CEESA 100% Renewable Energy Transport Scenarios towards 2050

Technical Background Report Part 2

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Coherent Energy and Environmental System Analysis

Technical Background Report Part 2

A strategic research project financed by

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Foreword

This report presents the results regarding 100% renewable energy transport scenarios in the strategic research project "Coherent Energy and Environmental System Analysis" (CEESA) which was conducted in 2007-2011 and funded by the Danish Strategic Research Council together with the participating parties. Transport is one of the key challenges in society and has had special attention in the 100% renewable energy scenarios also developed in CEESA.

This report also presents the TransportPLAN scenario tool developed in the CEESA project for analysing renewable energy in transport.

The CEESA project was interdisciplinary and involved more than 20 researchers from 7 different universities or research institutions in Denmark. Moreover, the project was supported by an international advisory panel. The results include further development and integration of existing tools and methodologies into coherent energy and environmental analysis tools as well as analyses of the design and implementation of future renewable energy systems.

For practical reasons, the work has been carried out as an interaction between five work packages, and a number of reports, papers and tools have been reported separately from each part of the project. A list of the separate work package reports is given at the end of this foreword. This report documents the technical and economic analyses covering renewable energy for transport gathered in the Final report published in 2011.

The many authors listed in the report represent those who have contributed directly as well as indirectly via the work of the different work packages. This means that each individual author cannot be responsible for every detail of the different reports and papers of work packages conducted by others. Such responsibility relies on the specific authors of the sub-reports and papers. Moreover, individual participants may have personal views that differ from parts of the recommendations of this main report.

List of CEESA Background Reports:
Part 1: CEESA 100% Renewable Energy Scenarios towards 2050
Part 2: CEESA 100% Renewable Energy Transport Scenarios towards 2050 (This report)
Part 3: Electric power systems for a transition to 100% renewable energy systems in Denmark before 2050
Part 4: Policies for a Transition to 100% Renewable Energy Systems in Denmark Before 2050
Part 5: Environmental Assessment of Renewable Energy Scenarios towards 2050

Final report: Coherent Energy and Environmental System Analysis

Brian Vad Mathiesen, June 2014

Nomenclature

Acronym	Description
BAU	Business-as-usual
Bio	Any fuel derived from bioenergy resource
CEESA	Coherent Energy and Environmental System Analyses
CCR	Carbon capture and recycling
CHP	Combined heat and power
CO_2Hydro	CO_2 hydrogenation
CPH	Copenhagen
DEA	Danish Energy Agency
DME	Dimethyl ether
DK	Denmark
DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
EEI module	Energy efficiency growth module
ICE	Internal combustion engine
KPI	Key performance indicator
LPG	Liquid petroleum gas
MS module	Modal shift module
O&M	Operation and maintenance
PLDV	Passenger light-duty vehicle
PISI	Port Injection Spark Ignition
TDG module	Transport demand growth module
CO_2-	Electrofuels created by combining electrolysers and carbon capturing technologies
WP	Work package

Common Units

Unit	Description
km	Kilometres
pkm	Passenger kilometres
tkm	Ton-kilometres
kJ	Kilojoule
MJ	Megajoule (1 thousand kJ)
TJ	Terajoule (1 million MJ)
PJ	Petajoule (1billion MJ)
g	Gram
kg	Kilogram (1000 g)
t	Ton (1000 kg)
Mt	Megaton (1 million t)
kWh	Kilowatt hour (3.6 MJ)
MWh	Megawatt hour (1 thousand kWh)

Economy units

Unit	Description
DKK	Danish kroner
$	US dollar
€	Euro

Executive Summary

The research aim in this report is to develop scenarios for renewable energy in the transport sector. The transport sector poses a significant problem in renewable energy systems since it has historically relied on liquid fuels (typically over 95% oil). The energy demand for transport has increased rapidly in recent decades and the transport sector is characterised by a wide variety of modes and needs. It is therefore essential that the future transport system is assessed in detail so that it complements the needs of a 100% renewable energy system in Denmark.

The methodology used in CEESA to assess the Danish transport sector is outlined in Figure 1, while the resulting scenarios are displayed in Figure 2. Initially, a 2010 *reference model* of the existing Danish transport system is created based on existing transport demands, transport-energy demands, and technologies. This data is collected for 26 different modes of transport and where adequate data is available; these characteristics are further subdivided by trip length and the type of trip. After the 2010 *reference model* is complete, a *reference scenario* for the years 2020 and 2030 is developed based on forecasts from the Danish Infrastructure Commission (Infrastrukturkommissionen). A *reference scenario* is also projected for the year 2050 based on a number of business-as-usual assumptions. A significant amount of data was collected and a large number of calculations are required to make the 2010 *reference model* and the *reference scenario*. Hence, a new spreadsheet Transport Energy Scenario Tool, which has been named TransportPLAN, was created during the CEESA project. Due to the wide range of data and outputs available in TransportPLAN, it can be used to assess a variety of different transport scenarios, which are also displayed in Figure 1. In CEESA, these outputs are used as inputs to the energy-system-analysis tool, EnergyPLAN, so the implications of various transport scenarios on the complete energy system can be assessed (which is the research aim in the CEESA-WP report [1]).

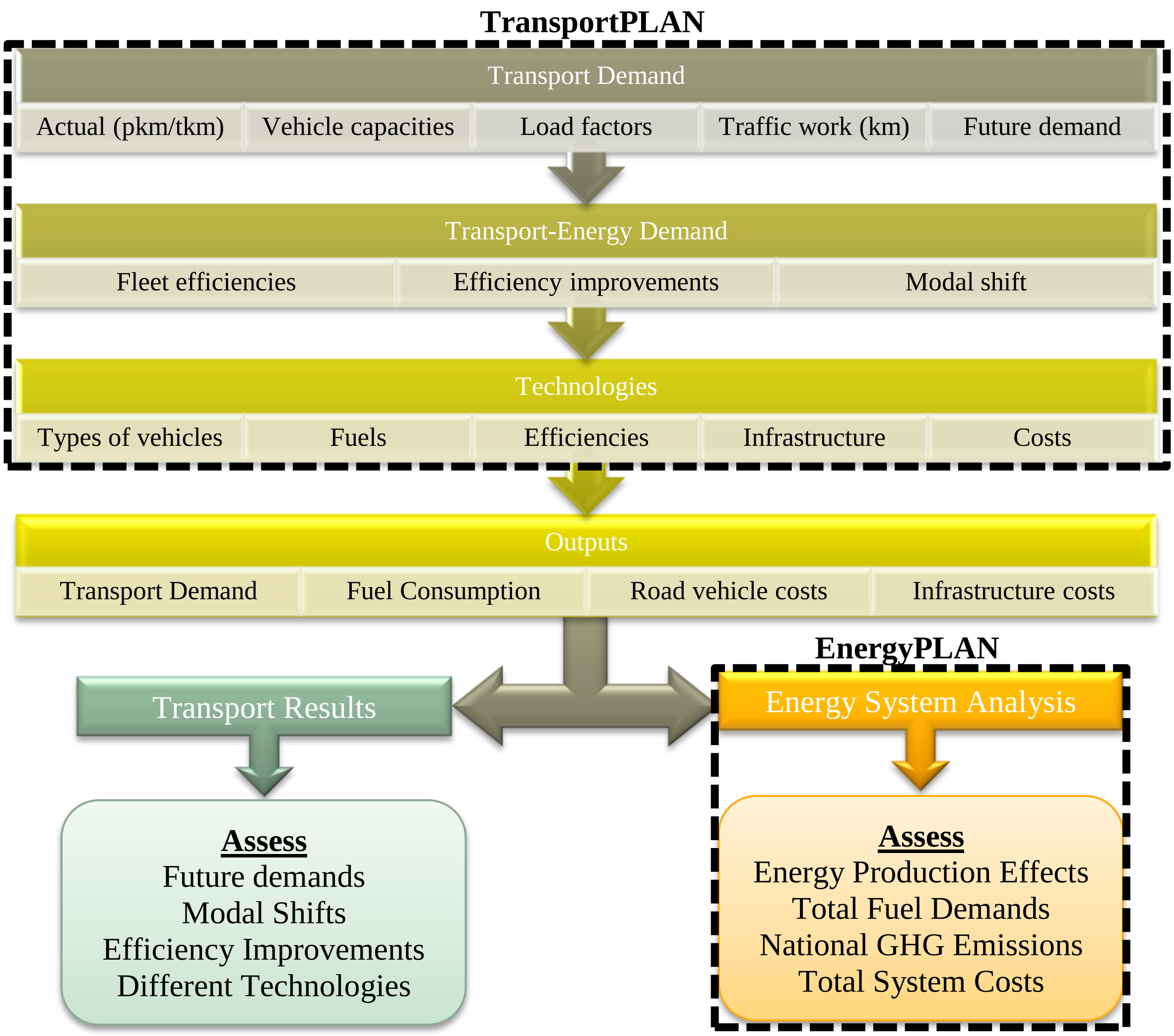

Figure 1: Methodology used to assess the transport sector in the CEESA project.

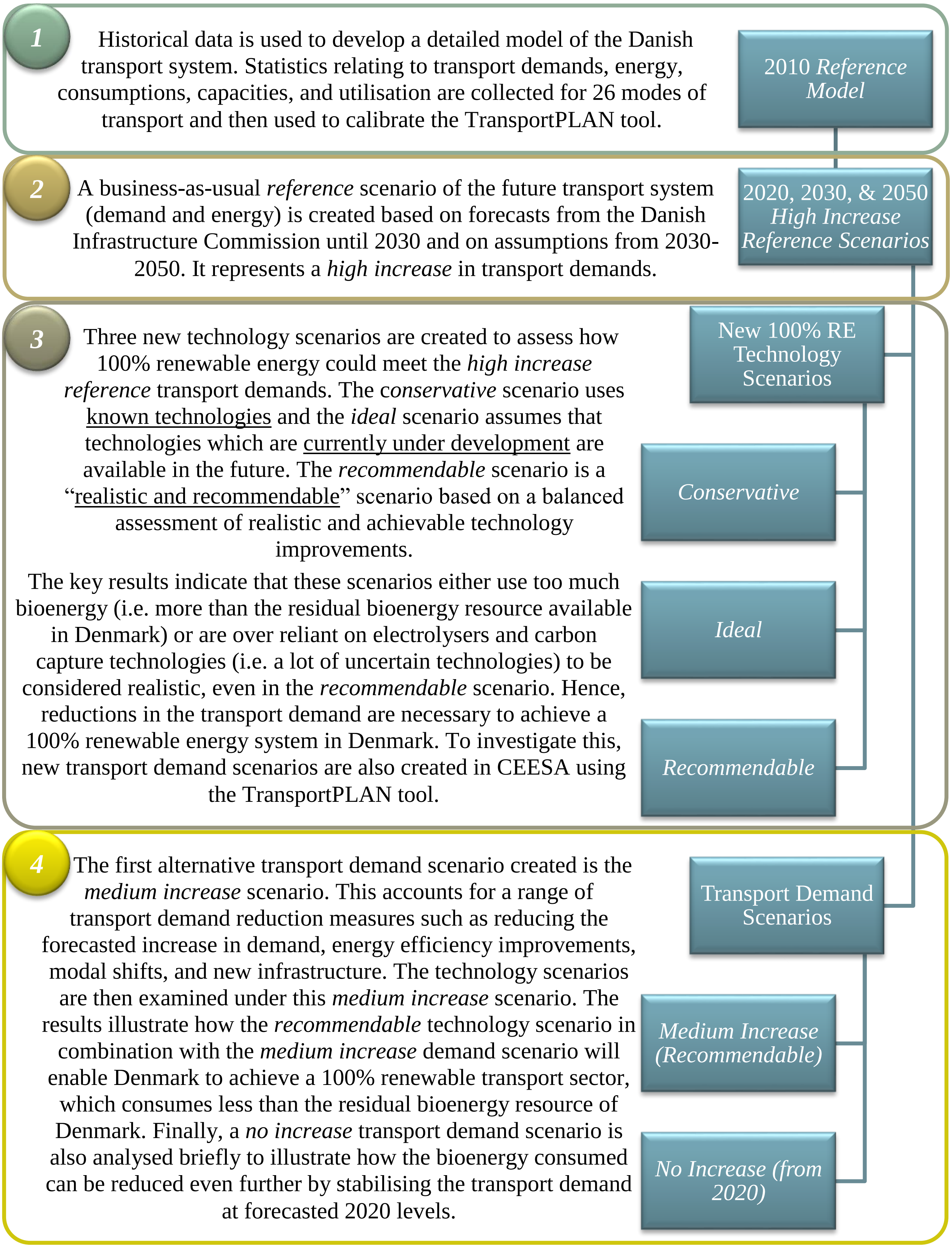

Figure 2: Transport scenarios created during the CEESA project, including a brief description of the scenarios and their main findings.

