050* transport sector. In addition to this change, there is a need to change from fossil kerosene to bio-kerosene for aviation. In order to realize such development, we suggest putting a subsidy on second-generation (2G) bio-kerosene production. A comparison of the marginal cost of producing 2G bio-kerosene (including applicable bi-products, e.g. biodiesel, bio-naphtha and excess heat) to the import price of fossil kerosene gives an estimated subsidy level of 130 DKK/GJ, which is very high compared to other subsidy schemes. Fine-tuning of the optimal subsidy level results in our second recommended policy change, which is applying a subsidy of 125 DKK/GJ on 2G bio-kerosene production from 2020 onwards. This subsidy level is ideal in a systems perspective, since the production of 2G bio-kerosene production with this subsidy level is estimated to use the entire national straw potential, which is recommended in our *R2050* scenario. However, using the entire national straw potential for 2G bio-kerosene production is not enough to supply the total demand for aviation fuel. Thus, the remaining consumption of bio-kerosene should be imported, which is recommended in the *R2050* scenario. Realizing an energy system in TIMES-DK, where all aviation fuel is bio-kerosene, can be achieved by either subsidizing import of bio-kerosene by the price difference between fossil kerosene and imported bio-kerosene, or alternatively by legally prohibiting the use of fossil kerosene. We have not implemented a subsidy in bio-kerosene import in our *Incentive Structure* scenario. Instead, we recommend a legal prohibition on the use of fossil

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[31] The regulation regarding registration fee for electric vehicles has been updated during the process of this project, so that the fee is fully implemented in 2022. However, we have used the previous policy in this study, i.e. full implementation in 2020.

kerosene for aviation. Such a prohibition will benefit from being on an EU level to have a substantial effect on GHG emissions from aviation. Generally, a combined EU regulation on biofuels for aviation is necessary to have the needed effect (also in the case of subsidies); however, Denmark should be a front-runner by implementing an early subsidy on 2G bio-kerosene production from 2020.

After the above changes, comparing the *Frozen Policy* scenario to the *R2050* scenario also shows a need for phasing out natural gas vehicles over time, so that they are non-existent in 2050. Therefore, we recommend increasing the energy fee on natural gas for transport purposes. In the current legislation, the fee is lower than for any other transport fuels used today, and increasing the fee will therefore contribute in leveling the tax scheme for transport. The recommended new tax level will phase out natural gas vehicles according to our long-term *R2050* scenario. We suggest increasing the tax to 65.5 DKK/GJ, since this will ensure no natural gas in the transport sector in 2050. This, in combination with subsidizing bio-fuel production, will keep the amount of natural gas vehicles low in the transition towards 2050.

After implementing the above changes to the regulatory incentive structure, we see that fossil gasoline is still preferred over bioethanol in 2050, although all hybrid- and gasoline vehicles in the market (except vintage vehicles) can use both fuel types. In order to make the vehicles use the renewable alternative, we recommend adding a subsidy of 25 DKK/GJ on 2G bioethanol production to the existing policies, which will make bioethanol competitive with gasoline. Domestic production of 2G bioethanol for transport requires large amounts of wood chips. However, both the production of bioethanol and bio-kerosene will result in increased amounts of excess heat, which should be used in district heating.

Finally, the last recommended change related to achieving the correct mix of technologies and commodities in the transport sector is it lower the electricity fee for transport from 245.8 DKK/GJ to 230 DKK/GJ. This is necessary to increase the amount of hybrid vehicles in the system to the recommended level. This change in policy increases the electricity consumption for transport and converts all personal cars to hybrid vehicles by 2050.

3.4.1.3 Industry and refineries

The primary industrial change needed in the expected energy system development is a change from combustion of coal to combustion of wood pellets and wood chips. In order to realize such change, we recommend increasing the energy fee on coal for industrial processes from the EU minimum level to the level applicable for non-industrial purposes today. This means increasing the tax on coal to 54.9 DKK/GJ for industrial processes. While this high tax is contrary to the idea that industry should be mostly exempt from taxes to allow for international competitiveness, we believe a high tax on coal in industry is necessary for a transition to biofuels. In addition, setting the tax level equal to the level for non-industrial processes increases simplicity and is a strong signal to the industry that Denmark has to become fossil-free by 2050. The issue with competitiveness may be resolved by working for an EU wide increase in energy fees on coal.

3.4.1.4 Heating sector

The entire energy sector should be moving towards a large degree of electrification, including the residential- and district heating sectors. In the *Frozen policy* scenario, residential heating is expected to have some wood pellet boilers left in 2050. This capacity should be phased out and replaced with more electric heat pumps and more district heating. The district heating sector should also have an increased capacity of large-scale electric heat pumps, as well as a larger amount of excess heat. Our recommended solution for achieving a larger degree of electrification in both sectors is to lower the electricity fee for heating from today's level of 106.4 DKK/GJ to 40 DKK/GJ. This will affect both the residential- and district heating sector, and will ensure a larger share of electric heat pumps in the system. This recommendation is similar to a recent recommendation from the Danish Council on Climate Change, which recommend an electricity fee of 70.4 DKK/GJ (Danish Council on Climate Change, 2016). The tax rate of 40 DKK/GJ is a 64 % decrease from today's level. While this may seem like a large decrease, it outlines the need for a drastic change in energy policy, if the energy system is to have an increased degree of electricity-to-heat technologies in the heating sector. Since this is a large decrease, we have conducted a sensitivity analysis on this tax level in order to find the point at which the net tax revenue of the system is maximized, all other things equal. The results of this analysis are presented in Figure 3.26, and show that the optimal value (in terms of net tax revenue) is around 70 DKK/GJ, which is close to the recommendation of 70.4 DKK/GJ from the Danish Council on Climate Change.

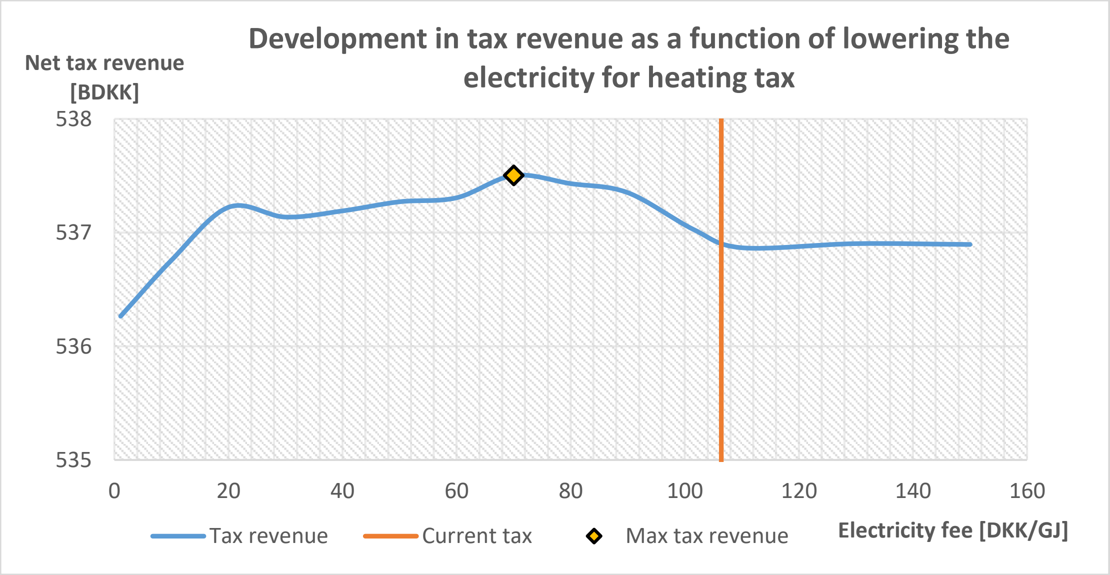

Figure 3.26: Analysis of total tax revenue from variating energy fees on electricity used for space heating, with the current taxation level indicated.

This proves that the net tax revenue can be increased if the current tax on electricity for heating is decreased. Although this might seem counterintuitive, it is a result of increasing consumption of electricity when the tax rate is decreased. While the optimal level is at 70 DKK/GJ, this level does not implement enough electricity into the heating sector. However, it is also clear from the figure that a tax rate of 40 DKK/GJ will also increase net tax revenue across the energy sector compared with today's level of 106.4 DKK/GJ.

The updated electricity fee for heating results in the energy system coming closer to the recommended scenario. However, it is not enough to implement the same capacity of heat pumps in the system as proposed by the *R2050* scenario, but neither is setting the tax rate to the EU minimum tax rate. This is because the *Incentive Structure* scenario invests in solar heating for district heating in the middle of the time horizon, which is still operational at the end of the horizon. Since the marginal cost of production on these units is near zero, the model will (understandably) continue using all of this capacity. Thus, the only immediate solution to recreating the *R2050* scenario in this regard, i.e. to remove some of the solar heating from the system, is to impose a tax on solar heating. Since solar heating is also renewable and has low cost, we do not recommend imposing such a tax.

3.4.1.5 Electricity sector

Finally, another way of introducing more electricity-consuming technologies into the system is to lower the cost of electricity production. The comparison of the *Frozen Policy* scenario and the *R2050* scenario shows a need for increasing the capacity of offshore wind turbines. In order to achieve this, and indirectly increase electrification, we recommend extending the existing subsidy scheme for *offshore* wind turbines. We suggest extending the subsidy until 2030 to support short-term implementation of more offshore wind. After 2030, we recommend decreasing the subsidy to 4/5 of the current level, and removing it completely primo 2036 as offshore wind turbines become more competitive.

The extension of the subsidy scheme for offshore wind power is the last policy change recommended in this report. Implementing this change into the *Incentive Structure* scenario in TIMES-DK shows an increased capacity of offshore wind, with additional small increases in electric heat pumps in the heating sector.

3.4.2 Summary of recommended policy changes

Table 3.5 summarizes the recommended policy changes described above. By implementing these changes to the existing regulatory incentive structure in the energy system, it is more likely that the Danish energy sector will become fossil-free by 2050 and that many of the system benefits of the *R2050* scenario will be realized.

Description	Sector	Type	Existing value	Suggested value
Registration fee	Transportation	Fee	Incl. battery cost	Excl. battery cost
Coal	Industry	Fee	4.5	54.9
Natural Gas	Transportation	Fee	54.9	65.5
Electricity	Heating	Fee	106.4	40
Electricity	Transportation	Fee	245.8	230
Bio-kerosene	Transportation	Subsidy	0	125
Bioethanol	Transportation	Subsidy	0	25
Offshore wind	Electricity	Subsidy	68.3	68.3-42.5[32]

Table 3.5: Summary of the recommended policy changes for achieving the R2050 scenario

As indicated in the table, we suggest changing 8 parameters in the existing incentive structure. The combination of these changes and the remaining parts of the existing regulatory framework will provide companies and individuals with the right incentives to make those decisions that in theory will take Denmark in the direction of the *R2050* scenario. In the following section, we provide an overview of the estimated energy system development under this new incentive structure.

3.4.3 Expected development toward 2050 with new incentive structure

In this section, we describe the estimated development of the Danish energy system, which is likely to occur if implementing the above described policy changes into the Danish energy policy. Based on TIMES-DK, we have modelled the pathway to a 2050 energy system using the updated policy setting and compared them to the recommended *R2050* scenario. The details of this analysis is presented in the following.

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[32] An extension of the current subsidy scheme until 2030 and a new lower value until 2035.

3.4.3.1 Electricity sector

It was shown in the *Frozen Policy* scenario that the electricity sector is already well underway towards a sector with 100 % renewable energy, also under the existing incentive structure. However, implementing our recommended incentive structure is estimated to increase the amount of offshore wind power further to reach a level close to the *R2050* scenario.

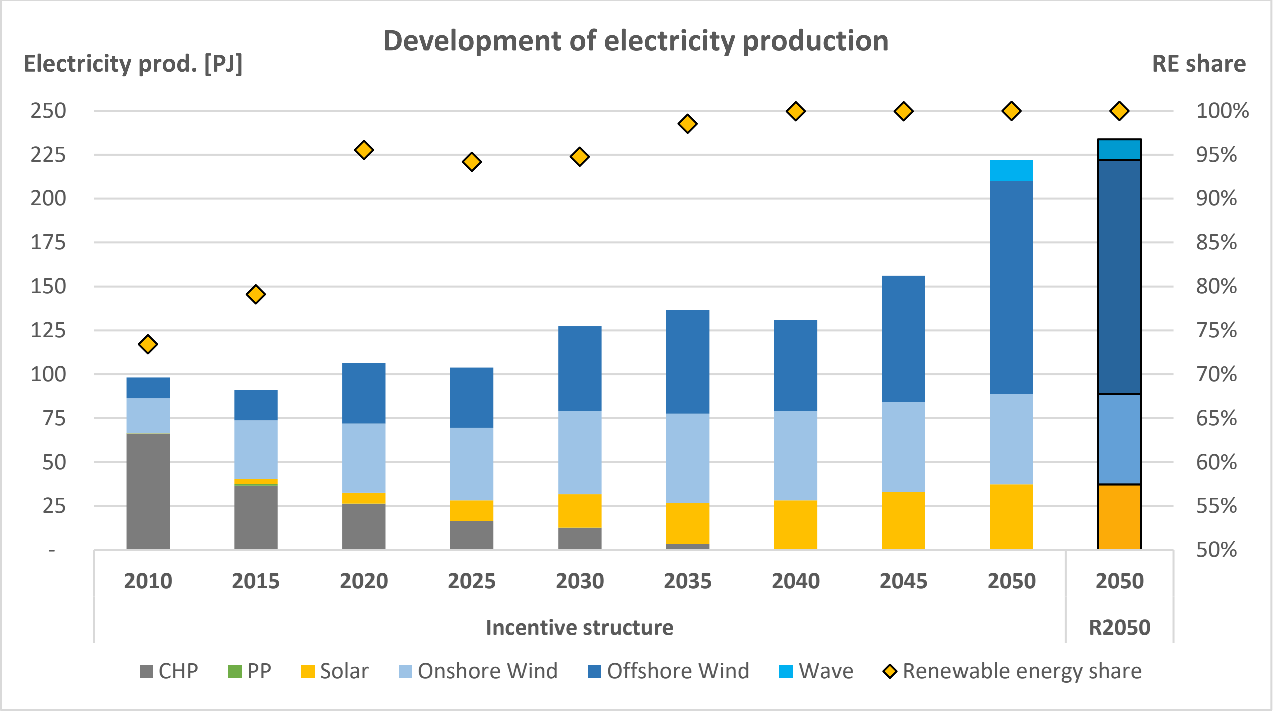

Figure 3.27: The development of the electricity production and share of renewable electricity production towards 2050, with R2050 as a reference scenario.

Overall, the pathway towards 2050 under the new incentive structure is similar to the *Frozen Policy* scenario, except for the fact that offshore wind remains constant in the middle of the time horizon instead of decreasing, while having a similar increase towards the end of the time horizon. This development can be largely attributed to the reduced taxes on electricity consumption for heating and transport, as well as the prolonged subsidy scheme for offshore wind. It is especially apparent from 2045 to 2050, when a large increase in offshore wind is expected, due to simultaneous increases of hybrid vehicles and electric heat pumps in the other sectors. Compared to the *Frozen Policy* scenario, we estimate an additional 24 PJ of electricity production in 2050 under the new incentive structure.