A key challenge encountered when developing the methodology in this report is the definition of the geographical transport boundary. In CEESA, the objective is to account for all transport demands associated with Denmark and hence the *reference* includes all passenger and freight demands, for both domestic and international transport. To do this, three distinct boundary conditions are defined and considered for each mode of transport assessed: national, transit, and international as displayed in Figure 3. In CEESA, 100% of the national transport demand and 100% of the Danish transit demand in other countries is included. The international transport demand is calculated by assuming that 50% of the demand is assigned to Denmark and 50% is assigned to the other country of origin. In this way, both countries share responsibility for the transport demand they create between them. By using these boundary conditions for the transport sector, CEESA is not completely comparable to other publications. For example, the 'Grøn Energi' report completed by the Danish Commission on Climate Change [2] did not include the international component of the transport demand and it did include the transit component of other countries in Denmark. As a result, the energy consumed by transport in 2050 is approximately 90 PJ (approximately double) higher in the CEESA *reference* than in the Danish Climate Commission's 2050 reference [2].

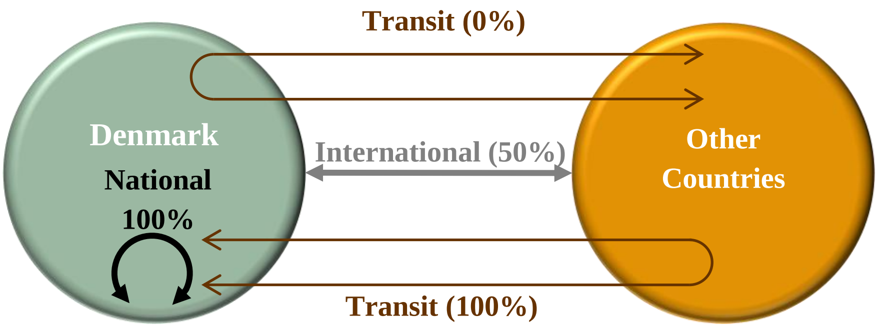

Figure 3: Boundary conditions defined when calculating the energy consumed by in the Danish transport sector.

Once the *reference scenario* is completed, the next step (see Figure 2) is to create a variety of 100% renewable energy scenarios, which can satisfy the *high increase* transport demand forecasted in the *reference scenario* for Denmark. (The term *high increase* defines this transport demand scenario since the *reference* forecasts a transport demand for 2050, which is double the current 2010 transport demand.) In total, three technology scenarios are designed which fit the following criteria: a *conservative* scenario is based on known technologies, an *ideal* scenario uses technologies which are currently under development, and a *recommendable* scenario is a "realistic and recommendable" scenario based on a balanced assessment of realistic and achievable technology improvements. To create these scenarios, the different transport technologies are assessed to establish what currently exists, what is in development, what is ideal, and what is realistic.

To establish the current state of transport technologies, the various fuels required are compared in terms of 1) primary energy consumption of conversion technologies, 2) the land area required and 3) the costs of different technologies. This enables a prioritisation between different "fuels" for transport technologies. From this, it is clear that direct electrification is the most energy efficient form of transport and also that bioenergy consumption is a key concern for future 100% renewable energy systems, primarily due to the limited residual resource available and the large amount of land required to produce them. For example, many first generation biofuels are already available on the market so they are well established, but the land area required to produce these fuels is very large. To put this in context, wind turbines require 500-600 times less land area to produce the same energy as second generation biofuels which are expected to be developed (see Figure 32 in the main report). Hence, there is a trade-off here: bioenergy-based technologies are already available so they are suitable for the *conservative* scenario, but in an *ideal* world the transport sector will be electrified as much as possible which will typically require more expensive technologies.

In all of the scenarios created, it is not possible to supply all of the transport demands with electricity, primarily due to the relatively low energy-density of batteries. Furthermore, as part of this work package, a number of detailed, generic and transparent analyses of current state-of-the-art battery electric vehicles have been conducted under realistic conditions. Such analyses show that the present technology has challenges to overcome before it can meet the general expectations as presented in most literature. Consequently, it should be stressed that the present technology needs further development in order to be able to fulfil the preconditions behind the CEESA scenarios. As a result, the electrification of the transport sector needs to be supported by some form of energy dense fuel for applications such as trucks, aeroplanes, and ships. To identify a suitable fuel, four additional transport fuel pathways are explored in this report: fermentation, bioenergy hydrogenation, CO_2 hydrogenation, and co-electrolysis. These are defined and compared in terms of the bioenergy and the electricity required to produce enough liquid and gas fuel to meet 100 Gpkm of passenger transport (Figure 4) or 100 Gtkm of freight transport (Figure 5). The results indicate that when there is a bioenergy resource available, then bio-electrofuel[1] (bio-methanol/DME) based on biomass hydrogenation is more energy efficient and requires less biomass. When there is not any bioenergy resource available, CO_2-electrofuel (CO_2-methanol/DME) based on CO_2 hydrogenation enables liquid/gaseous fuel to be created without exceeding the biomass resources available in Denmark. These results formed the basis for the three technology scenarios subsequently created in the CEESA project.

[1] Throughout this report, the term electrofuel refers to fuel production by combined use of electrolysers with carbon source. If the carbon source is from the biomass gasification the term bio-electrofuel (bio-methanol/DME, bio-jetfuel), and in case the carbon source are CO_2-emissions the term CO_2-electrofuel (CO_2-methanol/DME, CO_2-jetfuel) is used. The key message from this work is that an electrofuel will be required in the future, but the exact type is still uncertain i.e. methanol, DME, methane, etc. Therefore, methanol/DME is used here as an example, but it is still unclear if this is the optimum choice of electrofuel.

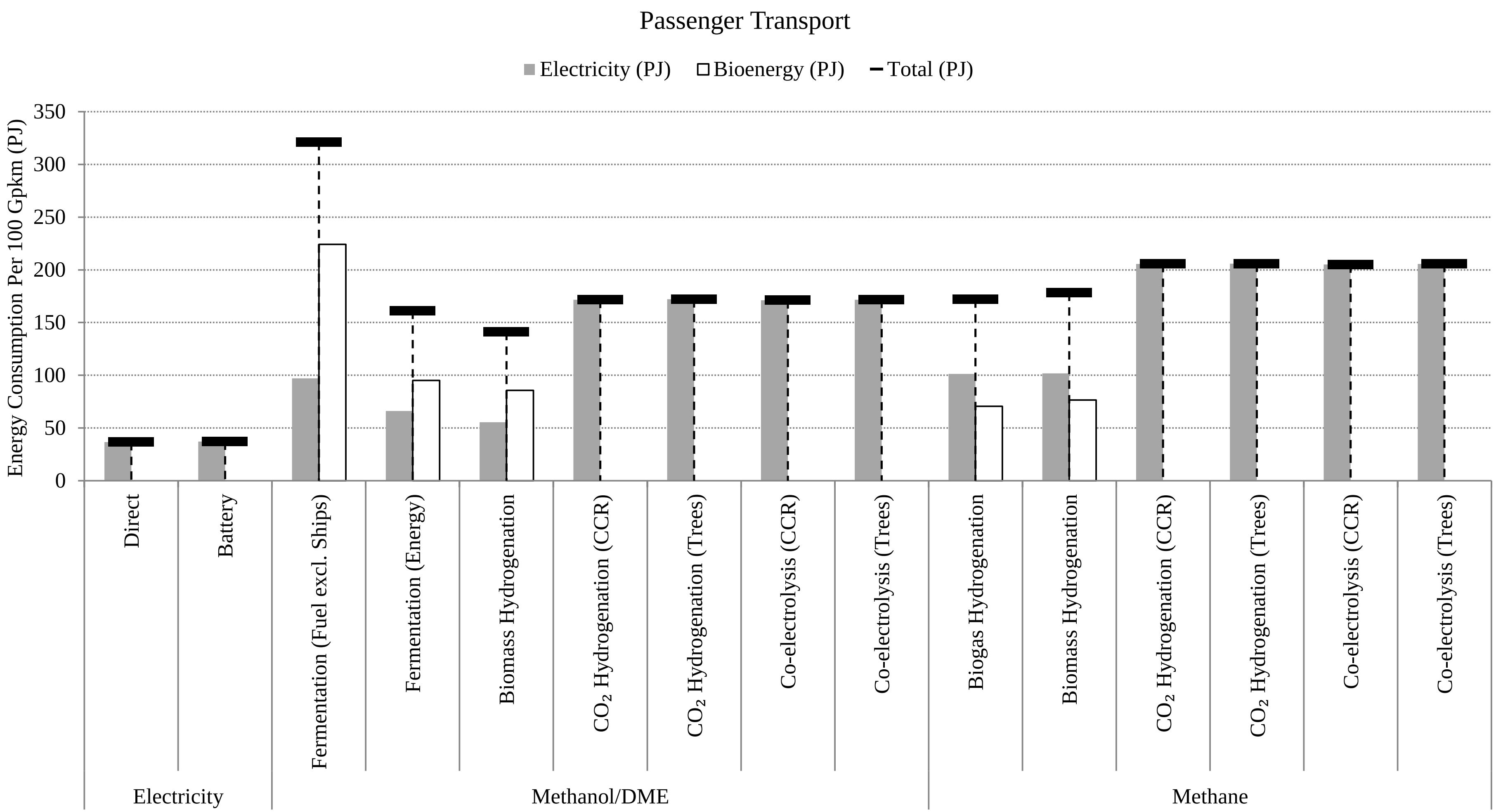

Figure 4: Electricity and bioenergy required for each transport fuel pathway to provide 100 Gpkm of passenger transport.