3.4.3.2 District heating sector

Compared to the *Frozen Policy* scenario, the expected development under the new incentive structure is characterized by a faster phase-out of biomass for district heating combined with more excess heat and more electric heat pumps at the end of the time horizon.

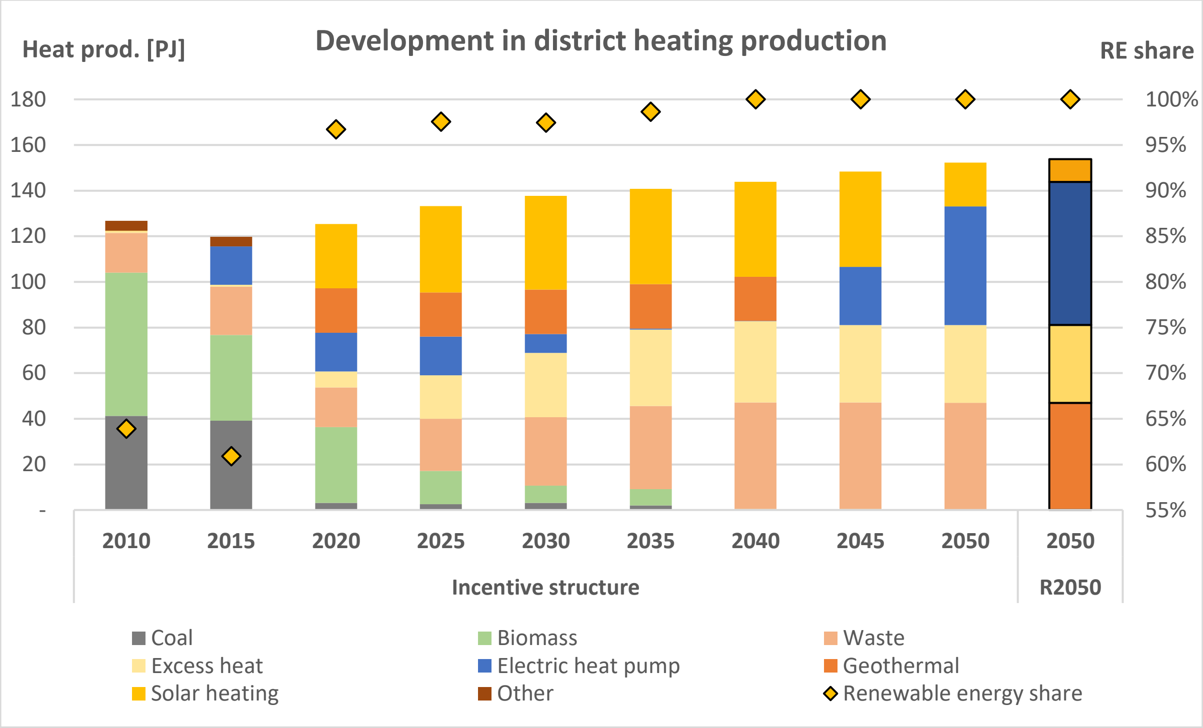

Figure 3.28: The development of the district heating production and share of renewable district heating production towards 2050, with R2050 as a reference scenario.

The primary contributor to the early disappearance of biomass is the added amount of excess heat, which is the result of more national biofuel production. This biofuel production appears in the system primarily due to the subsidies for bio-kerosene and bioethanol production, but also because of the more favorable tax conditions for hybrid vehicles, which dominate personal transport in 2050 and consume bioethanol. Overall, the resulting distribution of district heating production in 2050 is relatively close to the recommended *R2050* district heating system, but differs in the production from electric heat pumps. This is slightly lower under the new incentive structure, with the difference instead being supplied by solar heating. The primary reason why the new incentive structure does not completely accomplish the *R2050* scenario distribution is that more solar heating is installed in the middle of the period. Some of this capacity is still operational in 2050 and the model therefore does not invest in additional heat pump capacity. However, it is likely that the solar heating capacity will be replaced by more electric heat pumps within 10-15 years after 2050.

3.4.3.3 Industrial sector

The development in the industrial sector under the new incentive structure is very similar to the *Frozen Policy* scenario throughout the model horizon. The main difference is a larger reduction in consumption of coal from 2020 to 2030, which is a result of the increased energy fee on coal used for process heat, which is phased in from 2020 to 2025. Thus, this increased tax removes coal from the industry and increases the consumption of woody biomass for process heat instead.

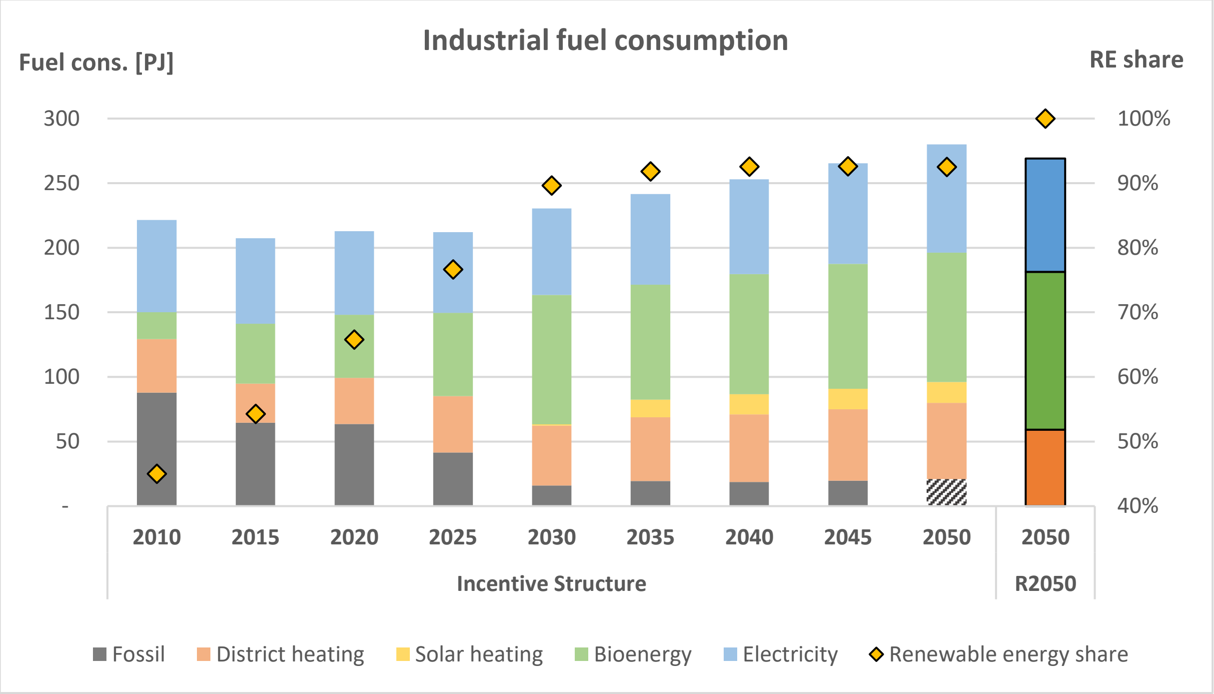

Figure 3.29: The development of the industrial fuel consumption and share of renewable fuels towards 2050, with R2050 as a reference scenario.

The industry sector is expected to have a renewable energy share over 90 % from 2030 onwards, taking into account the renewable shares of consumed electricity and district heating. The remaining 7-8 % is mostly diesel consumption for industrial processes and heavy machinery, which can only operate on diesel or biodiesel. Since the national potential for producing biodiesel is fully utilized in this energy system, the remaining biodiesel must be imported from international markets. As mentioned in Section 3.4.1.2, we recommend ensuring that fossil diesel is replaced with biodiesel by legally prohibiting the use of fossil diesel no later than 2050.

3.4.3.4 Residential sector

The residential heating sector is expected to become increasingly reliant on district heating in our *Incentive Structure* scenario, with around 80 % of fuel consumption in residential heating coming from district heating. The scenario shows that wood pellet boilers are phased out by 2045 under the new incentive structure, while the share of electric heat pumps has increased.

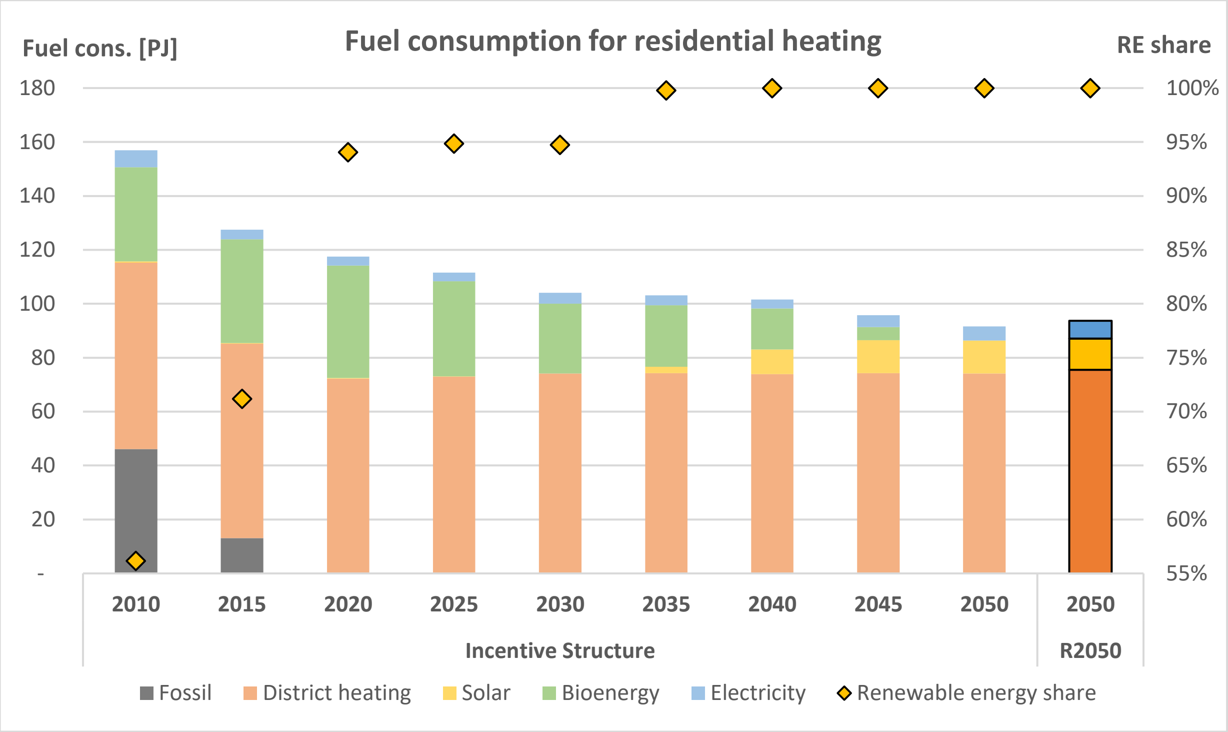

Figure 3.30: The development of the residential fuel consumption and share of renewable fuels used for heating towards 2050, with R2050 as a reference scenario.

The increase in electric heat pumps is a result of the lower electricity fee for heating, as well as the increased electricity production caused by the prolonged subsidy scheme for offshore wind power. The larger share of district heating is a result of the increased capacity of large-scale electric heat pumps and the additional excess heat available from biofuel production.

3.4.3.5 Transport sector

The transport sector is expected to have the largest change under the new incentive structure, compared with the expected development if current policies remain unchanged. The most significant change is the fuel consumption for personal cars. In the *Frozen Policy* scenario, we expect a large amount of natural gas cars to dominate the sector, while the expectation is that personal cars will be entirely hybrid cars under our recommended incentive structure. These cars will be fueled by electricity and bioethanol, which is produced nationally.

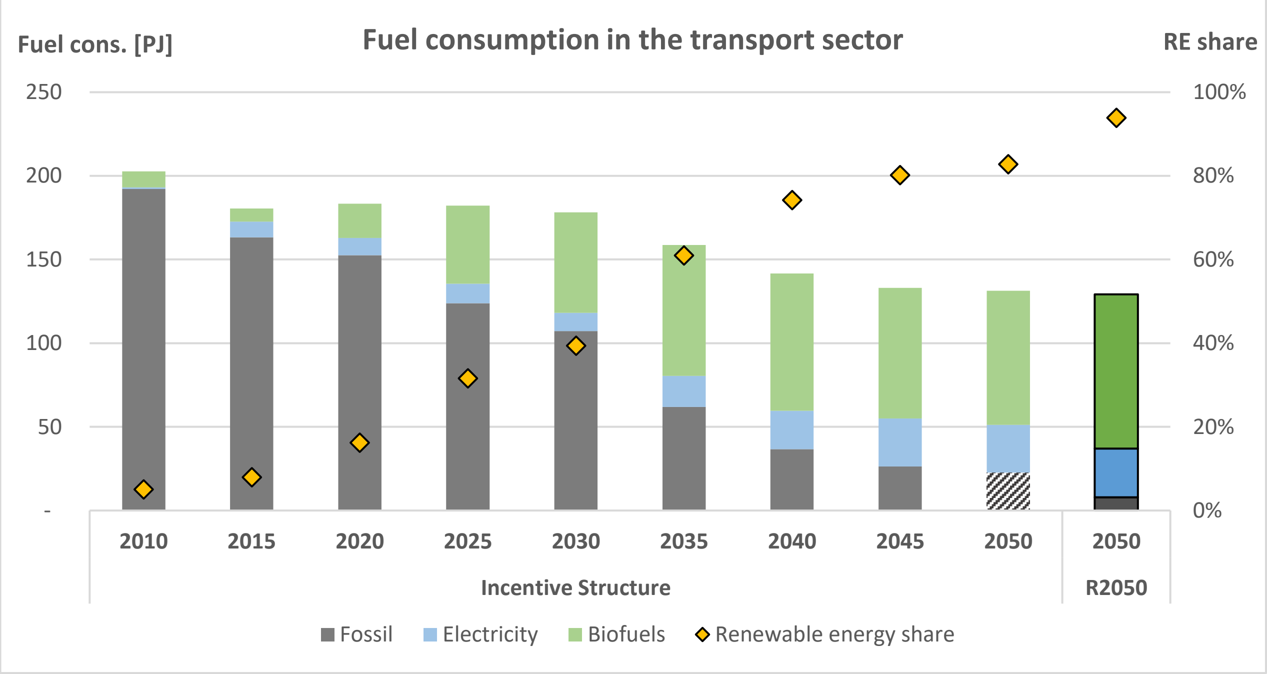

Figure 3.31: The development of the transport sectors fuel consumption and share of renewable fuels towards 2050, with R2050 as a reference scenario.

Furthermore, air transport is expected to replace a large part of fossil kerosene with bio-kerosene. Overall, the transport sector is expected to transition towards a highly renewable sector with an increasingly large share of biofuels to replace both fossil diesel, -gasoline and -kerosene. A relatively large decrease in fossil fuel use can be seen from 2030 to 2035, since hybrid vehicles become more competitive at this point. There is still some fossil fuel left in the system in 2050, which is because the national potential for biofuel production is fully utilized. Thus, as previously stated, we recommend a legal prohibition on use of fossil fuels no later than 2050. This should ensure that the remaining fossil fuel is replaced with imported biofuels.[33]

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[33] Recall that there is a remaining share of fuel oil used in ships in all scenarios. This is because TIMES-DK does not have any ships, which can operate without the use of some fuel oil.

3.4.3.6 Gross energy consumption

The expected gross energy consumption under the suggested incentive structure is characterized by a larger share of intermittent renewables and bioenergy compared to the *Frozen Policy* scenario. These energy commodities replace most fossil fuels, which remain a large fuel source in the *Frozen Policy* scenario.

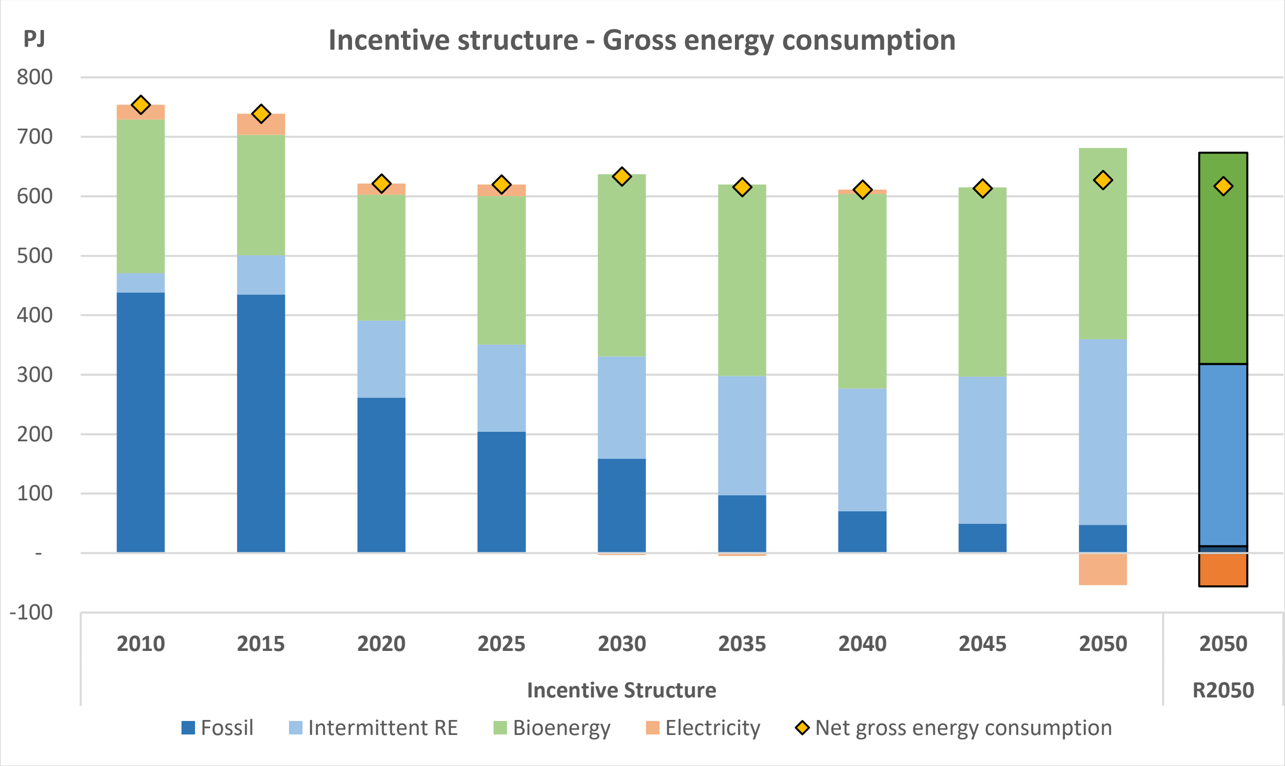

Figure 3.32: The development of the gross energy consumption of the energy sector towards 2050, with R2050 as a reference scenario.

The resulting gross energy consumption in 2050 is relatively similar to the recommended *R2050* scenario, with the primary difference being a larger amount of fossil diesel and –kerosene, which as mentioned will need to be imported in order to become completely free of fossil fuels.

3.4.3.7 Projection for CO_2 emissions

The projection for CO_2 emissions under the recommended incentive structure almost results in an energy system without fossil CO_2 emissions. Note that emissions from bioenergy and waste is not included in Figure 3.33. The only remaining fossil CO_2 emissions are those from the remaining amount of fossil diesel and kerosene, as well as a small amount from combustion of fuel oil in ships.

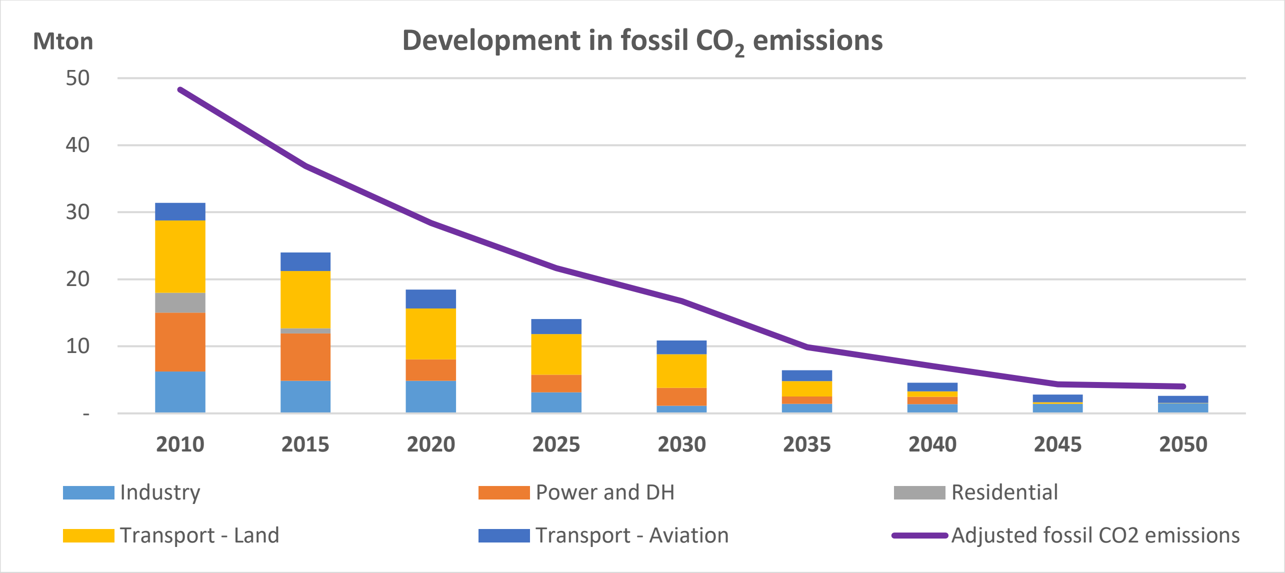

Figure 3.33: The development of CO_2 emissions by the energy sector towards 2050.
Note that emissions from bioenergy and waste is not included.

Similar to Section 3.2.7, we have included an adjusted CO_2 emission to the figure based on a correction factor. Again, note that this method only approximates the actual emission that would occur in the specific energy system, since TIMES-DK does not model the exact same energy system in 2015 as actually existed.

Thus, based on this projection, we can conclude that the recommended incentive structure is likely to guide Denmark in the right direction towards a low emission society in 2050.

3.4.3.8 Net revenue from taxes and subsidies

The suggested changes to existing energy policy will have an impact on the net tax revenue from the energy sector in the future. Compared with the *Frozen Policy* scenario, we estimate an average loss of tax revenue of about 3 BDKK per year from 2020 to 2050. However, we believe this is a relatively low cost for transitioning the Danish energy system to a low emission society.

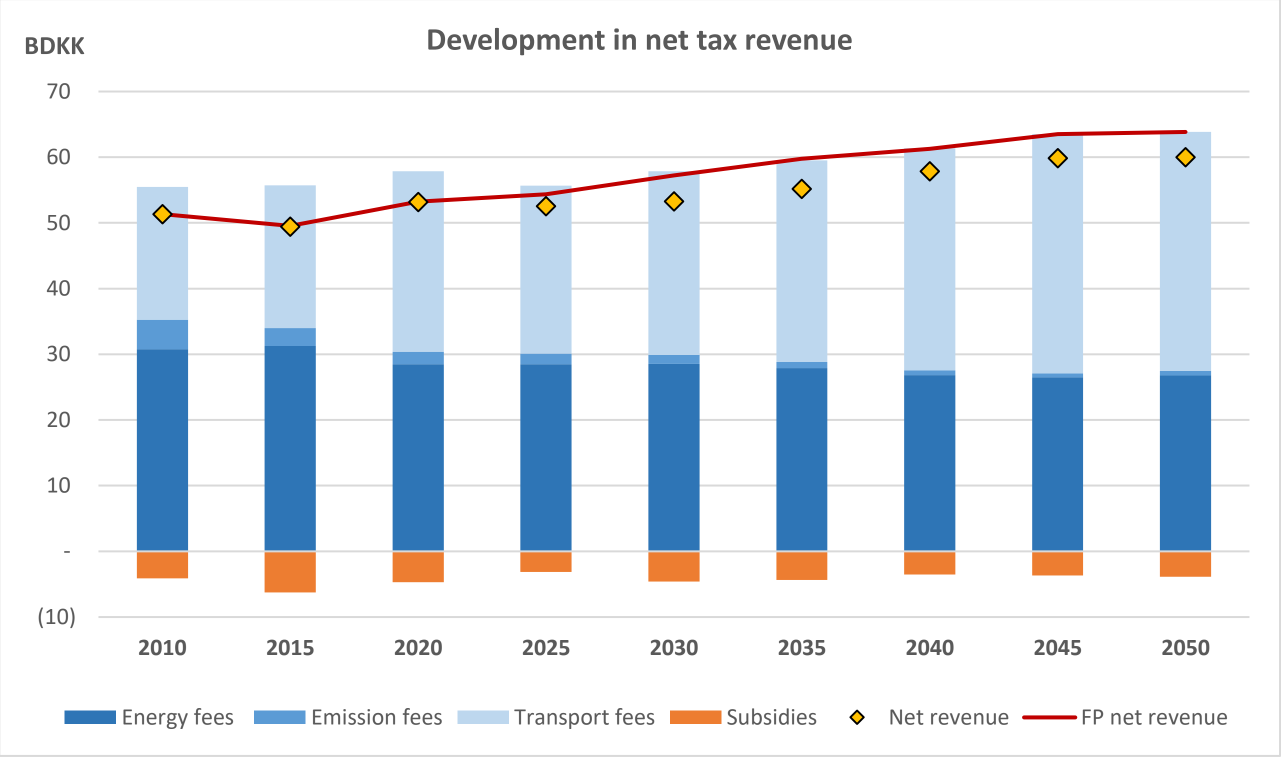

Figure 3.34 The development of the governmental tax revenue in billion DKK towards 2050, with the Frozen Policy scenario (FP) baseline for tax revenues as a reference line..

It is clear from Figure 3.34 that the overall tax revenue will be more or less the same compared to our *Frozen Policy* scenario. The combination of a reduction in the registration fee, lowering the electricity fee for transport and adding the subsidy for bio-kerosene and bioethanol makes the transport sector invest in cars that are more expensive, thereby resulting in a net positive difference in revenue from transport fees. The emission fees are becoming a smaller part of the tax revenue as fossil fuels are being phased out towards 2050. The overall revenue from energy fees is only slightly reduced, even though the electricity fee for heating has been strongly reduced, while fossil fuels simultaneously have been removed. This indicates that there are large potentials for added value by lowering the electricity fee for heating, since more heating capacity will be converted to electric heat pumps. The subsidies recommended will contribute with a loss in the national budget; however, they are smaller than the amount spent on subsidies today.

3.4.4 Summary of difference between R2050 and Incentive Structure

The third objective of this report was to identify a new incentive structure, which is likely to accomplish the recommended energy system for 2050 found in the *R2050* scenario. By changing and adding only 8 parameters in the Danish energy regulation, we have identified an incentive structure, which comes very close to the recommended scenario. Overall, the similarity between the *R2050* scenario and the *Incentive Structure* scenario has been estimated to 94 % across all sectors.[34] It is possible to achieve completely equal scenarios; however, if this should be achieved it is necessary to apply taxes on e.g. solar heating and subsidies on import of biofuels, which we do not recommend.

3.4.5 Comparison of results with other studies

This report is one of many concerning a change in the incentive structure to guide the Danish energy system towards our climate goal in 2050. There is a lot of debate on which changes are recommended and more importantly what the tax rates should be to ensure the optimal development of the energy system. As previously identified in Section 1.5, the debate is mainly centered on 2 subjects: 1) Need for electrification and 2) Taking advantage of excess heat.

Since one of the primary aims of this report is to provide policy-makers with actual values for taxes and subsidies, we try to find recommendations in other reports that contain actual values for taxes and subsidies. In the following section, the results and conclusions from other reports are summarized and compared to our results.

3.4.5.1 Need for electrification

Electrification is often regarded as paramount for achieving our climate goals. One way of ensuring increased electrification is to lower the cost of consuming electricity. The DCCC argue in their report *"Charges which transform"* that a decreased electricity fee for heating will have beneficial properties for the energy system (Danish Council on Climate Change, 2016). They recommend decreasing the fee with 36 DKK/GJ, which should be enough to implement more heat pumps into the Danish energy system. In our analysis of changing the incentive structure, we implemented a similar decrease. Our analysis resulted in a recommended decrease of 66 DKK/GJ, which is a large decrease but as our analysis shows it is necessary in order to implement the much-needed electric heat pumps. In addition, our sensitivity analysis shows that lowering the electricity for heating to their recommended 70.4 DKK/GJ will benefit the net tax revenue. In short, there seems to be no real argument against decreasing the electricity fee for heating.

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[34] See Appendix 09 for the calculation method used in estimating this deviation.

Another way of increasing electrification is to lower the registration fee on electric vehicles. Today, the registration fee is being phased in to the standard registration fee, but the total price of an electric vehicle is higher than a fossil fuel alternative. Lowering the registration fee on electric cars has shown an increased number of electric vehicles being purchased in our *Incentive Structure* scenario. The report, "*Charges which transform*", recommend excluding the battery cost from the calculation of the registration fee, thereby lowering the registration fee on electric vehicles (Danish Council on Climate Change, 2016). In our analysis, we needed an increased electrification in the transport sector, and as stated in Section 3.4.1.2 it is irrational to tax the battery pack in electric vehicles as it limits the consumer's interest in purchasing a bigger battery pack for additional range. Thus, we implemented the recommendation from the DCCC in our incentive structure. It had the desired effect and enabled the implementation of more electricity consumption in the transport sector.