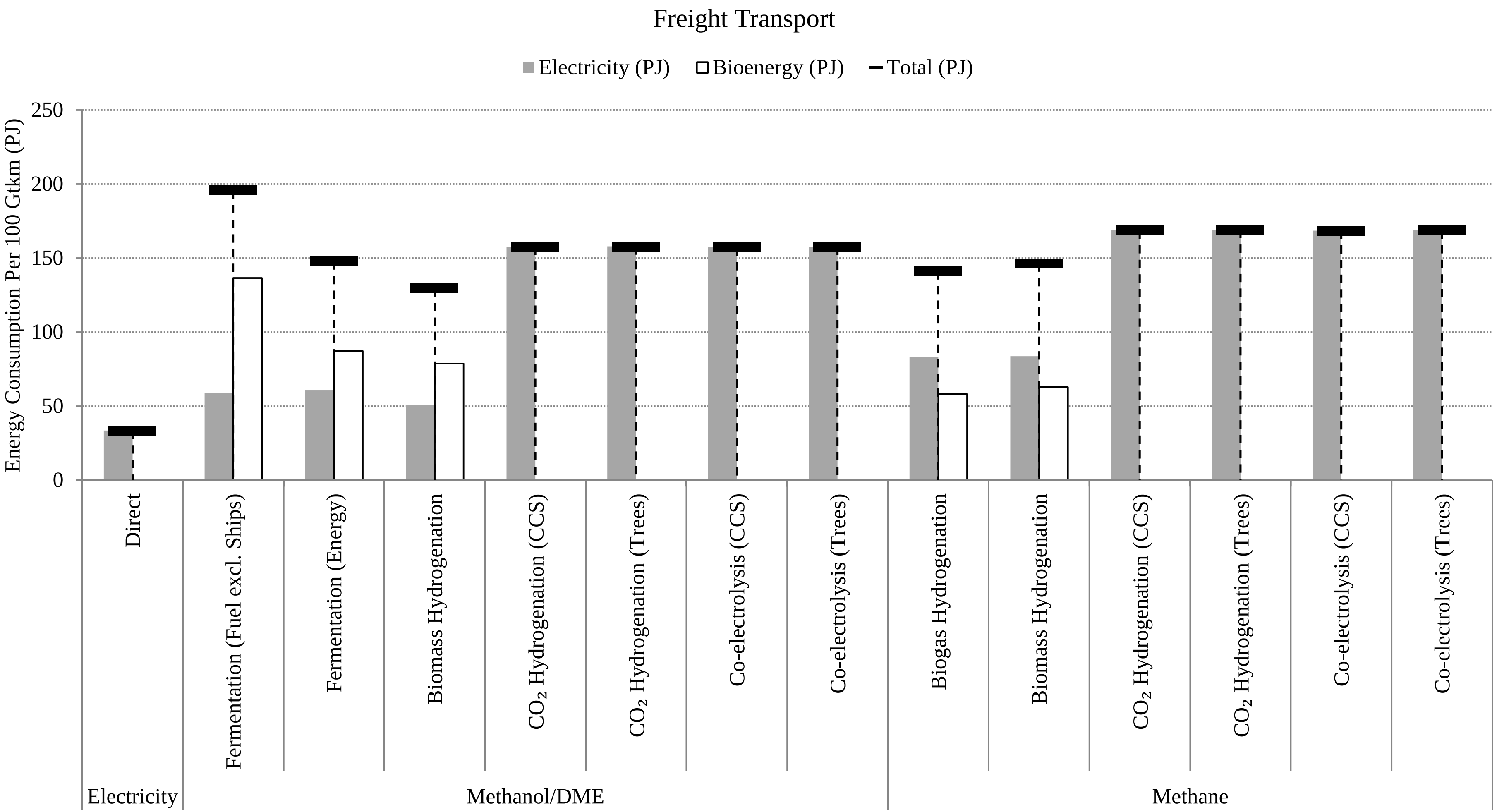

Figure 5: Electricity and bioenergy required for each transport fuel pathway to provide 100 Gtkm of freight transport.

For the *conservative* 100% renewable energy scenario, it is assumed that bio-methanol/DME will be used extensively in the transport sector. The final electrofuel could be many different fuels such as methanol, DME, and methane. This study does not identify an optimum final electrofuel, but instead it uses methanol/DME as one example of what an energy system with electrofuels in the future could look like. The energy balances developed here reflect the methanol production process, but this is very similar to DME (when the vehicle efficiency is also accounted for), so in general the analysis here reflects the impact of producing electrofuel in the form of either methanol or DME. Further research is required to establish the 'optimum' electrofuel, which could even be methane for example. However, many of the key technologies are the same regardless of the final electrofuel.

The principal technological development required for this fuel is biomass gasification and there are countries that had demonstration and commercial plants for biomass gasification in place such as Denmark [3], Japan [4], Sweden [5,6], and China [7]. However, most of the existing biomass gasifiers are not used for transport fuel production purposes but rather for heat generation. The technology development is driving towards wider spectrum of application, and the focus is slowly directed towards gasification for fuel production. Denmark is internationally recognized for its work on biomass gasification [8], however the recently closed gasification plant Pyroneer could slow down the commercialization of biomass gasification on the Danish market. The other technologies (steam electrolysis with alkaline electrolysers and chemical synthesis) are already well-established: chemical synthesis is commercially available and steam electrolysis is a very promising technology that has been proven at the MW scale in case of alkaline electrolysers. The other type of electrolysers such as polymer membrane (PEM) are commercially available but their capacities are limited, while solid oxide electrolysers cell (SOEC) are still on the research and development level with some demonstration units in place but the commercialization is yet to come. Denmark is particularly strong in the area of steam electrolysis via SOEC due to the research environments at DTU Risø and Haldor Topsøe. Due to the stage of the development of high temperature electrolysis, the cost assumed in this report could be subjected to changes depending on the future technological development. In any case alkaline electrolysis, which is well developed, can be applied without significant changes in the recommendations here. SOECs are however preferable due to potential higher efficiencies and lower costs [9]. Furthermore, biomass gasification is an essential technology for other sectors of the energy system [1], so it is assumed that bio-methanol/DME will available by 2020 in the *conservative* scenario. Direct electrification is also used in this scenario, but in a conservative way: for example, in 2050, only 35% of private cars are electric even though over 95% of car journeys today are below 100 km [10] and the range of commercially available electric vehicles today is approximately 160 km [11]. After implementing these technological changes to the *reference*, it is clear that the *conservative* transport scenario will lead to a heavy dependence on biofuels. Approximately 189 PJ of bio-methanol/DME and bio-jetfuel is necessary in 2050. However, since there is only ~240 PJ/year of bioenergy available in Denmark (see Technical Background Report 1 of this study [1]), this would only leave ~50 PJ/year of bioenergy for the rest of the energy system (e.g. electricity, heating, and industry). These sectors will require 100-150 PJ/year (see Figure 3.13 of the main report [12]), so moving to 100% renewable energy using mainly existing technologies and under existing demand projections will mean that Denmark is over dependent on bioenergy.

To assess the other extreme, none of the transport technologies considered in the *ideal* scenario consumed bioenergy, but instead the entire transport sector is electrified. Naturally for many transport modes, the potential for direct electrification is limited, especially for modes with a large proportion of long journeys such as trucks and aeroplanes. Hence, liquid fuels are still produced in the *ideal* scenario (i.e. methanol/DME), but instead of using carbon from bioenergy to create them, the carbon is sequestered using carbon capture technology to create electrofuels CO_2-methanol/DME . Again, methanol/DME is used here as an example of an electrofuel, which could also be methane for example. These CO_2-electrofuels create a new challenge: uncertainty. At present the *ideal* scenario seems unlikely due to the uncertainties surrounding the development of electrofuels, particularly in relation to the development of adequate electrolysers and carbon capture techniques. Since the *ideal* scenario requires 133 PJ of electrofuel in 2050, it is too risky to assume that the technical development, technical capability, and adequate costs will be reached to produce such large volumes of electrofuel. Hence, the *recommendable* scenario includes a mix from both the *conservative* and *ideal* scenarios.

Once again, the main priority in the *recommendable* scenario is the direct electrification of the transport sector, with significant proportions of cars, vans, and rail directly electrified. Bio-based fuels are used to supply approximately half of the remaining liquid fuels, with the other half supplied using electrofuels. However, even with this significant penetration of electrofuels, the biofuel demand of 70 PJ/year is still more than the biofuel resource of 40-50 PJ/year available for the transport sector in Denmark. Hence, to create a sustainable 100% renewable energy system in Denmark, the forecasted increase in the transport demand will need to be reduced. To investigate this, a *medium increase* scenario is also developed here using the TransportPLAN tool (see Figure 2).

To reduce the energy required in the transport sector, the following key changes are implemented in the *medium increase* scenario:

1. The high forecasted transport increase is reduced. In the *reference* scenario passenger transport is expected to increase by 50% between 2010 and 2050, while freight transport is expected to almost double. In the *medium increase* scenario, passenger transport only increases by 10% in 2050 compared to 2010.
2. The efficiency of conventional cars is increased. Only the efficiency of cars is improved since there are already significant energy efficiency improvements in the *reference* for other vehicles. If the efficiency gains for conventional vehicles in the *reference* were not included then the total energy demand for transport would be approximately 430 PJ in 2050 and not the forecasted 285 PJ.
3. Vehicles are utilised more. In the *reference model* the existing transport sector has very poor utilisation factors. For example, in 2010 national trucks only utilise approximately 42% of their capacity. In the *medium increase* scenario, utilisation factors are increased for different freight vehicles by approximately 5% of the original value.
4. Different modes of transport which are more efficient and use more sustainable fuels are utilised more in the *medium increase scenario*. For example, rail is a particularly suitable replacement for long road journeys since it is very efficient and it can be completely electrified. Therefore, a modal shift from road to rail is carried out, where the transport demand for electric rail is doubled in the *medium scenario*.

To incorporate these measures into TransportPLAN, a number of modules were added to the tool including a modal shift module, infrastructure cost calculator, and an energy efficiency improvement module. Using these, the three technology scenarios are assessed with the *medium increase* transport demand scenario. As displayed in Figure 6, there is a reduction in the overall energy demand of approximately 88 PJ for the *reference* and 40 PJ for the *recommendable* scenarios, if the *medium increase* transport demand is implemented. Therefore, implementing the *medium increase* scenario is not just beneficial for a 100% renewable energy system, it is also beneficial for the *reference* transport system. In addition, if the *medium increase* scenario is implemented with the *recommendable* technology mix, then the biofuel consumption in 2050 is reduced to approximately 52 PJ/year, which is in line with the bio-methanol/DME and bio-jetfuel that can be created from residual resources in Denmark. However, the key issue which also needs to be addressed in relation to this dramatic transition for the transport sector is cost.

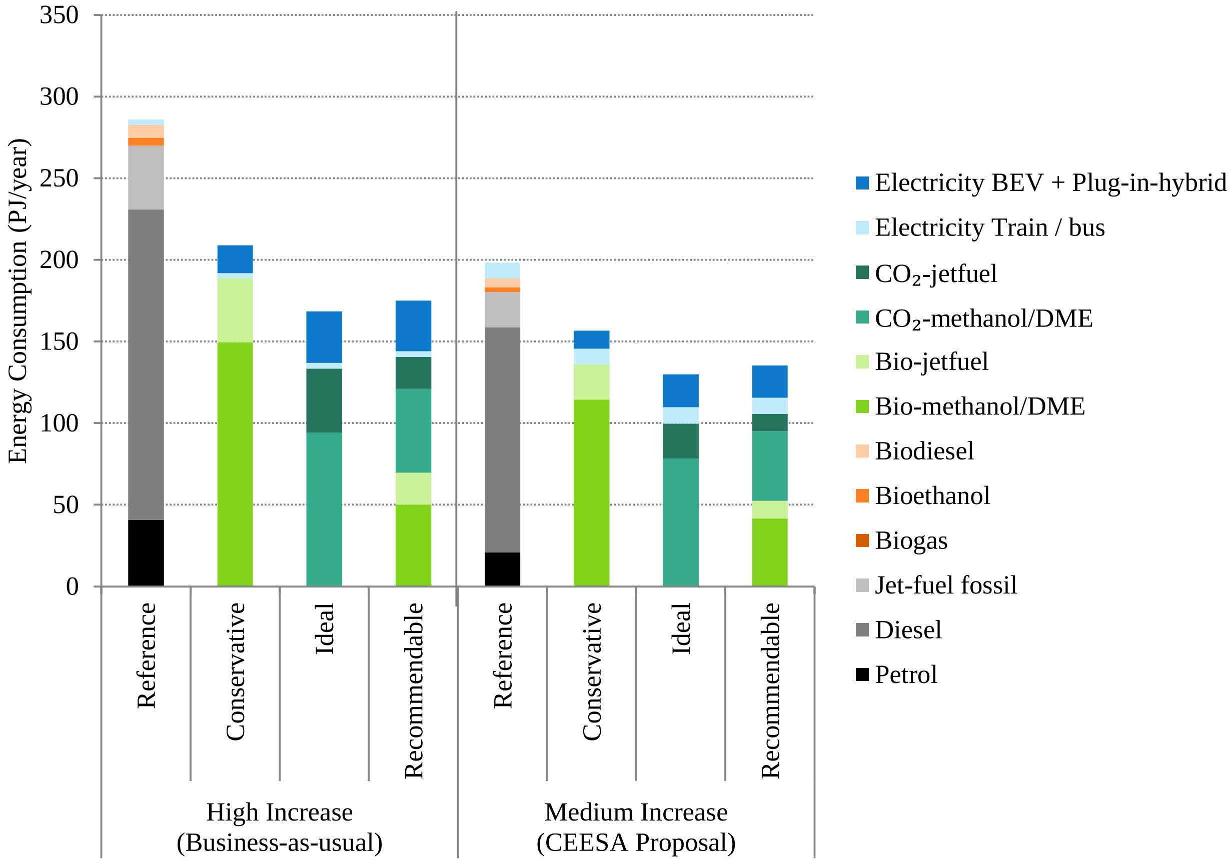

Figure 6: Energy consumed by fuel type in 2050 for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

To establish the costs relating to the transport sector, the entire energy system needs to be accounted for in a 100% renewable energy system, including both liquid fuel and electricity. Therefore, changes in the transport sector have implications for the electricity and heat sectors also. For example, even though the biofuel demand has been reduced to 52 PJ/year in the *medium increase recommendable* scenario, there may be an indirect increase in bioenergy for electricity production (which is investigated and discussed the CEESA-WP1 report [1]). This is relevant since the costs associated with the variation in electricity demand can only be accounted for by modelling the entire energy system with and without the transport sector. Hence, these costs are calculated in conjunction with the energy system analysis in the CEESA-WP1 report [1], which uses the EnergyPLAN tool to model the complete energy system and the TransportPLAN tool to supply the transport inputs necessary (see Figure 2).

The results, which are displayed in Figure 7 for each scenario in 2050, indicate that the *medium increase* demand is cheaper than the *high increase* demand for all scenarios. This is to be expected since the overall transport demand is lower, but since the *medium increase* demand also includes a significant expansion of the rail network, the magnitude of the savings (i.e. approximately 35 BDKK/year cheaper) is significant. Figure 7 also indicates that the *reference* scenario is approximately the same price as all of the 100% renewable energy scenarios for the *medium increase* in the transport demand. However, there is a change in the breakdown of the costs in the *reference* compared to the 100% renewable energy scenarios. In the *reference*, there are more fuel/energy costs which are caused by a high dependency on limited oil. In contrast, the 100% renewable energy scenarios have less fuel/energy costs, but higher investment costs since they use new and more efficient transport technologies. Hence, transforming to a 100% renewable energy transport sector will not require additional costs for society, but it will require a switch in the type of costs. Finally, since the *medium increase recommendable* scenario is relatively the same cost as the other *medium increase* scenarios, it makes sense to follow this pathway since there is a balanced consumption of bio-based fuels from biomass hydrogenation and CO_2 based fuels from CO_2 hydrogenation. A more detailed comparison of the costs between the individual pathways is available in Connolly *et al.* [13], which are evaluated from an energy system perspective in Ridjan *et al.* [14].

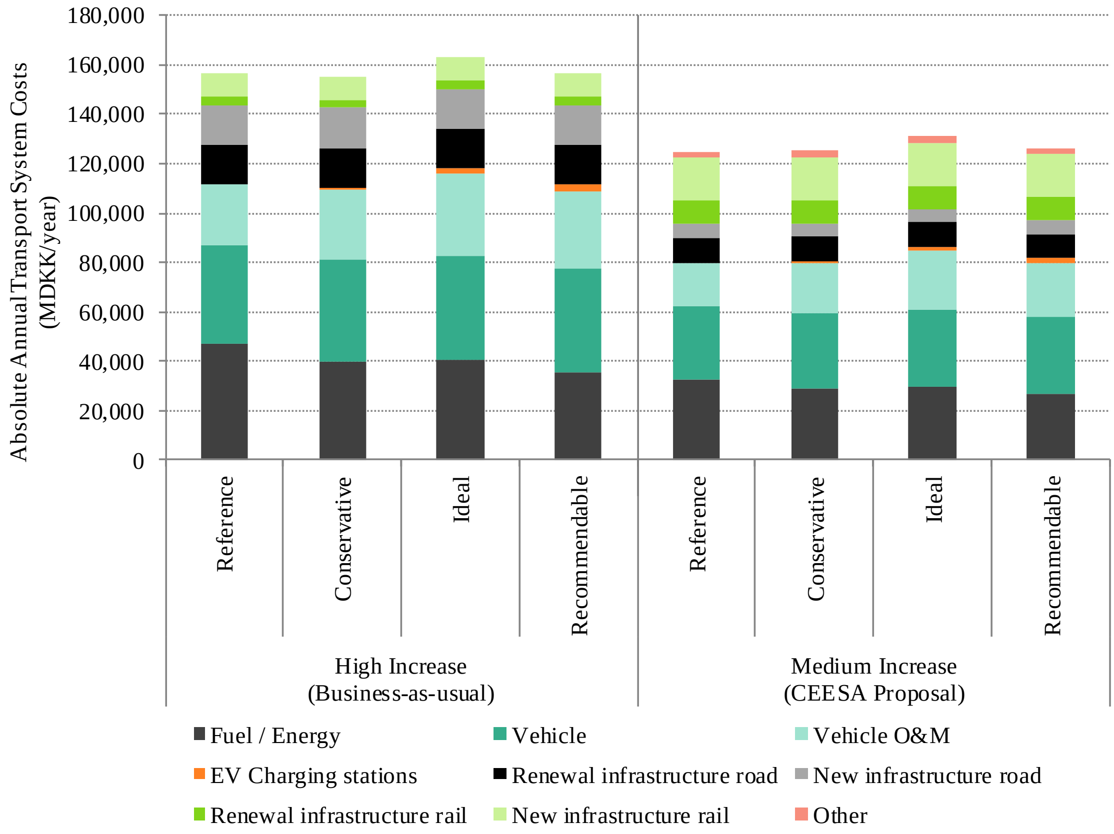

Figure 7: Transport system costs in 2050 for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

To demonstrate how the *recommendable* scenario evolves over time, Figure 8 illustrates the energy demands for the *medium increase recommendable* scenario from 2010 to 2050. Direct electrification and bio-methanol/DME should be introduced by 2020 to begin the transition to a 100% renewable transport sector. This enables methanol/DME vehicles to develop while electrolysers and carbon capture technologies are also developing for electrofuels. As CO_2-methanol/DME production advances, it will also supplement the bio-methanol/DME as an additional liquid fuel and thus reduce the dependency on bioenergy. After 2030 the share of bio-methanol/DME begins to stabilise as more CO_2-methanol/DME is introduced into the energy system. The objective here is to ensure that the peak demand for bioenergy in the transport sector does not surpass the residual bioenergy resources available in the Danish energy system. Figure 8 also indicates that there is an overall energy reduction of approximately 118 PJ/year between 2010 and 2050 in the *recommendable* scenario, even though the transport demand is increasing (particularly for freight transport): this occurs since the vehicles used in the *recommendable* scenario are more efficient than those used in 2010. In comparison to the *high increase (business-as-usual) reference scenario*, there is also an overall energy saving of approximately 151 PJ (48%) in 2050 for the *medium increase recommendable scenario*, while both scenarios require the same costs (see Figure 7). Therefore, the Danish transport sector can be affordably transformed into a renewable and sustainable sector by 2050, by supporting more energy efficient transport technologies which are currently close to commercialisation (such as electric vehicles) and by reducing the high increase in the forecasted transport demand. The results from this research are applied to a complete energy system context in the CEESA-WP1 report [1].

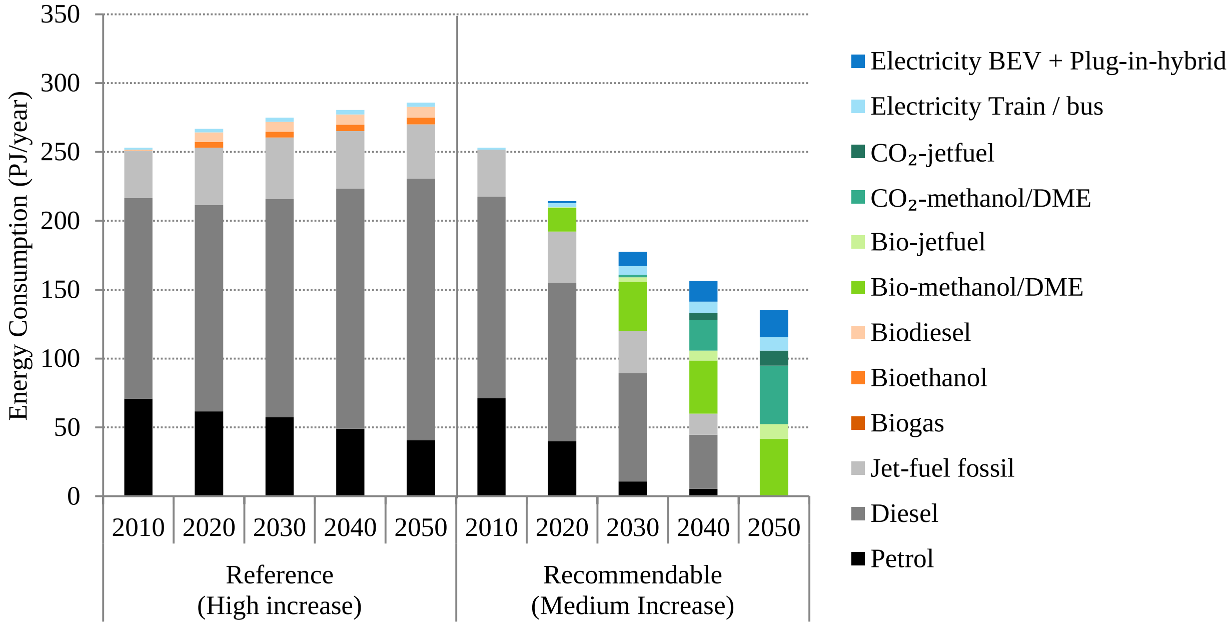

Figure 8: Energy consumed by fuel type for the *reference* and *recommendable* scenarios between 2010 and 2050 for a *high increase (business-as-usual)* and *medium increase (CEESA proposal)* respectively in the transport demand.