The increased electricity consumption should come from a renewable energy source. Since onshore wind turbines are already very competitive in the electricity sector, the model chooses to implement the entire potential. Subsidizing renewable energy sources will increase the incentive to implement more capacity into the energy system. The Danish Ministry of Taxation has published a report concerning the subsidies for renewable energy sources (Danish Ministry of Taxation, 2016b). The sixth part of their six-part analysis of the Danish incentive structure is concerning the subsidy for onshore wind. As our model opts to implement as much onshore wind as possible in all scenarios, we did not consider subsidizing onshore wind turbines. Instead, we extended the current subsidy for offshore wind turbines to get an increased penetration of electricity. Contrary to the other subsidies we suggest in our *Incentive Structure* scenario, we chose to phase out this subsidy by 2036. This is partly in accordance with one of the recommendations from the Energy Commission report (Energy Commission, 2017). They recommend that subsidies given to all kinds of renewable energy should be decreasing and ultimately removed.

3.4.5.2 Taking advantage of excess heat

The Danish Ministry of Taxation has investigated the excess heating area of the energy system. They conclude that there is a big potential that could be utilized in the energy system. Many argue that it is the excess heating tax that is limiting the implementation of excess heat. The main conclusion in their report is that the excess heating tax is not the primary cause of the lack of implementation. In addition to this, they conclude that the excess heat provides an increased incentive for businesses to utilize their excess heat. In our analyses, we repeatedly see large amounts of excess heating in the heating sector. This is implemented into the energy system even with the current tax level of 50 DKK/GJ. This suggests that the Danish Ministry of Taxation is correct in their conclusion that the excess heating tax is at the correct level. Instead of correcting the excess heating tax they suggest a simplification of the regulation, which will help implement more excess heat. Ultimately, they suggest that the excess heating tax could be lowered to 22.8 DKK/GJ for all types of excess heat. We did not test this in our modelling, since TIMES-DK model is not detailed enough in terms of different excess heat outputs or processes.

3.4.6 Summary

Changing the current incentive structure on 8 parameters is likely to shift the expected development in the *Frozen Policy* scenario towards the *R2050* scenario. Many of the changes are in accordance with expert reports but some changes are more dramatic, e.g. the tax on electricity for heating. We have not been able to test all of the expert recommendations, since the TIMES-DK model still needs some further development to include these. We suggest these areas to be added in order to utilize the TIMES-DK model for future evaluation of changes in the incentive structure.

Some of our changes are in accordance with other sources e.g. the decrease on registration fee on electric- and hybrid vehicles. Some changes are much lower than recommended by other sources, e.g. the tax on electricity for heating. However, they agree that change is needed.

Overall, our new incentive structure is able to achieve 94 % of our recommended scenario *R2050*. Our changes are creating a path for the Danish energy system and compared to our *Frozen Policy* scenario it would only cost 3 BDKK per year to achieve our long-term goal of a fossil-free energy sector in 2050.

3.5 Sensitivity Analysis

The energy sector consists of ever-changing markets and regulation. Therefore, the scenarios in this report are a best guess of the future development under the given inputs and assumptions. However, the likelihood of the future market- and framework conditions in the Danish energy system to be exactly as stated in this report is very unlikely. It is more correct to assume that the results in this report indicate a pattern or a possible pathway for 2050. The Danish energy system is highly connected to the neighboring countries and their development is also uncertain. This combination of interconnection and global trade increases the number of uncertainties. In this section, we try to cover some of the biggest uncertainties and policies for each of our scenarios. A summary of the specific sensitivity analyses provided in this section is shown in Table 3.6.

Scenario	Parameter tested
R2050	Fuel prices on bioenergy
R2050	Renewable energy potentials
R2050	Bioenergy potentials
Incentive Structure	Fuel prices
Incentive Structure	ETS prices

Table 3.6: Overview of sensitivity analyses by scenario.

3.5.1 Uncertainties in R2050

In this section, we present the results of several sensitivity analyses on uncertainties such as fuel prices and bioenergy potentials. Furthermore, an analysis of the impact of different assumptions on onshore wind potential will be evaluated.

3.5.1.1 Fuel prices on bioenergy

The fuel prices on woody biomass fuels has been evaluated, because these directly influence the amount of biofuel produced in Denmark. Both wood pellets and wood chips have been analyzed in a high- and low cost scenario, in which the assumed future prices have been increased to 150 % and decreased to 67 % of base case assumptions.

Straw has been excluded from the analysis, as the need for biofuels for aviation can only be supplied through import or national production of bio-kerosene. As import prices on bio-kerosene are extremely high, the straw price should increase multiple times before biorefineries become economically unattractive compared to imported bio-kerosene.

The main analysis has therefore focused on the prices of wood pellets and wood chips, which in *R2050* is being used by all sectors. Because woody biomass is a widely used fuel in all sectors in this scenario, a change in the price will influence not only one but all sectors.

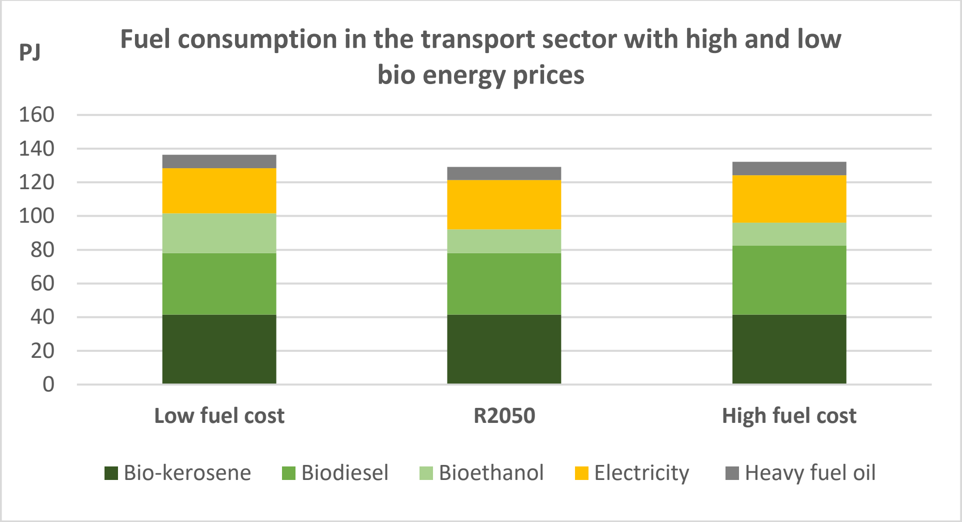

Figure 3.35: Sensitivity analysis of the impact from increasing and decreasing woody biomass prices in the transport sector, with the R2050 scenario as a reference

As seen in Figure 3.35, the total energy consumption in the transport sector will in fact increase for both the low and high fuel price scenario. The reason is that when fuel cost on wood chips increase the model imports corn instead to be used for bioethanol production. This results in an increase in operation and fuel cost on hybrid vehicles which allow conventional biodiesel cars to reappear in the market with a 5 % share. Opposite, if the price for wood chips decreases, the production of bioethanol becomes more competitive as a fuel for cars. This further creates a market for conventional ethanol vehicles to enter at the expense of hybrid cars, due to low fuel costs, with a market share of 13 %.

The change in consumption of wood chips in biorefineries that produce bioethanol combined with a maximum limit of 80 PJ wood chips will affect other sectors. One of them is the industrial sector, which in the *R2050* scenario utilized more than half of the wood chips potential.

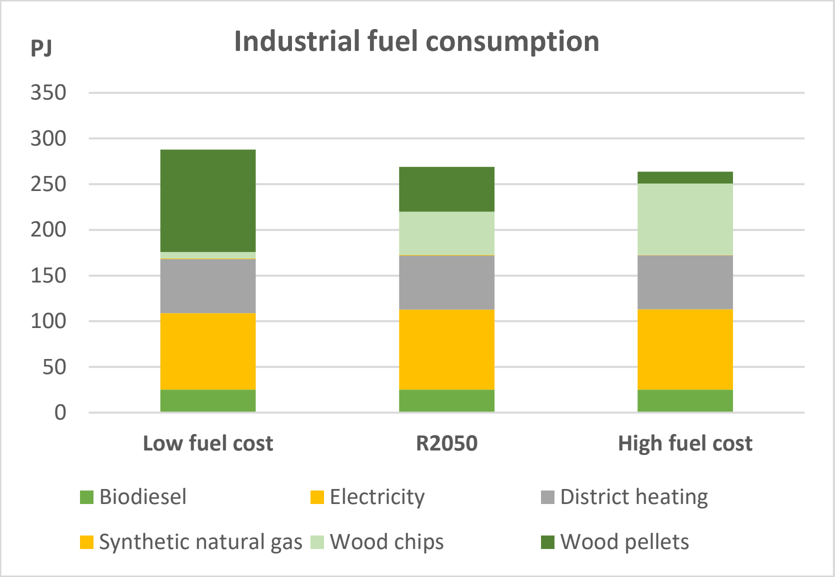

Figure 3.36: Sensitivity analysis of the impact from increasing and decreasing woody biomass prices in the industrial sector, with the R2050 scenario as a reference

It is notable that the amount of wood chips used in the industrial sector decreases, as the prices are lowered. This is because the benefits of utilizing wood chips as input for bioethanol production, which is used in other sectors, has a greater socio-economic benefit than simply using it in industrial boilers. The missing energy consumption in the industry is replaced by wood pellets, since they are the cheapest renewable alternative to wood chips.[35] The opposite appears when the price increases, in which the wood chips consumption in the industry increases. Simultaneously, and as previously discussed, the ethanol production from wood chips is replaced by corn.

Specific for the lower wood chips price scenario is that the industry further uses 19 PJ less than the amount transferred to the bioethanol production plants. This unused wood chips potential has been transferred to the electricity- and heating sector, in which it has been used in a CHP unit. Furthermore, in this scenario heat pumps and offshore wind power are being replaced by CHPs fueled by wood chips, which in fact increases the total fuel consumption of the sector, since CHP units are less efficient.

We can conclude that changes in prices of woody biomass will change the optimal energy scenario for 2050 by primarily influencing the transport sector's consumption of 2nd generation ethanol. This will further create ripple-effects that change the industrial sectors use of wood chips and wood pellets. Overall, the resulting changes are minor over the entire energy system.

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[35] Recall that the *R2050* scenario is forced to be free of fossil fuels from 2035.

3.5.1.2 Bioenergy potentials

In addition to the bioenergy price, the national potential of straw and wood chips has been evaluated, because these two have both been fully utilized in the *R2050* energy system. Since both fuels are scarce resources, a change in the potentials may influence the energy system greatly.

The straw potential has been evaluated in a higher and lower case. The lower is 68 PJ, which is the straw potential from 2010 with no expected increase, while the higher has 148 PJ potential in 2050 which is the estimated potential in the Energy Scenarios report by DEA.[36] Since all straw potentials in the *R2050* scenario has been utilized for bio-kerosene production, the changes in the transport sector and district heating sectors has been evaluated.

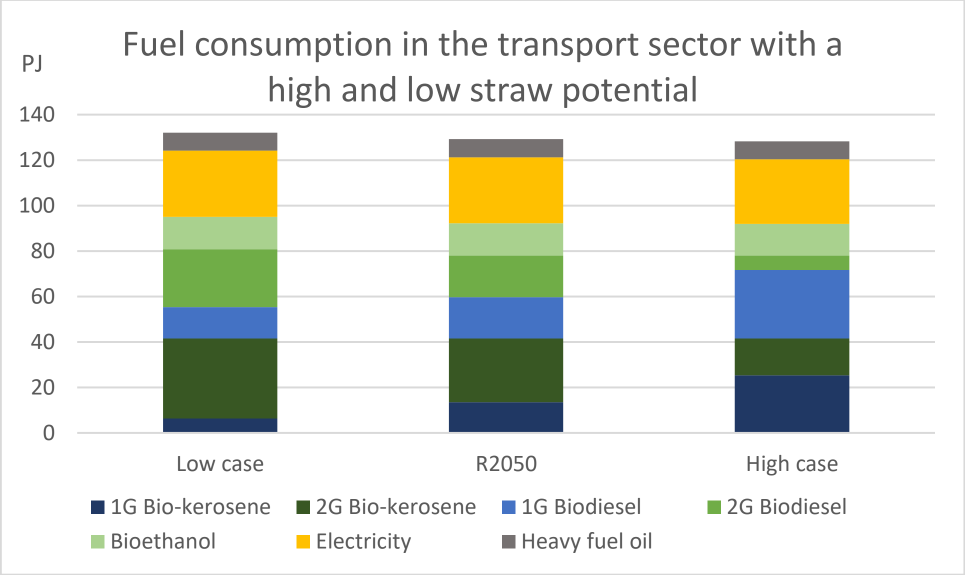

Figure 3.37: Sensitivity analysis of the impact from increasing and decreasing straw potentials in the transport sector, with the R2050 scenario as a reference

As the straw potential varies, it results in changes in the import of 1st generation bio-kerosene and 1st generation biodiesel, since only 2nd generation of the two biofuels are produced nationally. The changes in the case of low straw potential is that a larger amount of biofuels will be imported. Furthermore, the lack of production of biofuels affects the district heating sector, since biofuel facilities all produce excess heat as a bi-product. The capacity of heat pumps is therefore increased, since it is the most feasible alternative to excess heat. Opposite occurs with an increased straw potential, where the import of biofuels are decreasing.

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[36] The Danish potential for all 1 year crops (straw, rape seeds, etc.) is 148 PJ, in this scenario the straw potential is equal to the entire crops potential (Danish Energy Agency, 2014)

Second, the impact of a different wood chips potential has been analyzed because the entire potential is used in the *R2050* scenario. The analysis has been conducted in a high- and low scenario with the low being 40 PJ[37] and the high scenario being an unlimited supply. The only sector in which changes occur for this analysis is the fuel consumption in the industrial sector.

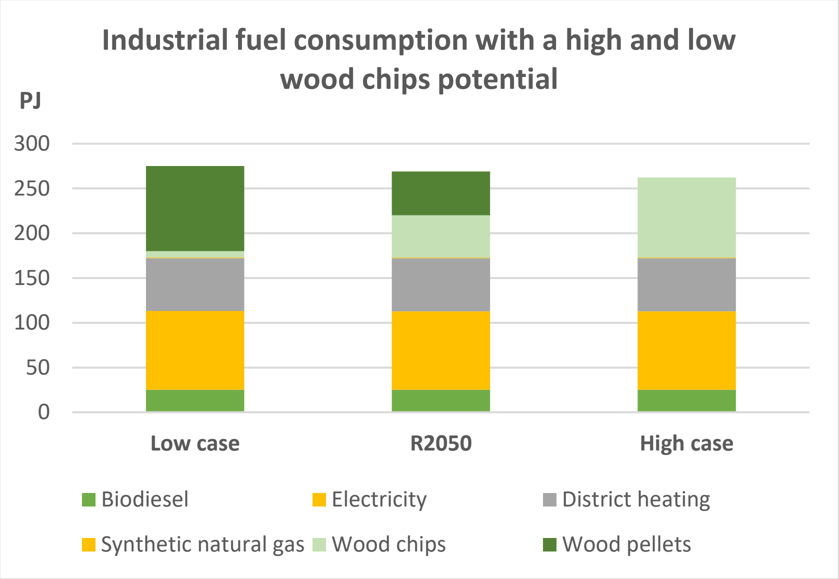

Figure 3.38: Sensitivity analysis of the impact from increasing and decreasing wood chips potentials in the transport sector, with the R2050 scenario as a reference

As seen in the Figure 3.38, the increase and decrease of the wood chips potential only affects the wood pellet consumption of the industry. More specific it affects the medium and high temperature processes in the industry, since these rely in general on commodities like gasses, solid fuels or electricity, the cost of alternatives to either wood chips or wood pellets are too great for implementation.