1 Introduction

The strategic research project Coherent Energy and Environmental System Analyses (CEESA) is concerned with developing the tools and methodologies required to design and implement a 100% renewable energy system in Denmark by 2050. In the CEESA project, particular focus has been placed on the transport sector due to the significant challenges it will face when converting to 100% renewable energy.

There is no easy single solution for the transport sector especially when considering a 100% renewable energy system [15]. In a previous 100% renewable energy study, the IDA Climate Plan [16], it was evident that the transport sector currently faces the most uncertainty due to both the scale of energy consumed and the diversity of needs it satisfies. As outlined in Figure 9, the energy consumed in Denmark has reduced or almost stabilised for every sector between 1980 and 2010 except transport. In fact, all of the energy efficiency measures introduced in Denmark over the last 40 years have been totally counteracted by an increase in transport energy demand: these measures include new building standards, the widespread implementation of CHP (combined heat and power), and the development of wind turbines. In addition, more energy was consumed in the transport sector than any other sector in Denmark in 2010. This reflects two very concerning trends: the transport-energy demand is increasing and the energy consumed in transport is now the most significant proportion of Denmark's energy consumption.

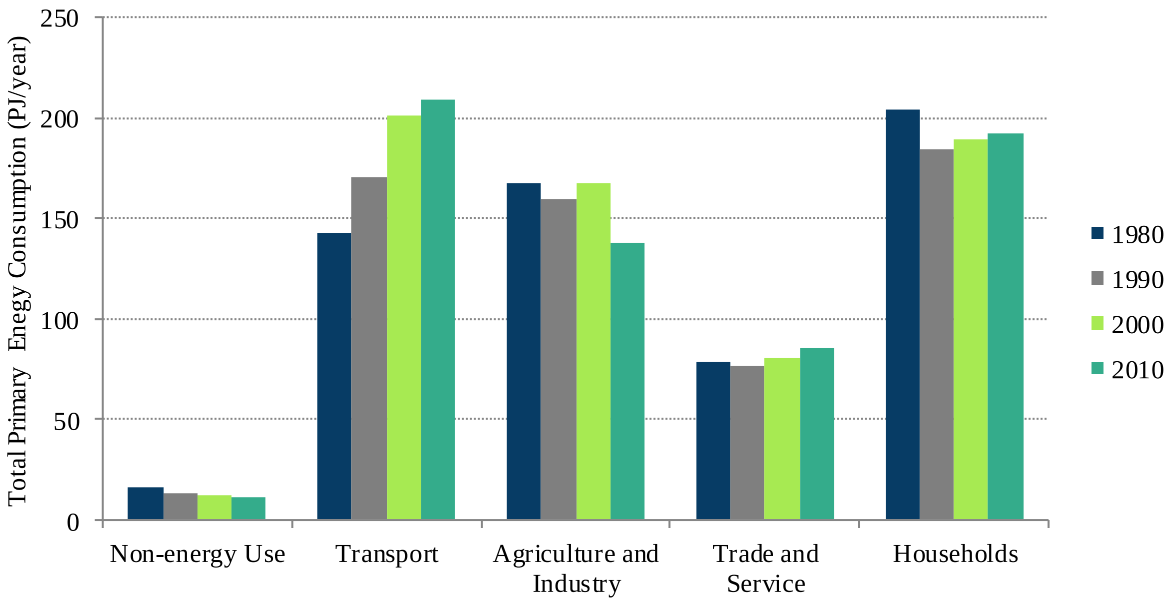

Figure 9: Total primary energy consumption in Denmark divided by sector from 1980 to 2010 [17].

Adding to this concern is the profile of energy consumed in the transport sector. As displayed in **Figure 10**, practically all of the energy consumed in the Danish transport sector is from oil products. Unlike the other sectors of the Danish energy sector, no notable proportion of renewable energy has been implemented into the transport sector to date. Therefore, as the transport demand continues to grow it will naturally lead to an increasing dependence on oil. This is a key concern since Denmark's oil reserves are depleting, global oil reserves can only sustain current global consumption for approximately 50 years [18], oil prices are increasing rapidly in recent years (see Figure 11), and there are no obvious renewable alternatives currently available for the transport sector. It is extremely complex to identify and implement renewable energy solutions in the transport sector due to the variety of demands, modes, technologies, and fuels currently required in the sector. It is therefore essential that sustainable roadmaps are developed for the Danish transport sector, which compliments a transition towards more renewable energy, with the eventual aim of a 100% renewable energy system.

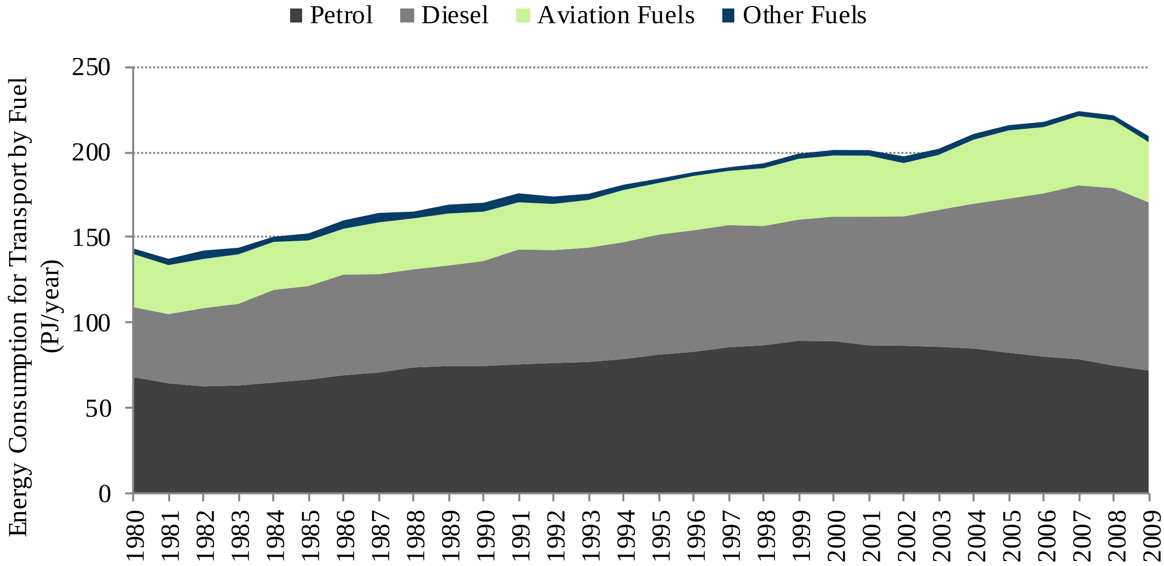

Figure 10: Fuel consumed in the Danish transport sector from 1980 to 2009 [17]**.**

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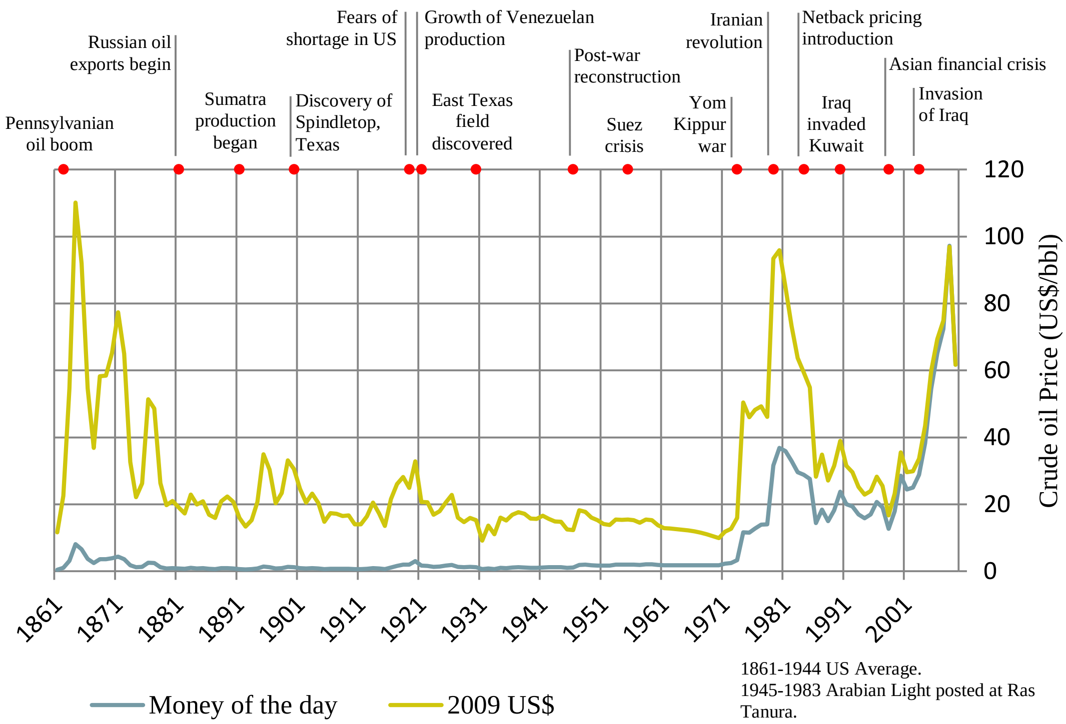

Figure 11: Historical price of crude oil corresponding to major global events [18]**.**

In line with this, the core objective in this report is to develop 100% renewable energy scenarios for the transport sector. To do so, a new transport scenario planning tool called TransportPLAN was created. It is used in this report to model the existing Danish transport sector as well as a projection towards 2050 to quantify the consequences of a business-as-usual (reference) scenario. All transport including air, sea, rail, and road, relating to Danish passengers and freight are included in the *reference scenario*. This enables a complete assessment of the requirements to implement a 100% renewable energy scenario in the sector. It also distinguishes CEESA from other reports, such as the report by the Danish Commission on Climate Change [2], which does not account for the demand relating to Danish international passenger and freight transport such as international aviation and shipping.

After creating the *reference scenario*, a variety of CEESA technology and demand alternatives are assessed using the TransportPLAN tool. These scenarios are used to establish the key challenges facing the transport sector when converting to a 100% renewable energy system. The overall results indicate that reductions in the transport demand are beneficial for all scenarios (including the reference), direct electricity should be utilised wherever possible in the transport sector, the availability of bioenergy will limit the utilisation of biofuels, and electrolysers will need to be developed further to ensure that electrofuels can reduce the consumption of bioenergy. The specific details relating to each of these measures are elaborated in this report.

1.1 Contents of this report

One of the key challenges in the transport sector is the diversity which needs to be accommodated in the transport sector: this relates to the many types of consumers such as urban, rural, global – passengers and freight - as well as the many different modes of transport such as bikes, cars, rail, ships, and more. Each mode of transport is required for a different type of journey, many of them require different sustainable energy solutions, and for some of them there is even no sustainable alternative available today. To illustrate these challenges, the methodology used in this research is documented in section 2. This section focuses on the approach used in the structure of the TransportPLAN tool which has been developed in this study as well as the relation to EnergyPLAN, the advanced energy-system-analyses tool (www.energyPLAN.eu).

In section 3, the *reference model* for 2010 is described in detail, which was used to calibrate the TransportPLAN tool for the various modes of transport. Section 3 also describes the assumptions used to project forward the transport demands in Denmark for the years 2020, 2030, and 2050. This is a 'business-as-usual' (BAU) *reference scenario* for the Danish transport sector which follows existing policies and trends.

After calibrating the 2010 *reference model* and creating the *reference scenario* to 2050, section 4 presents the alternative transport technologies which are considered when transforming the Danish transport sector to 100% renewable energy scenario. These 'alternative transport technologies' are then combined to produce different 'transport scenarios', which are compared in terms of their energy demands between now and 2050. Afterwards, in section 5 these technology scenarios are added to a new 'transport demand scenario'. This outlines the impacts of reducing Denmark's future transport demand and using different modes of transport. Based on the results in section 4 and section 5, a *recommendable* scenario is produced from the CEESA project which is presented in detail in section 6. The results of the report are then concluded in section 7.

2 Methodology

In this section, the methodology used to profile the Danish transport sector and analyse alternatives scenarios is described. The TransportPLAN tool is introduced and the motivation behind the various technology and demand scenarios considered is discussed.

2.1 Analysing the Danish transport sector

To evaluate alternatives for the energy supply in the transport sector, the first step is to identify how energy is being consumed. It was evident from an early stage in this investigation that profiling the Danish transport sector was very complex, primarily due to the variety of modes in the transport sector. As outlined in Figure 12, 26 different modes of transport were considered in CEESA when developing a profile of the Danish energy sector. For each mode of transport a wide range of key parameters need to be defined to create a profile of energy consumption in the present and forecasted Danish transport sector. As outlined in Table 1, the four key parameters which needed to be identified were the transport demand, transport-energy demand, new technologies, and costs. Naturally this led to a significant collection of data and calculations, so a spreadsheet tool was created based on the Danish transport system.

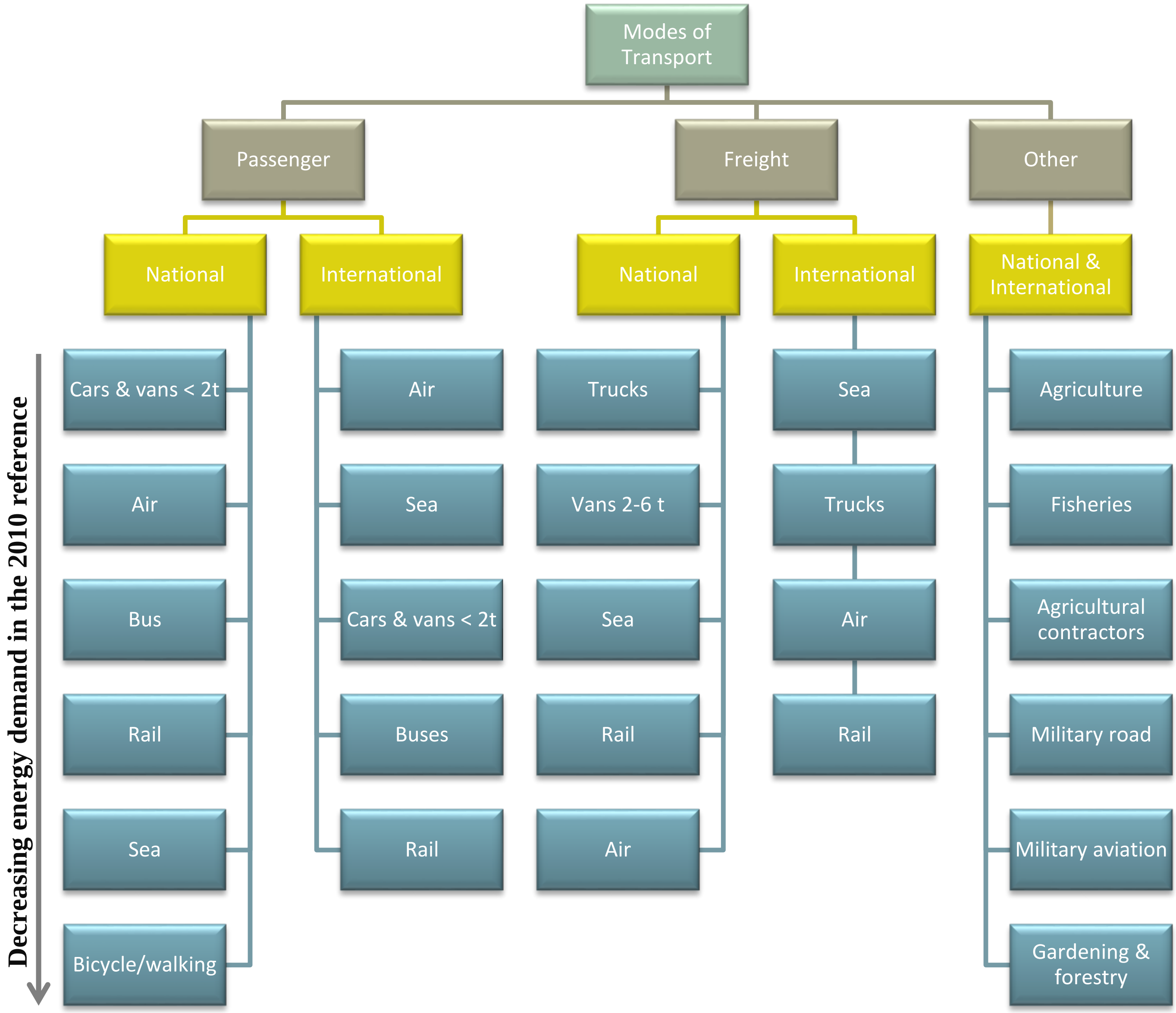

Figure 12: Primary modes of transport considered in this study. These were further divided by type and length of trip where the data was available.

Table 1: Key parameters estimated for each mode of transport to profile the energy consumed in the existing and future Danish transport sector.

Parameter Profiled	Data Required	Notes
Transport Demand	Boundary condition Transport demand Traffic work Vehicle capacity Load factor Type of journey Length of journey	The boundary condition in CEESA includes all transport which Danish citizens are responsible for, including international transport. The type and length of journey is not available for all modes. Transport demand and traffic work are recorded separately due to the data available and also to accommodate the modal shift measures
Transport-Energy Demand	Annual energy demand Specific energy consumption	The specific energy consumption is obtained in both MJ/pkm and in MJ/km to accommodate various statistics. These are calibrated with the total annual energy demand using the 2010 *reference* model.
Technologies	Type of technologies Market share Energy efficiency Total energy demand by fuel Number of vehicles Number of charging stations	The energy efficiency was calculated using seven different types of data. This was to accommodate a wide variety of data sources which document existing and forecasted efficiencies using different methodologies. In total, approximately 60 new technologies were identified and considered across passenger and freight transport. Vehicles accounted for include cars, buses, trucks, and trains.
Costs	Vehicle investments Vehicle O&M Charging stations Infrastructure	Infrastructure costs are included for road and rail transport. The costs are not included for air and sea infrastructure since it is assumed that these will not vary significantly between scenarios, since fuel is the primary cost for these modes.

The CEESA Transport Energy Scenario Tool, which is called TransportPLAN, includes a *reference* model of the Danish transport sector based on the year 2010. A *reference* scenario is also included in the tool for the years 2020 and 2030, which is based on forecasts from the Danish Infrastructure Commission (Infrastrukturkommissionen) [19] and the Danish government's Energy Strategy 2025 [20]. Since these forecasts do not go beyond 2030, a *reference scenario* is forecasted based on a number of assumptions for the year 2050. TransportPLAN is able to assess new transport technologies, modal shifts across different forms of transport, and the consequences of various public regulations. As outlined in Figure 13, the results from the TransportPLAN tool can be used to either assess the transport sector individually or as inputs to an energy system analysis tool, which enables the user to investigate the consequences of various transport alternatives on the complete energy system. In CEESA, an energy system analysis is carried out using the EnergyPLAN tool, which focused on the transition to a 100% renewable energy system by 2050 for Denmark [1]. A detailed description of TransportPLAN and the role of EnergyPLAN [21] is available in Appendix A.

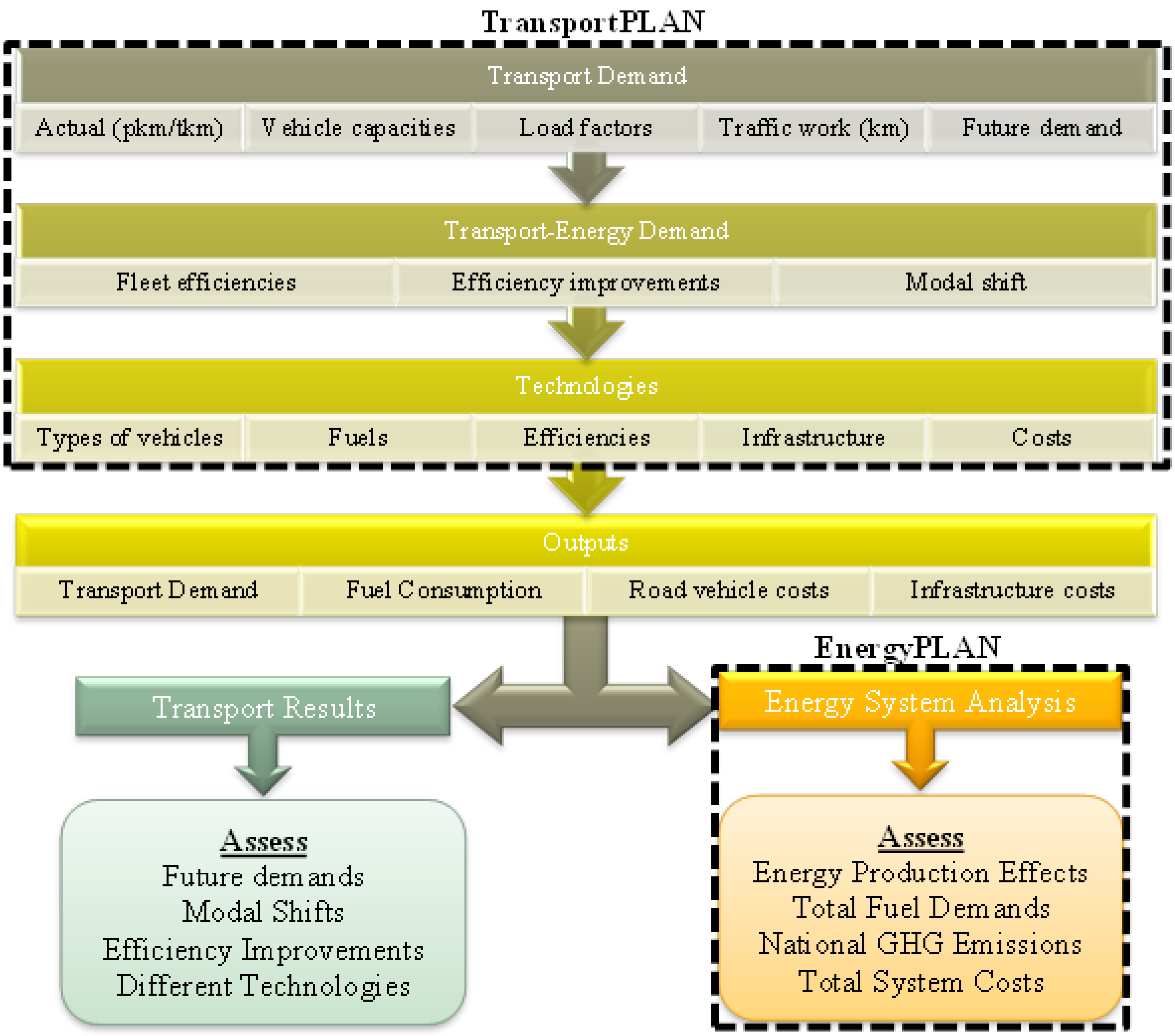

Figure 13: Methodology used to assess the transport sector in the CEESA project.