A change in the potential reserves of biofuels will only affect the *R2050* scenario by a small deviation, as e.g. the decrease in biofuel potentials will increase the alternative biofuel in the respective sectors. Furthermore, no greater symbiosis effects will appear by a change in potential bio resources.

3.5.1.3 Renewable energy potentials and policies

In the previous section the potential for scarce bioenergy resources were evaluated. This section will evaluate the potential of onshore wind turbines as the potential is often limited by local

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[37] Equivalent to the estimated national potential of wood chips (Danish Energy Agency, 2014)

policies. As the cost for onshore wind turbines is very competitive to all other electricity production units, it would be cheaper for the system to implement a higher share of onshore wind power. But as onshore wind turbines are often described as destroying the natural landscape, the construction of new onshore wind turbines is often limited by local regulations and public counteracts.

According to Energinet.dk, the total potential of onshore wind is up to 12 GW, which is almost 3 times the amount compared to the *R2050* scenario (Energinet.dk, 2015a). The potential for onshore wind turbines has therefore been analyzed for capacities to increase to 8 GW and 12 GW.

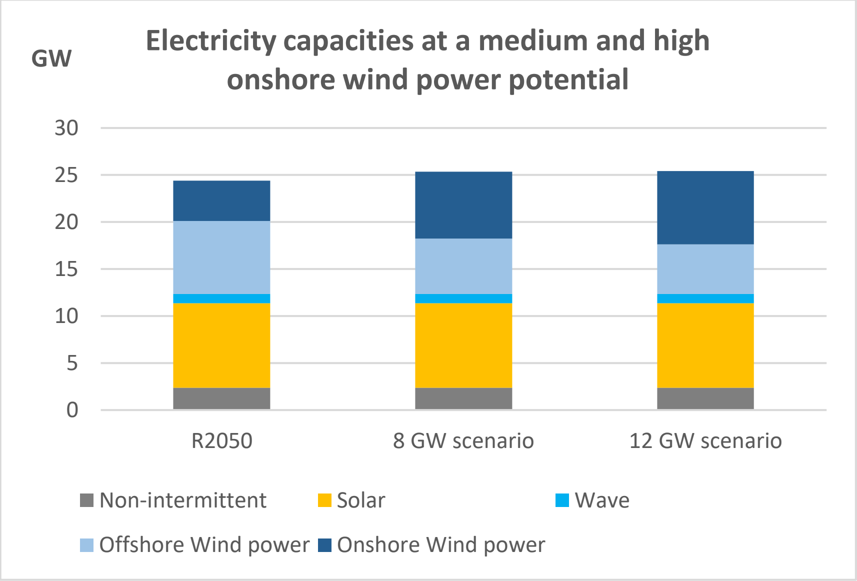

Figure 3.39: Sensitivity analysis of the impact from increasing and decreasing onshore wind power potentials in the electricity sector, with the R2050 scenario as a reference

By increasing the potential of onshore wind turbines, we see that the share of onshore wind power will increase and the amount of offshore wind turbines will decrease simultaneously. However, the full potentials will never be utilized as only 7.1 GW and 7.8 GW onshore wind power is installed for the 8 GW and 12 GW scenarios, respectively. This will influence the electricity prices, since the investment- and operation costs are generally lower. Furthermore, the total system costs will greatly decrease by 1.8 billion DKK in the year 2050 between the *R2050* scenario and the 12 GW scenario. Also, if a subsidy scheme on offshore wind power is applied in the future as shown in Section 3.4, the governmental expenditure on almost 2.5 GW less offshore wind power will affect the national finance positively.

As implementing a higher share of onshore wind turbines will not influence any other sectors in the energy system, it can be concluded that an implementation of a larger potential for onshore wind power would be beneficial to the total system cost and should by that matter be implemented in the future Danish energy system.

3.5.2 Uncertainties in Incentive Structure scenario

In this section, the robustness of the *Incentive Structure* scenario that is recommended in this report will be analyzed. The two parameters of fuel- and EU ETS prices has been increased and decreased by 150 % and 67 % to analyze which impact a change in prices will have on reaching the Danish goal of being fossil free in 2050 under or recommended incentive structure.

3.5.2.1 Fuel prices

Fuel prices historically develop fast and is often link to certain unpredictable events e.g. wars and financial crises, meaning that future market prices are hard to predict. Most notable is the oil price development in recent years in which oil prices within one year decreased by more than 50 % (Macrotrends, 2017a). This section will analyze the impact from price developments in coal, oil products, natural gas, straw and woody biomass as they are the current non-intermittent energy carriers of the energy system. Because of the large amount of information that can be extracted from the model, only the fuel consumptions in each of the four sectors, i.e. industrial, residential, transport and electricity/heating, have been used in this section. Furthermore, only major changes in the energy systems has been shown in this section.

3.5.2.1.1 Coal

In the analysis made on coal prices, only a small change in the short-term for the electricity- and heating sector appears. Only the phasing out of coal consumption appears at a faster rate compared to the *Incentive Structure* scenario, when the coal price is increased. Furthermore, the industrial sector has been applied a tax for coal consumption used by processes and an increase or decrease of coal prices show no further changes compared to the *Incentive Structure* scenario. This means that the increased tax on coal for industry is robust to price fluctuations and will work as intended.

3.5.2.1.2 Oil products

Changing the price of oil products include a change for all fossil fuels that are directly influenced by the crude oil price.[38] Today, the transport sector relies almost entirely on fossil oil products, therefore the sector is very dependent on the oil price development. If our suggested changes to the incentive structure is implemented in Denmark, the transport sector will gradually be less dependent on derivative fuels from crude oil. However, great changes could result in very different system and pathways towards 2050. If the oil price increases, the transition towards a fossil free society will occur at a faster pace and be almost 75 % renewable in 2040 and 95 % renewable from 2045 as seen in Figure 3.40.

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[38] Kerosene, diesel, gasoline and heavy fuel are among other fossil oils all directly related to the crude oil price.

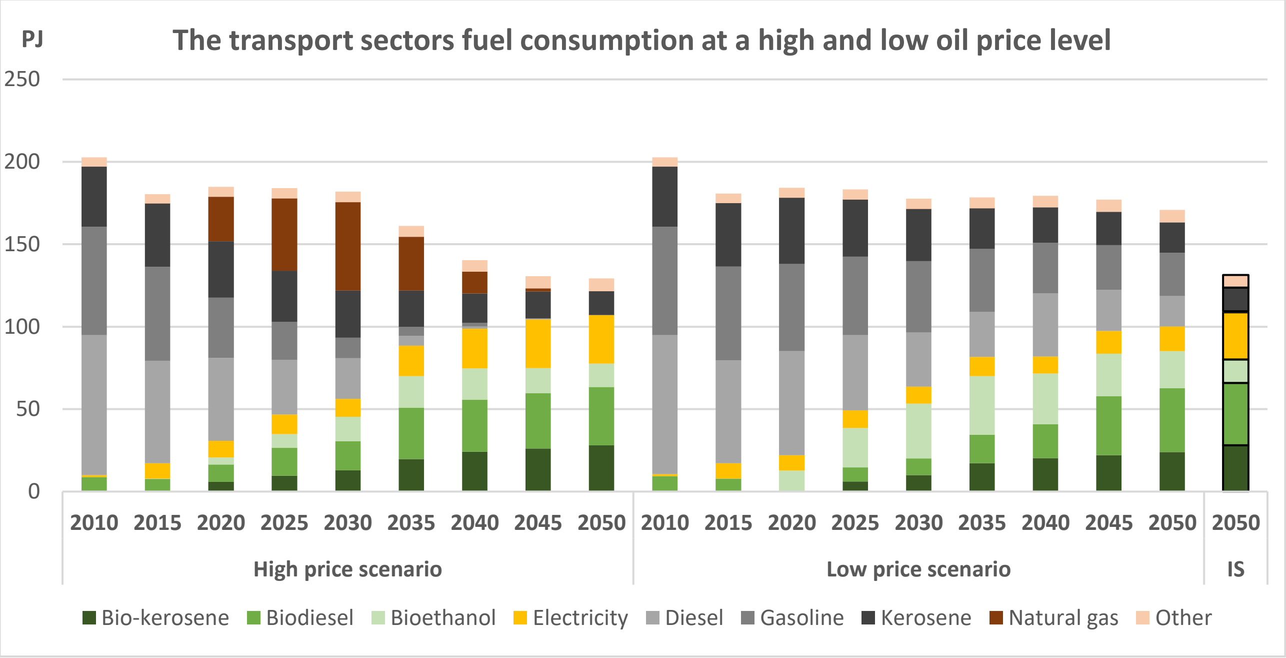

Figure 3.40: Sensitivity analysis of the impact from increasing and decreasing prices on oil products in the transport sector from 2010 to 2050.

Gasoline and diesel consumption by cars will decrease in the short- and medium term towards 2050 and be replaced by gas vehicles from 2020 and hybrid vehicles from 2035. A decrease in the oil prices will influence the sector by gasoline and diesel blends with high amounts of fossil fuels continuing in the market. Although hybrid vehicles are expected to become competitive in 2035, they will not be fully competitive compared to traditional diesel and gasoline vehicles.

Not only does the transport sector get influenced by changing oil prices. The industrial sector will see a large consumption of heavy foul oil for high and medium processes heat, if the oil price development is lower than expected, thereby limiting the consumption of biomass. This is partly a result of the increased fee on coal for industry used in the *Incentive Structure* scenario. Otherwise, coal would most likely be the dominant fuel source.

3.5.2.1.3 Natural gas

Gas has only been used as a limited commodity in the *Incentive Structure* scenario, therefore increasing prices have almost no influence on the energy system. Only a small amount of natural gas vehicles is expected to be used towards 2050, which will be replaced by gasoline and diesel vehicles.

A decrease in gas prices however will directly influence the transport sector and indirectly the industrial sector.

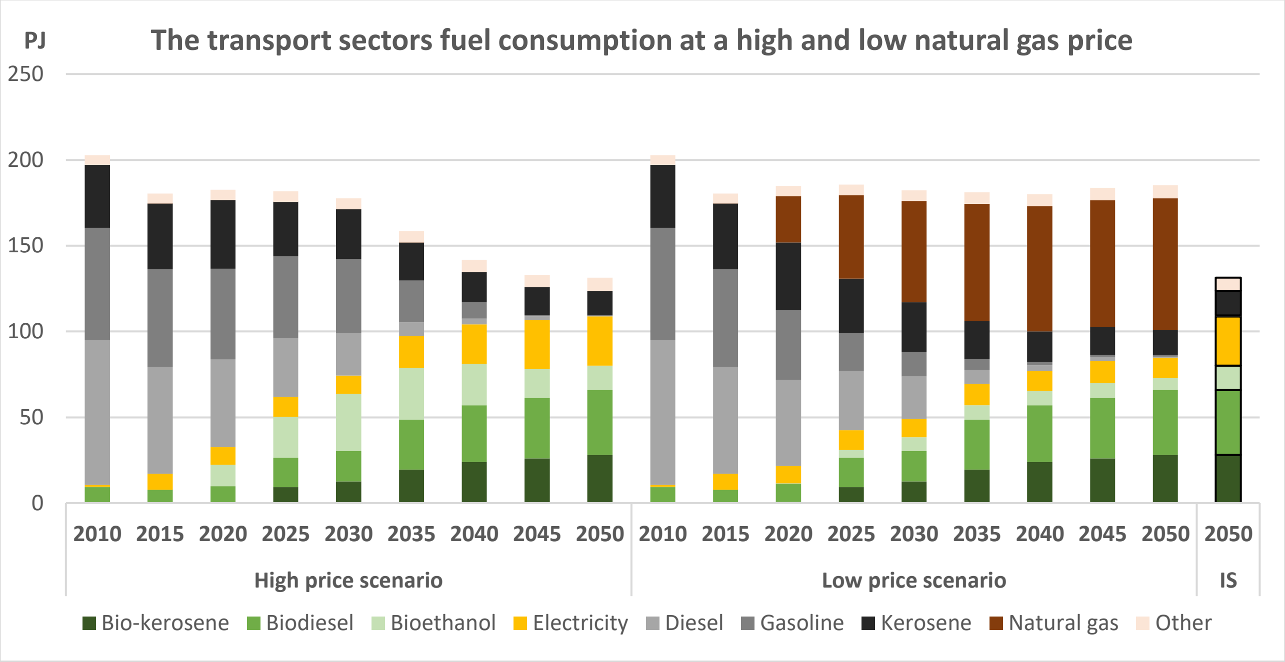

Figure 3.41: Sensitivity analysis of the impact from increasing and decreasing prices on natural gas in the transport sector from 2010 to 2050.

Compared to the *Incentive Structure* scenario, an overall observation of no further fuel efficiency increase in the sector will appear if the natural gas price is decreased. This is because natural gas will become the main fuel for personal passenger transportation and because a gas vehicle is less fuel efficient compared to a hybrid vehicle, thereby resulting in an increased total energy consumption. Furthermore, the entire transport sector will only become approx. 50 % covered by renewable energy in 2050, far from the expected goals of a fossil free society.

Indirectly, the industrial sector will become influenced as well. Because a lower amount of bioethanol is needed in the transport sector, a surplus of wood chips appear in the market, which the industrial processes use instead of wood pellets, due to lower fuel costs.

3.5.2.1.4 Straw

In the analysis of the straw prices similar effects appear in the market as stated in Section 3.5.1.1. In 2050, all straw potentials will still be used by the bio-kerosene production if prices increase. The effect of a decrease in prices only results in cheaper system cost and higher implementation rates, as the bio-kerosene becomes cheaper to produce. However, for the high straw cost scenario, in the short- and medium-term straw will be used by the electricity and heating sector by CHPs replacing both solar power and -heating plants. No further major changes appears in the analysis of the straw price.

3.5.2.1.5 Wood chips and wood pellets

Wood chips and wood pellets are closely related for price changes and have therefore been analyzed together. Because woody biomass in general is used by all sectors, a change in the price will influence the energy system as a whole. In this subsection, each sector will therefore be fully analyzed starting with the transport sector which undergoes most changes.