2.2 Boundary conditions

In CEESA, the data used to build the transport scenarios in TransportPLAN is governed by a specific set of boundary conditions, with the overall objective of including all transport relating to Danish citizens. As a result, all of the 26 modes of transport illustrated in Figure 12 are included in CEESA, which includes passenger, freight, agriculture, and military transport.

When collecting the data for each of these modes, three distinct boundary conditions (Appendix B) are defined and considered for each mode of transport assessed: national, transit, and international as displayed in Figure 14. In CEESA, 100% of the national transport demand and 100% of the Danish transit demand in other countries is included. The international transport demand is calculated by assuming that 50% of the demand was assigned to Denmark and 50% is assigned to the other country of origin. In this way, both countries share responsibility for the transport demand created between them. By using these boundary conditions for the transport sector, CEESA is not completely comparable to other publications. For example, the 'Grøn Energi' report completed by the Danish Commission on Climate Change [2] did not include the international component of the transport demand and it did not include the transit component of other counties in Denmark. As a result, the energy consumed by transport in 2050 is approximately 75 PJ (25%) higher in the CEESA *reference* than in the Danish Climate Commission's study.

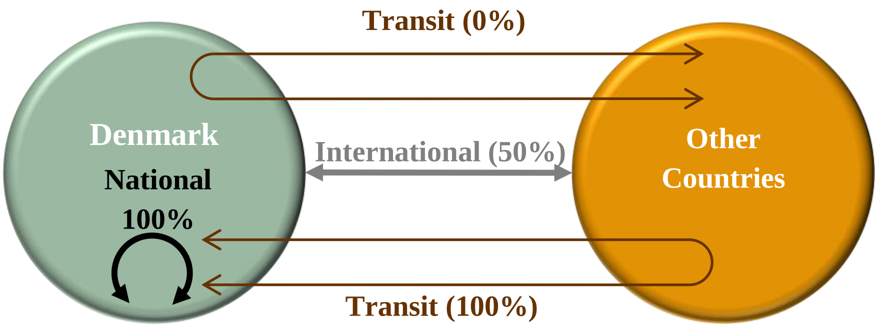

Figure 14: Boundary conditions defined when calculating the energy consumed in the Danish transport sector.

2.3 CEESA Transport Scenarios

Using TransportPLAN and the boundary conditions introduced above (which are described in more detail in Appendix A and B respectively), a variety of transport scenarios, which are displayed in Figure 15, were constructed in the CEESA project. The first task was to create a '*reference model*' of the Danish transport sector based on a historical year. The data available for a historical year is more detailed than a future year, so the *reference model* could provide the foundations for creating the future forecasts. The year 2010 was chosen to build the *reference model* since it was the most recent complete year at the time of the CEESA publication. Although every effort was made to collect data from the year 2010, in some cases this was not available and so the data available from the most recent year was used. The *reference model* was created by collecting the following data:

1. Transport-energy demands (PJ) for each type of transport: this outlines the source and magnitude of energy consumed by transport in 2010.
2. Traffic work (km) subdivided into each type of transport using the transport-energy demands, existing vehicle efficiencies (MJ/km) can be calculated.
3. Passenger transport demands (pkm) and freight transport demands (tkm) connected to the each type of transport in the traffic work. If possible the data should be subdivided into trip length and/or trip purpose (i.e. leisure or work). This data outlines how many passengers and how much freight needs to be moved, which can be used to assess various measures in CEESA i.e. modal shift.
4. Load factors (i.e. vehicle size) and utilisation rates: these are also necessary to assess the impact of different measures in the CEESA scenarios. For example, introducing congestion charging in Copenhagen will increase the utilisation of public transport.

This data provides a detailed breakdown of the 2010 Danish transport sector. However, in CEESA the objective is to assess the pathway towards a 100% renewable energy transport based on the years 2020, 2030, and 2050 (along with an interpolated representation of 2040). Hence, a '*reference scenario*' is also constructed based on each of these years outlining the 'business-as-usual' development of the existing transport sector. Less data is available for these future years than for the *reference model*. Therefore, the *reference scenario* was constructed by applying the following steps to the *reference model*:

5. Adding growth projections for the transport-energy demands (PJ) under a business-as-usual scenario in the statistics and/or literature.
6. Identifying energy efficiency improvements (MJ/km) in the business-as-usual projections.

7. Adjusting the business-as-usual projections for the traffic work (km) after considering the efficiency improvements included in the projections.
8. Calculating the passenger (pkm) and freight (tkm) transport demands for the forecasted *reference scenario* by using the load factors and utilisation rates from the 2010 *reference model*, along with the new transport-energy (PJ) and traffic work (km) demands.

The main challenge during this process was the availability of adequate data for all modes and types of transport, such as traffic work for international aviation and marine transport, transport-energy demands for international freight, and utilisation rates for almost all modes of transport. To overcome this, numerous assumptions were made based on the data available in the literature, expert-group meetings, and by conducting numerous interviews with different stakeholders involved in the Danish transport sector over the 5 year period of the CEESA project. A detailed description of the challenges, assumptions, and final data used can be found in Appendix B and Appendix C for the *reference model* and *reference scenario* respectively. The resulting energy and transport demands for the references are presented in section 3.

Once the *reference scenario* is complete, the next step (see Figure 15) is to create a variety of 100% renewable energy scenarios which could satisfy the *high increase*[2] forecasted in the *reference* transport demands. To create these scenarios, various different transport technologies were assessed. This began an iterative process where many different constraints needed to be considered such as the current technologies available, the potential for further technological development, the bioenergy resource available in Denmark, energy efficiencies, the flexibility created from various technologies, environmental implications, and costs. Hence, this process is discussed extensively in section 4.

[2] The term *high increase* is used to define the transport demand in the *reference*, since it forecasts a transport demand in 2050 that is double the current 2010 transport demand.

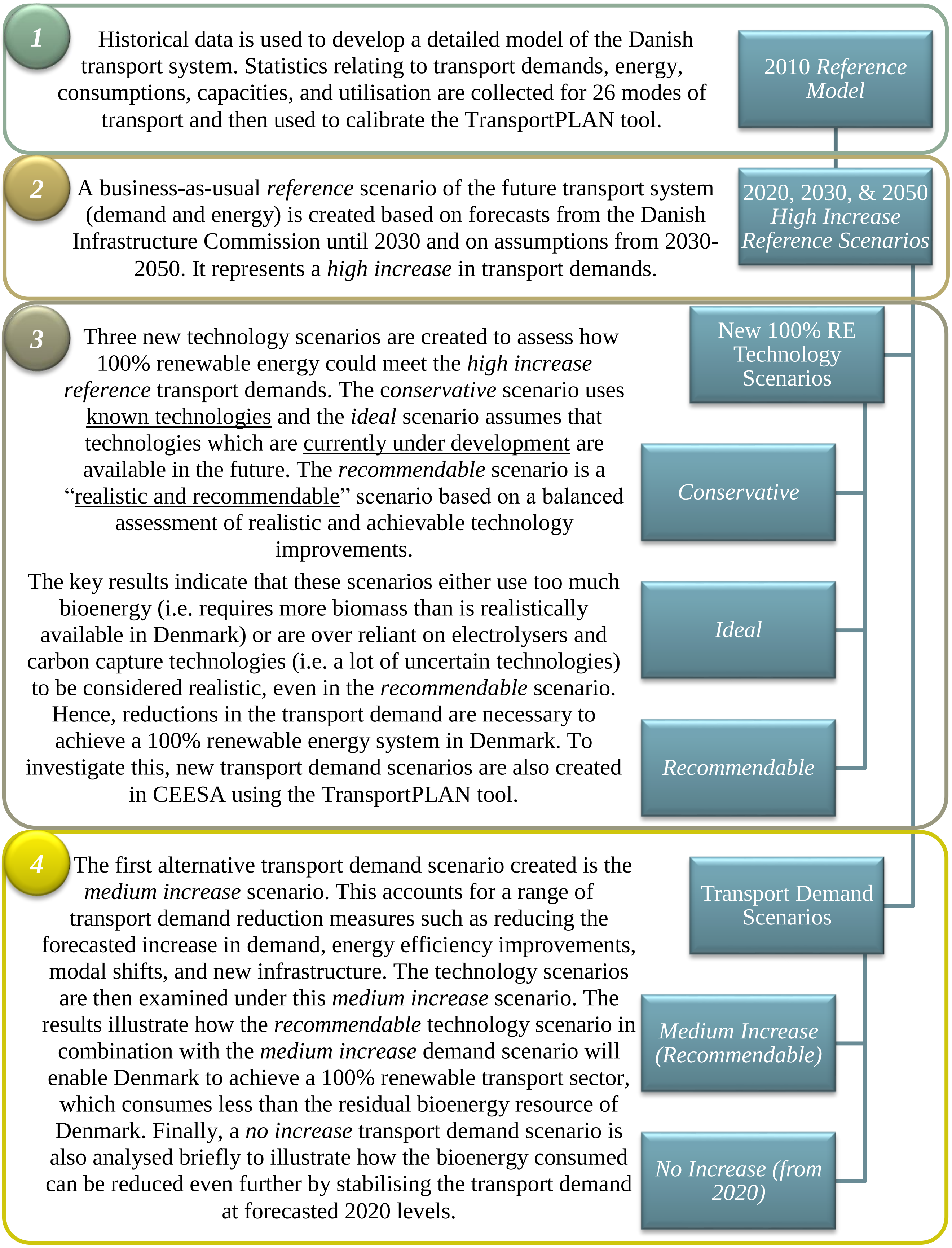

Figure 15: Transport scenarios created during the CEESA project, including a brief description of the scenarios and their main findings.

After evaluating the technologies available, three different ‘technology scenarios’ were designed to create a 100% renewable transport sector in CEESA:

1. A *conservative* scenario based on known technologies
2. An *ideal* scenario using technologies which are currently under development
3. A *recommendable* scenario which is a “realistic and recommendable” scenario based on a balanced assessment of realistic and achievable technology improvements.