The transport sector in the *Incentive Structure* scenario gradually implements bioethanol from 2020 towards 2050. In case of increasing fuel prices, the bioethanol production becomes less feasible, thereby causing production of bioethanol to be non-existing. This creates a ripple-effect allowing gasoline to continue into 2050 as a secondary fuel for the hybrid vehicles. Furthermore, in the transition period, natural gas vehicles is being implemented into personal passenger transportation before being phased out again in 2050.

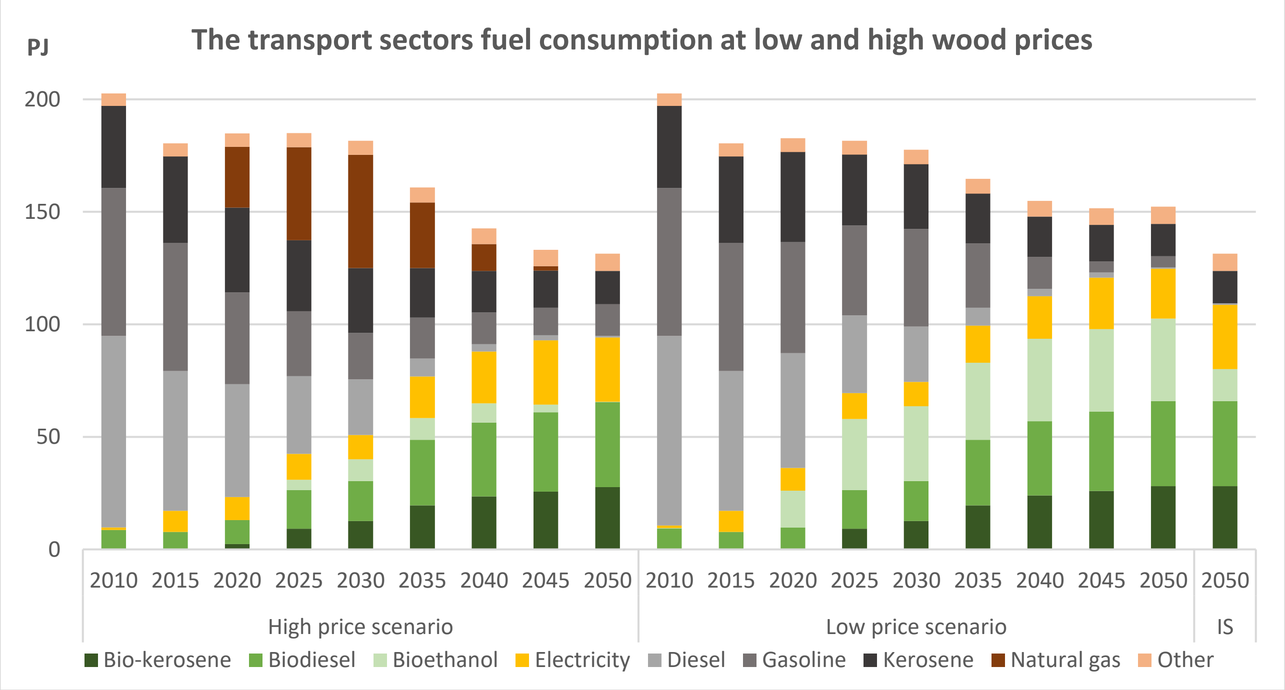

Figure 3.42: Sensitivity analysis of the impact from decreasing prices on woody biomass in the transport sector from 2010 to 2050.

In Figure 3.42 it can be seen how bioethanol will be implemented rapidly from the year 2020 in the low price scenario, and from 2025 the transport sector will have a total fuel consumption of bioethanol of 31 PJ, which is more than 4 times the amount in the *Incentive Structure* scenario. This would lower the consumption of fossil diesel and gasoline. Furthermore, from 2040 and forward all wood chips will be fully utilized by the production of bioethanol producing a total of 37 PJ. In 2050, the cars change to a mix of hybrid cars and standard gasoline cars consuming a gasoline blend with 88 % bioethanol.

The residential sector in the *Incentive Structure* scenario relies on wood pellets during the transition towards electrification of the sector. However, in a high price scenario, the electrification of the sector will appear at a faster rate since wood pellets becomes almost 100 % phased out from the year 2025. In contrast, the low price scenario continues with a high wood pellet consumption of 30 PJ until 2050, where solar heating becomes competitive and the fuel consumption decreases to 17 PJ, as seen in Figure 3.43.

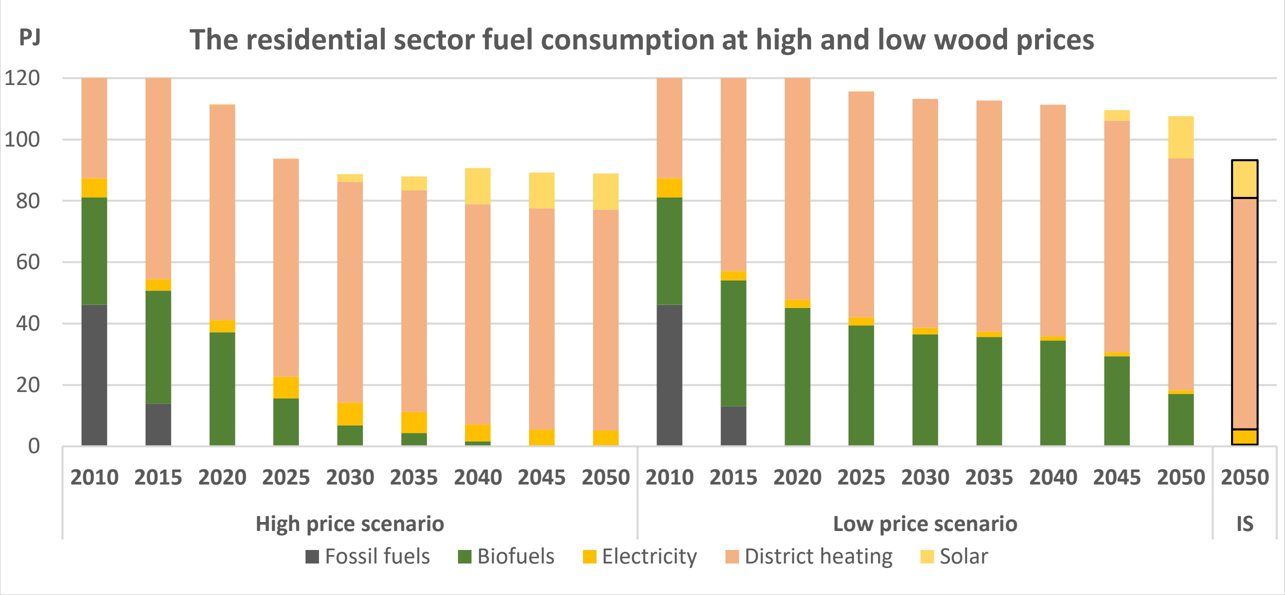

Figure 3.43: Sensitivity analysis of the impact on the residential sector from varying woody biomass prices from 2010 to 2050.

In previous analysis, it has been shown how the industrial sector is dependent on the transport sectors consumption of bioethanol. In the high price scenario, bioethanol is not being utilized by the transport sector, thereby creating a surplus of wood chips, which have been used in the industrial sector. In 2050, the sector consumes the entire potential of 80 PJ wood chips, while wood pellets become too expensive for the process industry to use it, thereby allowing coal, even with a high process fee, to re-enter the sector's fuel consumption. On the opposite, in a low price scenario where the transport sector utilizes the entire wood chips potential for bioethanol production, the industry must rely entirely on wood pellets and therefore consume 123 PJ in 2050.

In the electricity- and heating sector, both the high and low price scenario does not make any significant changes to the consumption of woody biomass during. However, the rate of the transition towards 2050 is slightly dependent on the price of wood. An increase in prices will result in a slightly faster transition and a higher amount of wind in the medium term. Furthermore, an increase in prices will lower the bi-product from bioethanol production, which is excess heat, thereby resulting in a larger share of heat pumps in the district heating sector. Opposite for a decrease in prices, in which the transition will appear at a slower rate and increase the amount of excess heat from biorefineries.

3.5.2.1.6 Summary

Overall, the *Incentive Structure* scenario is expected to reach a low emission system in 2050 if oil prices increase, or if biomass prices decrease. If these fuels develop in the opposite direction, it is likely that the incentive structure recommended in this scenario might not reach a fully fossil free energy system. It should be noted that only a decrease in natural gas- or oil prices will have a major impact on the energy system. However, as natural gas and oil prices in general follow similar trends, it is likely that they will have a simultaneous development. In this case, the energy scenario will be greatly affected by development from these commodities (Macrotrends, 2017b).

Increasing fossil fuel prices and decreasing bioenergy prices have in general shown that a quicker transition toward a low emission society will appear, resulting in meeting the expected goal of a low emission society in 2050, although the end result might deviate from the *R2050* scenario.

3.5.2.2 EU ETS prices

Similar to the fuel prices, the EU ETS prices can be hard to predict. Most notable is the large reserve of quotas that has been set aside due to the EU in total having overachieved their expected goals (Danish Council on Climate Change, 2017b).

We have analyzed three different development of the EU ETS price; a flat rate at the same cost from 2017 and forward, a price 67 % of the expected development in prices and a 150 % price of the expected development of the price. This will give us an understanding of the impact of price changes in the EU ETS. Until 2050, only an increase in the ETS price have shown any impacts. However, this is only by 2,000 kton of less CO_2 emissions in the year 2020. Furthermore, from 2030 and forward the CO_2 emission will deviate from the recommended incentive structure by less than 10 kton of annual CO_2 emissions. The only real impact of the EU ETS system appears in 2050 for the flat rate development of the price, which is shown in Figure 3.44.

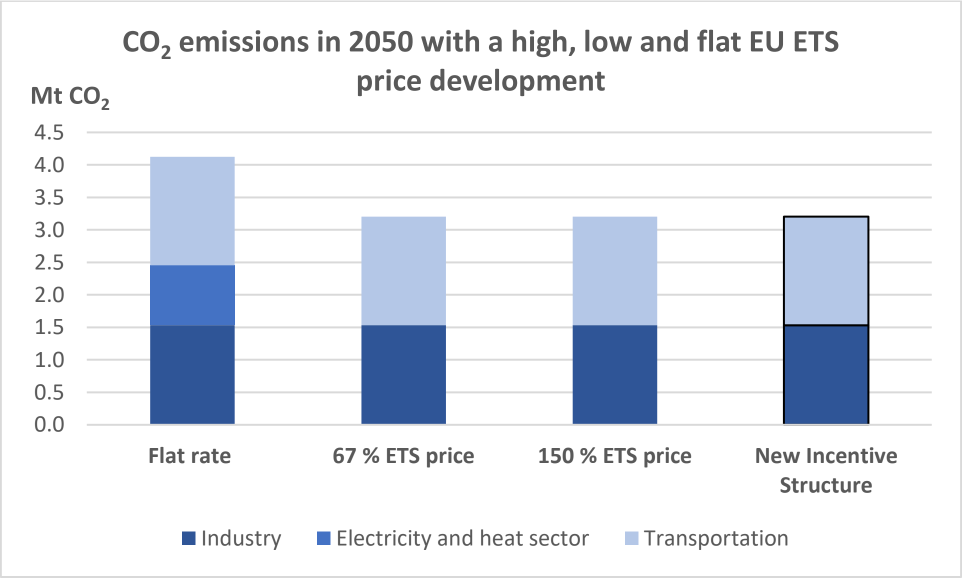

Figure 3.44: Sensitivity analysis of the CO_2 emission in 2050 by increasing and decreasing ETS prices. The industry and transport sectors emits CO_2 from fossil fuels, which only can be phased out by import of biofuels.

The CO_2 emission that appear in the flat rate ETS price scenario implements a geothermal heating plant using an absorption heat pump fueled by a coal boiler, thereby increasing the CO_2 emission even if a legal prohibition on fossil fuels in the transport sector is made.

Overall, it can be stated that an increase in the ETS price alone will only influence the short to medium development of the Danish energy system and on a long-term basis the ETS price will have little to no impact on our *Incentive Structure* scenario. However, a severe decrease in the expected development could result in a minor consumption of fossil fuels and thereby not meeting the 2050 target for the Danish energy system.

3.6 Conclusion

Denmark is highly committed to several climate goals both nationally and internationally. Denmark has generally been one of the pioneering countries in renewable energy integration and energy efficiency. From this front-runner position, Denmark has been able to set relatively ambitious climate goals, and has so far succeeded in reaching these goals. However, we have shown in this report that it is unlikely that Denmark will reach the 2050 target of a low emissions society, unless changes are made to the existing regulatory incentive structure. By modelling a *Frozen Policy* scenario, we estimate that the energy system will remain responsible for around 15 million ton of CO_2 emissions per year in 2050. This corresponds to a reduction of 72 % compared to 1990 level. While the emissions are expected to decrease through to 2050, the estimated actions taken by companies and individuals in Denmark will not be enough to ensure a fully renewable energy system by 2050. The electricity- and heating sectors are expected to become 100 % renewable under current policies, while the transport sector will continue to lack behind with only 50 % renewable energy in 2050. The industrial sector is expected to become 88 % renewable in 2050.

Since the expected development will not be enough to reach the 2050 target, we propose a strategy for the future energy system, called the *R2050* scenario, which we estimate to be a sustainable and low-cost solution prepared for the long-term after 2050. We recommend that the energy system of 2050 is characterized by a large degree of electrification across all sectors, where especially electric heat pumps and hybrid plug-in vehicles play a key role. The increased electricity consumption should be supplied by electricity from 12 GW wind turbines, of which almost 2/3 are offshore, combined with 9 GW solar PV and 1 GW wave power. There should be around 2.4 GW thermal capacity left in the electricity sector, primarily being CHPs using biomass and waste for combustion. The main purpose of the thermal capacity in the electricity sector is to supply peak demand and serve as reserve capacity.

We recommend that the district heating sector in 2050 is based on large-scale electric heat pumps, waste combustion and solar heating. Furthermore, excess heat from industry and from domestic production of biofuels should be used in district heating. Residential heating in non-district heating areas should be supplied by individual heat pumps and solar heating. The industry should use bioenergy for those processes, which require high temperature heat, and for machinery and vehicles, which require a combustion engine. The remaining energy demands in the industry should be supplied with district heating and electricity from the grid. The transport sector should use biofuels and electricity. Rail transport should be electrified, while personal cars should be hybrid vehicles, which use both electricity and bioethanol, which is produced domestically. Truck transport should use biodiesel, while aviation should be completely fueled by bio-kerosene.

Overall, our recommended *R2050* scenario is characterized by a total bioenergy consumption of 355 PJ per year, which is 90 PJ above the estimated national potential. Thus, the degree of self-sufficiency is estimated to 89 %, when not accounting for national extraction of oil and gas. The gross energy consumption in this scenario is estimated to 617 PJ per year, which is a reduction of 20 % compared to today's level. The reduction will primarily be a result of increased system efficiency from the cross-sectoral electrification.

As a result of analyzing the differences between the *Frozen Policy* development and our *R2050* recommended scenario, we have identified several changes to the existing incentive structure, which we believe are likely to guide Denmark in the direction of the *R2050* energy system and a full compliance with the 2050 target. We suggest changing 8 parameters in the existing incentive structure. Each specific change is carefully selected based on its specific purpose for individual technologies and -sectors, but also for the system benefits achieved by directly or indirectly aiding specific technologies and commodities in gaining market share. The recommended changes to the existing incentive structure are shown in Table 3.7 below.

Description	Sector	Type	Existing value	Suggested value
Registration fee	Transportation	Fee	Incl. battery cost	Excl. battery cost
Coal	Industry	Fee	4.5	54.9
Natural Gas	Transportation	Fee	54.9	65.5
Electricity	Heating	Fee	106.4	40
Electricity	Transportation	Fee	245.8	230
Bio-kerosene	Transportation	Subsidy	0	125
Bioethanol	Transportation	Subsidy	0	25
Offshore Wind	Electricity	Subsidy	68.3	68.3-42.5[39]

Table 3.7: Summary of the recommended policy changes for achieving the R2050 scenario

Overall, this adjusted incentive structure is able to achieve a similarity of 94 % of our recommended *R2050* scenario using only 8 changes to the incentive structure. Furthermore, due to limits on national bioenergy potential, we suggest working towards an EU wide prohibition on fossil kerosene and –diesel no later than 2050. These fuels serve very specific purposes in transport and industry, and the most appropriate alternatives are their bio-counterparts. Prohibiting the use of these fossil fuels either nationally or on an EU level will ensure that they are completely replaced by imported and domestically produced biofuels.

As the energy fee on electricity for heating is highly debated, we have investigated this value thoroughly, with the aim of finding an optimal value in terms of maximizing the net tax revenue across the energy system. In our recommended incentive structure, we decrease the current tax rate from 106.4 DKK/GJ to 40 DKK/GJ. However, lowering the tax to 70 DKK/GJ will maximize the net tax revenue, because more electricity will be used for heating, thereby providing a larger net tax

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[39] An extension of the current subsidy scheme until 2030 and a new lower value until 2035.

revenue. Thus, we can conclude that a decrease in the existing electricity fee for heating will both increase the national net tax revenue, as well as increase the incentive for companies and individuals to invest in electric heat pumps, which have a positive effect on the overall energy system.

We estimate that implementing our recommended incentive structure will reduce the net tax revenue by 3 billion DKK per year from 2020 to 2050 compared to frozen policy. However, we believe this a small price to pay for a successful achievement of the 2050 target.

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Appendices

Appendix 01 – TIMES-DK model files

See the attached USB stick for a copy of the TIMES-DK model used in this report.

There are 3 different groups of model files used in the TIMES-DK model. See Appendix 03 for an overview of which files have been updated. The files are grouped in the following folders:

- TIMES-DK_FINAL
    - Contains all of the *Base year templates* files, e.g. existing technologies, demands and fuel prices.
- SubRES_TMPL
    - Contains all *SubRes files* e.g. new technologies.
- SuppXLS
    - Contains all of the *Scenario files* used in this project e.g. tax & subsidy sheets.
        - All Scenario files starting with an X & Y was used in the creation of our incentive structure
        - All scenario file starting with a Z was used in the creation of our sensitivity analysis

Appendix 02 – Taxes and subsidies

This appendix contains our assumptions and consideration about the taxes and subsidy schemes that has been utilized for the creation of this thesis. We included only the major taxes and subsidy schemes as it is too much to implement everything during this study. Each assumption and how they have been applied in the model TIMES-DK will be further explained in this section.

4.1.1 Taxes

The taxation scheme sin Denmark is primarily based on three different taxation methods.

- Tax on consumption (Energy fee)
- Tax on negative externalities (Emission fee)
- Tax on ownership (annual and registration fee)[40]

Danish taxes within the energy sector is primarily applied on the amount of fuel used for a specific process. The general rule in Denmark is that an emission tax and an energy fee is applied either the producer or the consumer of a given energy unit. Emission tax is always applied on the consumption of a fuel, meaning that heating- or electricity producers always pay this fee, whereas in the transport sector the owner of a given vehicle pay the emission fee when purchasing the fuel[41]. Energy fees in the heating sector is applied on the fuel input during production/conversion, whereas electricity is applied an energy fee when consumed, meaning there is no energy fee on the fuel input for electricity production. Energy fees in the transport sector is applied similar to the emission fee. Furthermore, there does exist several ownerships taxations in the transport sector.

All fees up till 2017 used in this report is historic. Development in future fees prices is therefore based on the Danish Inflation (Statistics Denmark, 2017a) only to be corrected if a new law or change to an existing law is made e.g. the Danish PSO fee is now being phased out by 2022.

4.1.1.1 Energy fees

All energy fees used in this thesis has been found in the 1st partial analyses of the incentive structure from the Danish Ministry of Taxation (Danish Ministry of Taxation, 2016a) and verified in reference to the current legislation in Denmark. All data has been calculated in 2016 values since most values in the model currently is implemented in 2016 values.

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[40] In which ownership taxation is only applied in the transport sector.

[41] In Denmark fees in the transport sector is often applied at the gas station, who increase fuel cost equal to the total tax.

Biogas, bioethanol and biodiesel are all given same values at the fossil version, because as stated in the law energy fees are calculated based on energy density and regulated to fit with fossil energy fees (Danish Ministry of Taxation, 2014b).

Below in Table 4.1 is an overview of the 4 different tax sheets in the TIMES-DK model and which fuel types we have updated according to the applicable legislation.

Legislation	ELC	IND	RES	TRA
Energy Tax Act of Petroleum Products	Diesel Biodiesel Bioethanol LPG Heavy fuel oil	Diesel Biodiesel Gasoline Heavy fuel oil	Diesel Biodiesel	Diesel Biodiesel Gasoline Bioethanol LPG Heavy fuel oil
Energy Tax Act of Natural Gas	Natural gas Biogas Bio-SNG	Natural gas Biogas Bio-SNG	Natural gas Biogas Bio-SNG	Natural gas Biogas Bio-SNG
Energy Tax Act of Coal and Coke	Coal Waste	Coal Waste		
Energy Tax Act of Electricity	Electricity	Electricity	Electricity	Electricity
No tax	Wood chips Wood pellets	Wood chips Wood pellets	Wood chips Wood pellets	

Table 4.1: Overview of which fuels are updated in which sheets with which applicable legislation.

4.1.1.2 Emission fees

All Emission fess are based on calculation of the national negative impact of the emission to the environment. The type of fee is therefore a fee internalizing the socio-economic cost of emitting specific products into the world (Danish Ministry of Taxation, 2016c).

The existing EU ETS is implemented into the model and has the most recent exceptions for price development from *“Samfundsøkonomiske beregningsforudsætninger 2017”* by DEA (Danish Energy Agency, 2017c). As the EU ETS is regulated on a European level Denmark is not able to affect the price.

Emission fess are all found in three laws:

- Law on Carbon Dioxide (CO_2) (Danish Ministry of Taxation, 2011)
- Law on Sulphur (SO_2) (Danish Ministry of Taxation, 2015)
- Law on Nitrogen Oxide (NO_x) (Danish Ministry of Taxation, 2013)

4.1.1.2.1 CO_2 fee

As only unit with a capacity of 20 MW fuel input is included in EU ETS, all other CO_2 emitters incl. vehicles has to pay the CO_2 fee. This fee is often paid in an earlier stage of the supply-chain and is reflected in the price. The fee in the model is based upon the current legislation. The law states that biomass is not included in the CO_2 fee and is therefore excluded from the CO_2 fee.

4.1.1.2.2 SO_2 fee

SO_2 fee is calculated similar to CO_2 fees and is specified for separate processes. According to the law, all stationary processes with a capacity of less than 1 MW is not included to pay the tax, however in the model two stationary processes can possible be taxed because they have minimum capacity range of less than 1 MW.[42] It has been assumed that these two processes will always pay SO_2 fees although they possible could have been outside the legislation.

4.1.1.2.3 NO_x fee

Similar to both SO_2 and CO_2 fees the NO_x fee are applied based on emission of different processes.

4.1.1.3 Ownership fee in the transport sector

Ownership fees in the transport sector can be described in two different tax systems, onetime and annual payment. Similar for both tax types is that they are calculated based on the specific transportation type. In order to minimize the model and make the modelling simpler to understand we use the average Danish personal car has been used as reference value to calculate onetime and annual fees (EA Energi Analyse, 2015). Similar assumptions have been made for vans. The reason this assumption has been made is that cars in car generally are cheaper and smaller compered to EU standards. Other vehicles as rail, ship and aviation is based on European standards, because of more similar and a larger database for future investment cost and alternative fuels (Danish Energy Agency, 2016a).

4.1.1.3.1 Registration fee

The onetime ownership fee also known as registration fee is spilt into before and after 2016 values, because from 2016 several changes were introduced in to the taxation system. The fee itself is calculated based on the investment cost as a percentage of the investment cost of the specific vehicle. Furthermore, several reimbursements are valid if the vehicle comply with certain requirements as minimum fuel efficiency. Opposite the vehicle can have an increase in registration

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[42] The two processes in the TIMES-DK model has the process names ECCPWSTBPC6N and ECCPWSTBPD6N

fee if the fuel efficiency is below the standard value. In Table 4.2 the assumptions for the registration fee with possible reimbursements or additional tax is visualized.

Type of vehicle	Registration fee	Reimbursements	Extra tax
Coach	60 % of investment cost above 12,100 DKK	ESP system: 2,500 DKK	-
Public busses	No registration fee	-	-
Motorbikes	105 % of investment cost between 9,400 DKK and 31,400 DKK. 150 % of investment cost above 31400 DKK	ABS brakes: 4,165 DKK	-
Vans, with a maximum weight of 4 tons	50 % of investment cost above 17,500 DKK	-	8,000 DKK for both Petrol and Diesel vehicles
Vans, with a maximum weight of 2,5 tons and no windows in the back	30 % of investment cost above 33,727 DKK, however a maximum fee of 56,800 DKK	-	8,000 DKK for both Petrol and Diesel vehicles
Cars	105 % of investment cost up till 99,600 DKK. 150 % of investment cost above 99,600 DKK	Alarm on harness: 600 DKK Fuel efficient petrol cars: 8,000 DKK Fuel efficient diesel cars: 0 DKK ABS brakes: 3,750 DKK Airbags: 7,680 DKK	-
Electric cars	Calculated similar to cars, however until 2020 only by a certain percentage of the calculated fee: 20 % in 2016 40% in 2017 60% in 2018 80% in 2019 100% in 2020		
Plug-in Hybrid cars	Calculated similar to cars, however until 2020 only by a certain percentage of the calculated fee: 20 % in 2016 40% in 2017 60% in 2018 80% in 2019 100% in 2020		
Cars powered by fuel cells	Calculated similar to cars, however until 2023 only by a certain percentage of the calculated fee: 20 % in 2019 40% in 2020 60% in 2021 80% in 2022 100% in 2023		

Table 4.2: Registration fee on vehicles after 2016 assumptions for TIMES-DK model (2015 DKK).

Investment cost for average Danish vehicles is only given until 2030. Investment cost as of 2030 is therefore not assumed to change, except for battery cost for electric vehicles, which is in accordance to the EU standard values for expected vehicle cost.

4.1.1.3.2 Annual Ownership fee on vehicles

The annual ownership fee on vehicles is defined by three types' road fee, fuel efficiency fee and weight fee. The road fee is only applied on trucks both national and international trucks and the amount of wheel axles that exist on the vehicle. It has been assumed, that the average truck has 3 axles, since this type of truck is the most common type. Weight fee is applied for all other vehicles but public busses and it is assumed other busses have a weigh of 7.5 ton, whereas all weights on vehicles are calculated based on the average Danish vehicle. The two fees (weight and road fee) are both fees that are used for supporting construction and maintenance of public roads. The fuel efficiency tax is made for giving an incitement for purchasing a more environmental friendly vehicle, the fee is calculated based on the average Danish vehicle.

In Table 4.3 the annual taxation on vehicles has been visualized.

Vehicle	**Fuel type**	**Available in year**	**Road fee**	**Fuel efficiency fee**	**Weight fee**	**Total Fee**
Car	Diesel	all		4500	5780	10280
Car	Otto Engine (Gasoline)	all		1780	3320	5100
Car	Gas	all			4420	4420
Car	Electricity	all			5780	5780
Car	Hybrid - Electric/Gasoline	all		620	5780	6400
Car	Hydrogen	2015			7960	7960
Car	Hydrogen	2030			5780	5780
Car	Ethanol	all			3320	3320
Motorbike	Gasoline	all			690	690
Moped	Gasoline	all			690	690
Motorbike	Ethanol	all			690	690
Moped	Ethanol	all			690	690
Bus	Electricity - Public bus	all			0	0
Bus	Electricity - Coach	all			3640	3640
Bus	Diesel - Hybrid - Public Bus	all			0	0
Bus	Diesel - Hybrid - Coach	all			3640	3640
Bus	Diesel - Public Bus	all			0	0
Bus	Diesel - Coach	all			3640	3640
Bus	Gas - Public Bus	all			0	0
Bus	Gas - Coach	all			3640	3640
Truck	Diesel	all	5591			5591
Truck	Gas	all	5591			5591
Truck	RME	all	5591			5591
Van	Diesel	all		14240	1830	16070
Van	Gasoline	all		9960	1830	11790
Van	Electricity	all			1830	1830

Table 4.3: Table of annual ownership fees on vehicles in Denmark.

4.1.2 Subsidies

Subsidy scheme in Denmark is widely applied among both renewable technologies and technologies using fossil fuels within the electricity sector. All subsidies in the energy sector is currently supported by the energy consumers as a tariff within their respective sector, however as of 2022 the PSO (Public Service Obligations) tariff on the electricity sector disappears and subsidy schemes will from this point be fully supported by increasing the public tax income (Energi-, forsyning- og klimaministeriet, 2017). The subsidies is utilized in 4 main categories

- Surcharge on renewable electricity production (e.g. wind power).
- Securing the supply of electricity and natural gas
- Energy savings
- Research and development in the energy sector and environmental investigations.

Historically the total PSO tariff has been increasing since its implementation in 1996 up till approx. 8 BDKK in 2015. This off cause represent the increasing subsidies that has been supported to renewable energy production in these years. Furthermore it is expected that the future expenditures on support of renewable energy production to increase in the coming years and that the total PSO decreases as the support on decentral CHP is phased out as seen in Table 4.4.

MDKK (2016)	2016	2017	2018	2019	2020
Onshore Wind Power	1,824	1,576	1,400	1,246	1,066
Offshore Wind Power	2,504	2,484	2,788	3,789	4,350
Biomass	442	648	676	651	808
Biogas	552	417	384	369	356
Solar Power	192	388	406	426	439
Other Renewable energy	10	10	10	9	9
Decentral CHP	2,540	2,500	1,985	216	38
Other PSO	231	229	225	222	219
PSO-expenditure total	8,294	8,253	7,873	6,929	7,285

Table 4.4: Estimated PSO expenditures for 2016-2020 for specific production types and other purpose.

4.1.2.1 General assumptions for subsidies

In this thesis only the current subsidy scheme on biomass, biogas, wind power and solar power is used in the calculations for future developments in the energy sector. The assumption not to included support on decentral CHP is based on the already decided out phasing of this subsidy and the subsidy will most likely not be renewed. Furthermore, all production on CHP is fixed until 2020 forcing production on the plants.

The base case model is only created with existing legislation, because of this all subsidies schemes have an expiration date as shown in Figure 4.1.

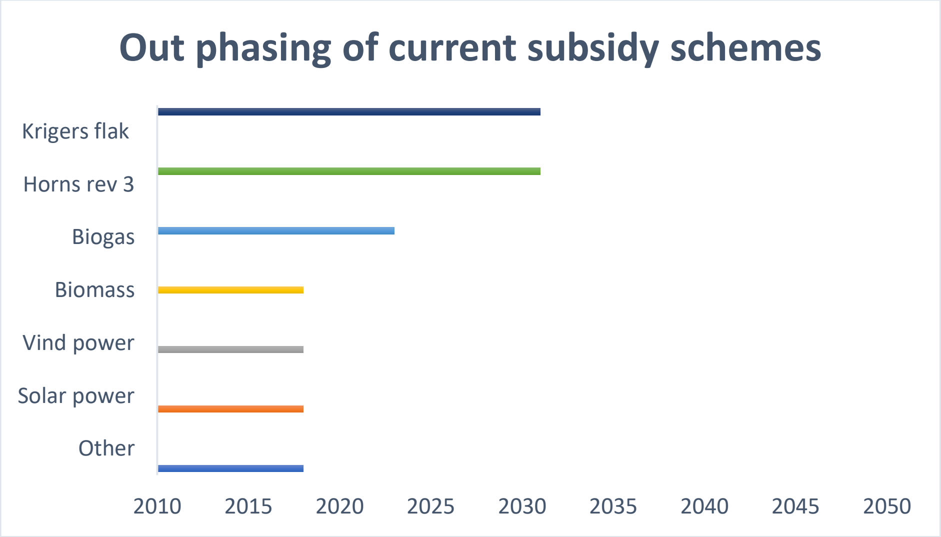

Figure 4.1: Ending of subsidies according to current legislation.

In the TIMES-DK it has been assumed that electricity prices will increase in the future, therefore the subsidies have been estimated to decrease by 10 %-point for every 5 year period after 2015 for all processes with a limit on a maximum subsidy or when a subsidy is created as a fixed subsidy, because the model only allows subsidies as a feed in tariff.

Although there does exist other subsidies in Denmark than the ones stated in this chapter it has been assumed that these, the main subsidies currently in Denmark, will provide a good model for the future expectations in the Danish energy sector.

Further assumptions made on specific processes is described in the coming sections.

4.1.2.2 **Wind power**

Wind power in general is subsidies by the same price by “the open door” concept, unless a governmental agreement on a specific project is being developed, like the subsidies on the offshore wind power facility near Anholt (Danish Ministry of Taxation, 2016a). Furthermore, existing wind power plants have had different subsidy schemes depending on the year of implementation therefore the subsidies supplied for these have been an estimated mix of previous legislation giving all wind power installed before 2010 the same subsidy.

This project have implemented current law for wind power and the coming Horns rev 3 and Kriegers Flak projects, that is due to being implemented 2019 and 2020, respectively. However since the model operates in 5 year intervals, the subsidy on these projects will not be implemented until the year 2020 and the following 11 years.

Wind power is subsidies for 25,000 full load hours or approx. 8 years for onshore and 6 years for offshore, calculated based on data of the specific technologies. The governmental agreed projects is subsidies for 50,000 full load hours or approx. 11 years (Danish Energy Agency, 2017a). The input data for subsidies on wind power is shown in Table 4.5.

Wind power	Year of implementation	Øre/kWh	Estimated length of subsidy
Onshore[43]	2010	22	8
	2012	26,8	8
	2015	26,8	8
Offshore[43]	2010	22	6
	2012	26,8	6
	2015	26,8	6
Existing offshore wind power	2010	43,9	11
Anholt Wind Farm[44]	2012	105,1	11
Horns rev 3[44]	2020	77	11
Kriegers flak	2020	37,2	11

Table 4.5: Subsidy schemes for wind turbines used in our Frozen Policy.

4.1.2.3 Biomass

Biomass used for electricity production is subsidies by 15 øre/kWh electricity produced. In order to include the subsidies only on the used amount of fuel it have been necessary to set subsidies on the fuel used, because some plants does use several other fuels e.g. waste, natural gas and coal. Therefore the subsidy has been calculated for separate technologies to include specific electricity efficiencies. However, this does imply that plant capable of optimizing production can have less electricity production compared to their maximum electric efficiency. By a random selected samples it has been estimated that biomass CHP mostly operates 5 % point under their maximum electricity efficiency. Therefore, this observation has been taken into account when the calculation on each separate plants subsidy has been made and it has been assumed that all plants, with variable

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[43] Subsidies are provided up to a maximum price for subsidies and electricity revenue of 58 øre/kWh.
[44] Subsidy for Anholt and Horns Rev 3 wind farms are fixed in tariff.

production pattern, on average produce at 5 % point lower than maximum electricity efficiency. All CHP units that cannot optimize production, subsidies have been calculated based on their respective efficiencies.

4.1.2.4 Biogas

Biogas in Denmark is subsidies when producing biogas, unless the biogas is used directly in electricity production, there it is subsidies based on the electricity output. The law is written so that a biogas engine with an electric efficiency of 36 % has the exact same subsidy as if the biogas was provide to the natural gas grid. In order to minimize the amount of subsidy schemes in the model it has therefore been assumed that biogas produced from electricity is not existing and that all biogas in the base case model is provided to the grid for natural gas. Thereby the biogas production is subsidies as expressed in Table 4.6.

Subsidy type	Type	Value	Unit	Notes
Subsidy 1	Feed in tariff	39	DKK/GJ biogas	Subsidy 1 increases annual by 60 % of the net price index
Subsidy 2	Feed in tariff	26	DKK/GJ biogas	Subsidy 2 is depended on the standard level of gas (53.2 DKK/GJ) and increase or decrease equal gas price, giving a minimum subsidy of 79.2
Subsidy 3	Feed in tariff	10	DKK/GJ biogas	Subsidy 3 decreases from 2016 to 2019 to disappear in 2020

Table 4.6: Overview of biogas subsidy for pure biogas production delivered to the grid used in the Frozen Policy scenario.

4.1.2.5 Solar and other electricity productions

Solar and other renewable electricity producing plants not expressed in any of the other subsidy schemes is subsidized by the 60/40 scheme. The 60/40 scheme subsidies for the first 10 years with 60 øre/kWh of electricity produced and 40 øre/kWh for the next 10 years of production. This includes solar PV and wave power.

Appendix 03 – Overview of model changes

During the course of this project we have updated the following input sheets in the TIMES-DK model. All of the excel sheets can be found in Appendix 01. Table 4.7 visualize the overall changes and deviations that the model has been though. Table 4.8 then describe briefly the changes made in each file. All changes are highlighted with yellow in the excel sheets.

BASE	SubRES	Scenario
BY_Trans	SubRES_ELC_DH-Pipes	ELC_BaseConstraints
SysSettings	SubRES_ELC_DH-Pipes_Trans	ELC_DONG_NoCoal2023
VT_DK_APP	SubRES_ELC_ImportExport	ELC_Limited_Fuels_2015
VT_DK_ELC	SubRES_ELC_ImportExport_Trans	ELC_NoFossil2035
VT_DK_HOU	SubRES_ELC_Plants2020	ELC_NetElcExports
VT_DK_IND	SubRES_ELC_Plants2020_Trans	ELC_RES_Buildrates
VT_DK_SUP	SubRES_ELC_Plants2025	ELC_TaxesSubsidies_FP
VT_DK_TRA	SubRES_ELC_Plants2025_Trans	ELC_TaxesSubsidies_NoTax
	SubRES_ELC_Techs	ELC_WindLowProd
	SubRES_ELC_Techs_Trans	ELC_WindMaxGrowth
	SubRES_IND_Techs	ETS-NETS_EmiCoeff
	SubRES_IND_Techs_Trans	IND_BaseConstraints
	SubRES_RES_APP_Techs	IND_Dem_UPD_E-Mat_to_E-Stat
	SubRES_RES_APP_Techs_Trans	IND_DemandFractions
	SubRES_RES_HeatSav	IND_EE-HIGH
	SubRES_RES_HeatSav_Trans	IND_EE-LOW
	SubRES_RES_Techs	IND_TaxesSubsidies_FP
	SubRES_RES_Techs_Trans	IND_TaxesSubsidies_NoTax
	SubRES_SUP_BiogasPlants	IND-RES-TRA_NoFossil2050
	SubRES_SUP_BiogasPlants_Trans	RES_BaseConstraints
	SubRES_SUP_BioRef	RES_BuildingStockProj
	SubRES_SUP_BioRef_Trans	RES_DemandFractions
	SubRES_SUP_H2_Chain	RES_RestrictHeatSav
	SubRES_SUP_H2_Chain_Trans	RES_TaxesSubsidies_FP
	SubRES_TRA_Techs	RES_TaxesSubsidies_NoTax
	SubRES_TRA_Techs_Trans	SUP_NorthSeaMiningProj
		SUP-ELC_RenewablePotentials
		SYS_DeliveryCosts
		TRA_BaseConstraints
		TRA_Blend1End_COMETS
		TRA_DemandFractions
		TRA_TaxesSubsidies_FP
		TRA_TaxesSubsidies_NoTax
		X_NoFossil2030
		X_NoFossil2035
		X_NoFossil2050
		X_NoFossil2050+2030
		X_SUP_NoCoal

Table 4.7: Overview of changes in the TIMES-DK model. Grey: no changes, Orange: Changes from original model, Red: deleted files or not used. Files with red text has been added during the project.

File	Sheet	Description
SYSSettings	Constants	Updated deflator and set the price year of the model to 2017.
VT_DK_ELC	Tech, TechA, TechB, Proc, Comm	Updated values in tech sheets to included newest values e.g. PV and wind power capacities BF17. Proc and Comm now includes an excess heat that can be utilizes in a heat pump
VT_DK_SUP	MIN-IMP-EXP, Commodities, Processes, ETS_NETS_Prices, NOX_Price, SO2_Price	Updated prices' for commodities and inserted the process excess heat for heat pumps, Implemented NO_x and SO_2 fees.
SubRes_ELC_Plants2020	ELC_TechC	Identification of specific units in order to verify with the commissioned units in BF17. Also correction of the expected development of Wind turbines, Solar PV-cells and Solar heating. Addition of DONG Energy plan to bioconvert all coal units in 2023 (Esbjergværket is affected).
SubRes_ELC_Techs	ELC_CEN, ELC_DEC, ELC_Processes_DEC, ELC_Processes_CEN, ELC_Comm	Update of technologies with the newest Technology Catalog AUG16 from DEA and for renewable plants created interpolated values every 5th year in order to slowly implement new cost for plants. Updated of the ELC_DEC so the technologies are getting the correct values from ELC_CEN.
SubRes_ELC_Tech_Tans	AF DATA, AFA fak, ELC_AF_WinOn, ELC_AF_WinOff, ELC_AF_PV	Interpolated values between newly inserted processes (interpolated wind and solar power processes), making their production pattern similar to the original model.

File	Sheet	Description
SubRes_RES_Techs	HOU_Multi, HOU_Deta	Update of technologies with the newest Technology Catalog AUG16 from DEA (Concerning only Heat Pumps).
SubRes_TRA_Techs	TRA_Cars, Market Prices for cars 2.0, Tra_Trucks_New, market price for Vans	Updated cars and vans to average Danish cost and sizes.
Scen_ELC_TaxesSubsidies	TAX_HPL_FuelInput, Sub_CHP_BIO, Sub_Biogas, Sub_Win_Sol, FuelTax	Updated values for taxation to only include energy fee and implemented tax on excess heat. Updated subsidies on wind, solar and biomass power production and included wave and offshore wind power (on current and upcoming project) subsidies. Included subsidies on biogas production.
Scen_IND_TaxesSubsidies	Input	Updated values to only include energy fees
Scen_RES_TaxesSubsidies	ResTAX	Updated values to only include energy fees
Scen_SUP-ELC_RenewablePotentials	BIO-PotACT	Updated bio potentials for Denmark using the Danish energy agencies values from the energy scenario rapport

File	Sheet	Description
Scen_SYS_DeliveryCost	TRA_Delivery_costRES_Delivery_cost IND_Delivery_cost	Updated values so that the PSO is now phased out by the year 2022.
Scen_TRA_TaxesSubsidies	TraTAX, Template_TAXCAR_ Ownership, Legislation_Vehicles, Data for vehicles	Updated values to only include energy fees. Inserted tax on ownership of vehicles.
Scen_ELC_DONG_NO_Coal_2023	All	Limit on all DONG plants to only produce heat and electricity on renewable fuels.
Scen_ELC_Limeted_Fuels_2015	All	Limit on fuels in 2015 based on actual production patterns
Scen_SYS_BioScenarioCap	All	Limit on fuels and capacities in 2050 in order to obtain the BIO scenario of the energy system from the Danish Energy Agency
Scen_ELC_RES_BuildRates	All	Limit on annual investment in fluctuating production units. Currently the maximum capacity is limited to 12,000 for Wind offshore with the need in 2050 for the Hydrogen scenario to be 17,500 MW

Table 4.8: Description of changes to TIMES-DK model files.

Appendix 04 – Verification of demand

Everything the model does is to fulfill an energy demand. Therefore it is important to verify that the model has the right energy demand. The demand in the model is very detailed as described in chapter 2. There are 3 groups in the model that has an energy demand. See the groups, their demand, where to find it and the comparison from the BF17 in Table 4.9 below. For calculation and sources, see Appendix 04 on the attached USB.

All the values from TIMES-DK and BF17 are from 2010.

Sector	TIMES-DK [PJ]	BF17 (DEA) [PJ]	Deviation [%]
Residential - Electricity	32.1	31.1	3.3
Residential - Heating	156.9	160.5	2.3
Industry	196.9	221.1	10.9
Transportation	203.3	209.7	3.1
Total	589.2	622.4	5.3

Table 4.9: Verification of the demand input used in TIMES-DK with historic data from BF17.

As the total deviation is around 5 % we believe that the results of the model is a good representation of reality. As updating the demands in the model is very complex as it requires a lot of data we have not been able to correct it in this thesis.

Appendix 05 – Electronic appendices

See USB for the electronic appendices.

Appendix 01 – TIMES-DK_FINAL_20170522

Folder containing all data files used in the model.

Appendix 06 – Overview of model inputs

This file contains an overview of which model files have been used in which scenario.

Appendix 07 - Vedabatch with FP+IS+PT+R2050

Output file from the model containing all data for our 4 scenarios.

Appendix 08 - Charts&Tables with FP+IS+PT+R2050

Presentation of data in Charts.

Appendix 09 - Charts&Tables_DevariationR2050+IS2

Calculation of deviation of our Incentive Structure and our R2050 scenario.