New technologies are only one solution for the transport sector in the future. A reduction in the transport demand growth can also play a very important role in a 100% renewable energy system. In line with this, a number of modules are available in TransportPLAN for simulating changes in the transport demand. These include:

- Transport demand growth module (TDG) can alter the forecasted growth rates in the transport demand.
- Energy efficiency improvement module (EEI) enables the user to increase the efficiency of new vehicles in the future.
- Modal shift module (MS) can simulate the transfer of a transport demand from one form of transport to another. For example, the MS module can be used to move 20% of car journeys above 50 km to rail in TransportPLAN.

These are discussed in more detail in Appendix A. Using these modules, a *medium increase* and a *no increase (from 2020)* transport demand scenarios are also created in CEESA, as described in more detail in section 5.

In summary, the scenarios created in CEESA are based on a detailed breakdown of a business-as-usual *reference scenario* (which is described in the next section). Initially, alternative 100% renewable energy scenarios are created based on new technologies (section 4) and afterwards, they are based on a combination of new technologies and reductions in the future transport demand (section 5).

3 Danish 2010 Transport Demands and Reference Scenario

This section describes the key findings from the 2010 *reference model* and the projected *reference scenarios*. These were constructed for 2020, 2030, and 2050 based on forecasts by various transport and energy institutions. A detailed breakdown of the *reference* is necessary to create the alternative transport scenarios in CEESA.

3.1 Reference model

The *reference model* is based on the year 2010 and constructed using historical data, primarily from Statistics of Denmark [22], the “Transport Habits Survey (Transportvaneundersøgelsen,)” from the Technical University of Denmark [10], the Danish Road Directorate [23], the Danish Ministry of Transport [24], and the Danish Energy Agency’s annual statistics [17]. A detailed description of the data collected and the assumptions made for the 2010 *reference model* is provided in Appendix B. In this chapter, the primary results are presented for the 2010 *reference model* to illustrate the variety of needs and challenges to be faced within the Danish transport sector.

3.1.1 Passenger transport

The resulting transport demands, traffic work, and energy demands from the 2010 *reference model* are displayed in Figure 16. It is evident from these results that four modes of transport stand out from the rest regarding their transport demand and energy demand. These four modes are national car, international air, national bus, and national rail. The national car mode accounts for approximately 55% of the total transport demand followed by international air with 18%, then national bus with 8%, and finally national rail with 7%. All other modes combined account for approximately 10% of the total transport demand. The same tendencies can be seen when comparing the energy consumed by the different modes: national car represents 65% of the total, international aviation 18%, national bus 6%, and national rail 3%. Due to the significant demand which these modes represent, more detailed data was collected and more informed alternatives created for these particular modes in the CEESA study.

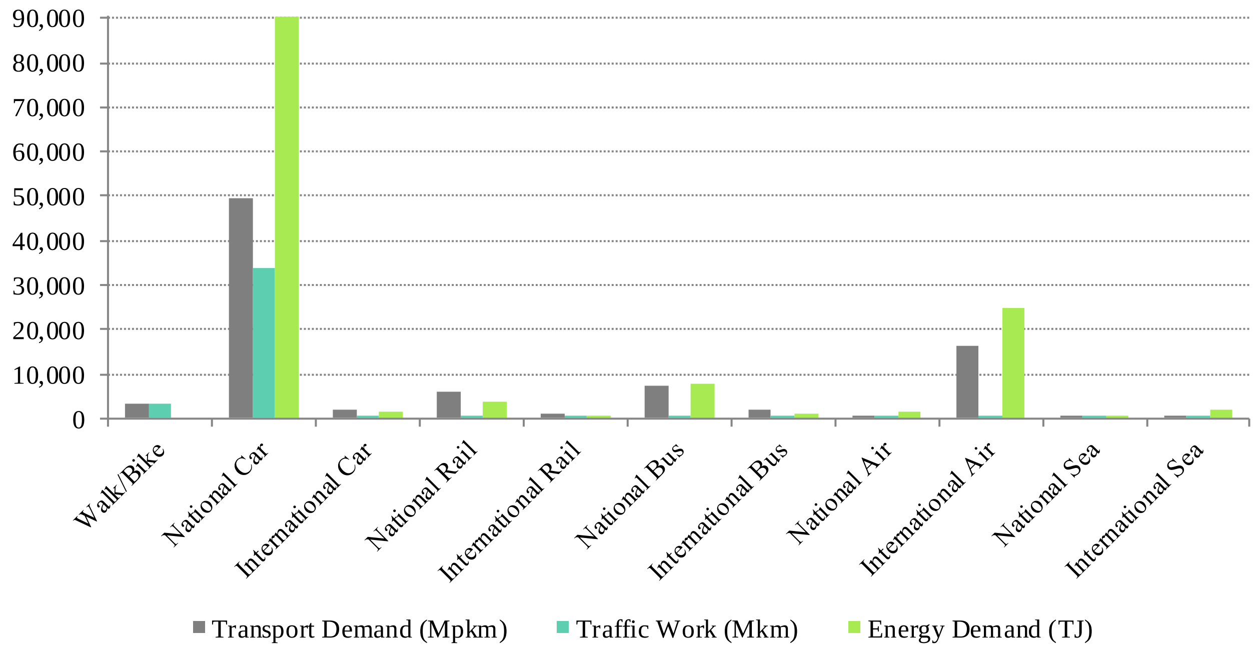

Figure 16: Transport demand, traffic work, and energy demand for each mode of passenger transport in the 2010 *reference model*.

The results from the 2010 *reference model* also indicate that international transport represents approximately 25% of the total transport demand and 23% of the total energy demand (see Figure 17). However, since the vehicles used for international transport (primarily aeroplanes) are characterised by relatively large vehicle capacities and load factors, international transport only accounts for approximately 3% of the traffic work.

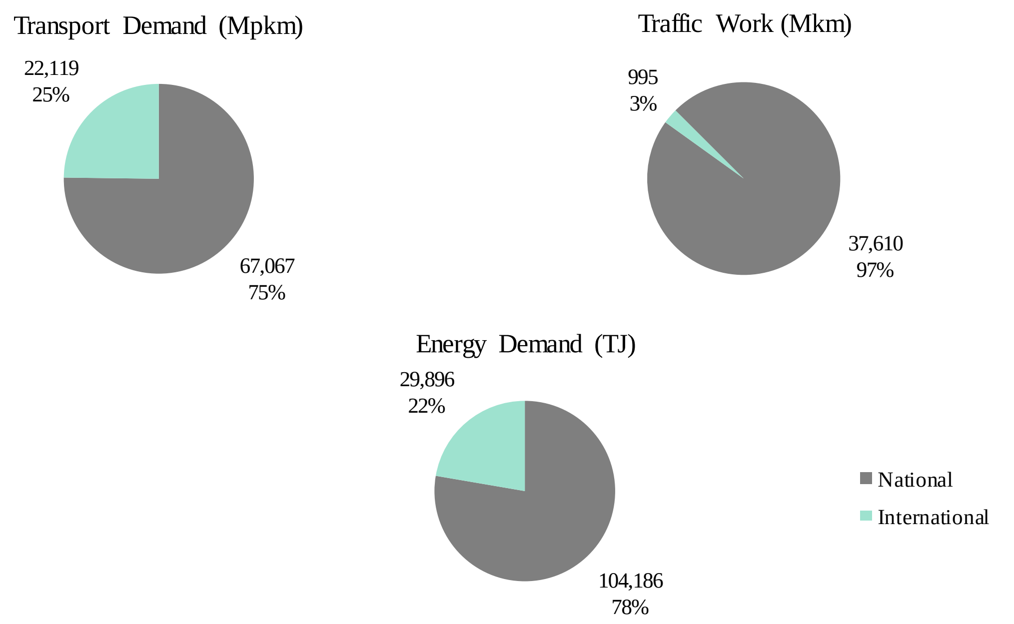

Figure 17: National and international transport demand, traffic work, and energy demand for passenger transport in the 2010 *reference model*.

By combining transport demand statistics with energy consumption data, it is possible to establish the specific energy consumption for the different modes in the 2010 Danish transport sector. As outlined in Figure 18 and Figure 19, rail is the most efficient form of transportation: for example, national rail consumes approximately 6 times less energy than national cars and international rail consumes approximately 5 times less energy than international aviation. Since rail only meets 8% of the transport demand (see Figure 16) compared to 55% and 18% for national car and international aviation respectively, there are considerably energy savings feasible by replacing some of these modes with rail. Hence, this was a key consideration when developing the alternatives for passenger transport in the CEESA project. Sea transport is the least efficient for passengers, but the data indicates that the current utilisation figures for sea are very low.

In addition, Figure 18 also presents the specific energy consumption of each mode under a hypothetical scenario where all of the vehicle capacities available are utilised. Here it is evident that rail is still the most energy efficient form of transportation. Furthermore, Figure 19 indicates that the energy efficiency of national cars, buses, aviation, and sea as well as international sea could be considerably improved if their existing load factors were improved. Therefore, this was also considered in the CEESA scenarios and demonstrates the benefits of using a detailed breakdown of the transport sector in the 2010 *reference model*.

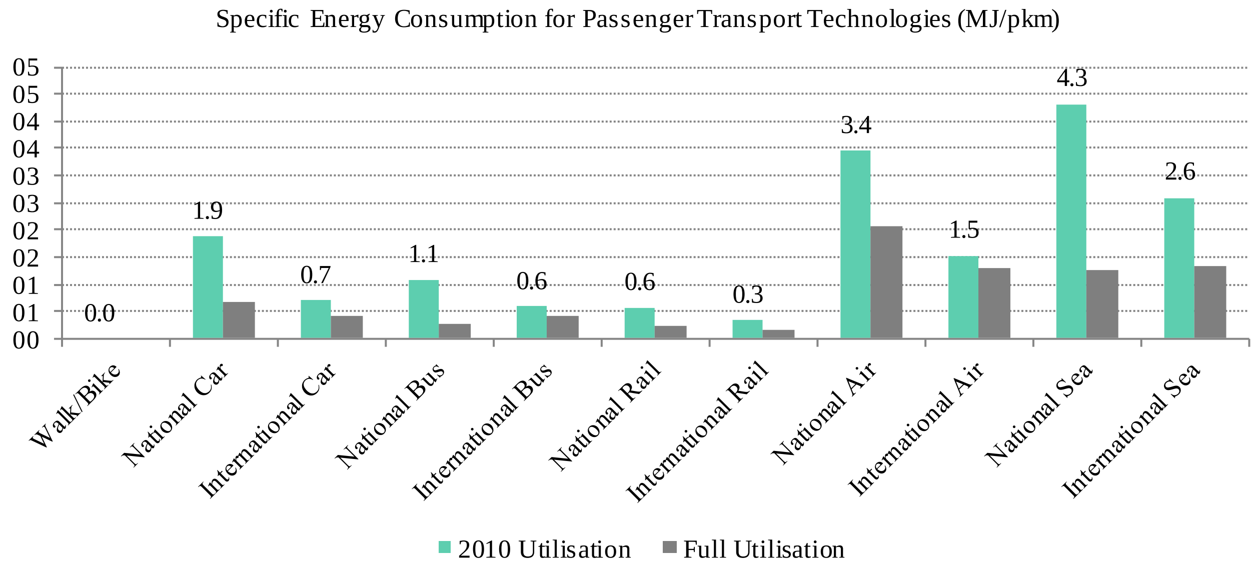

Figure 18: Specific energy consumption for passenger transport technologies in the 2010 *reference model* using actual 2010 utilisation statistics (load factors) and hypothetical full utilisation statistics.

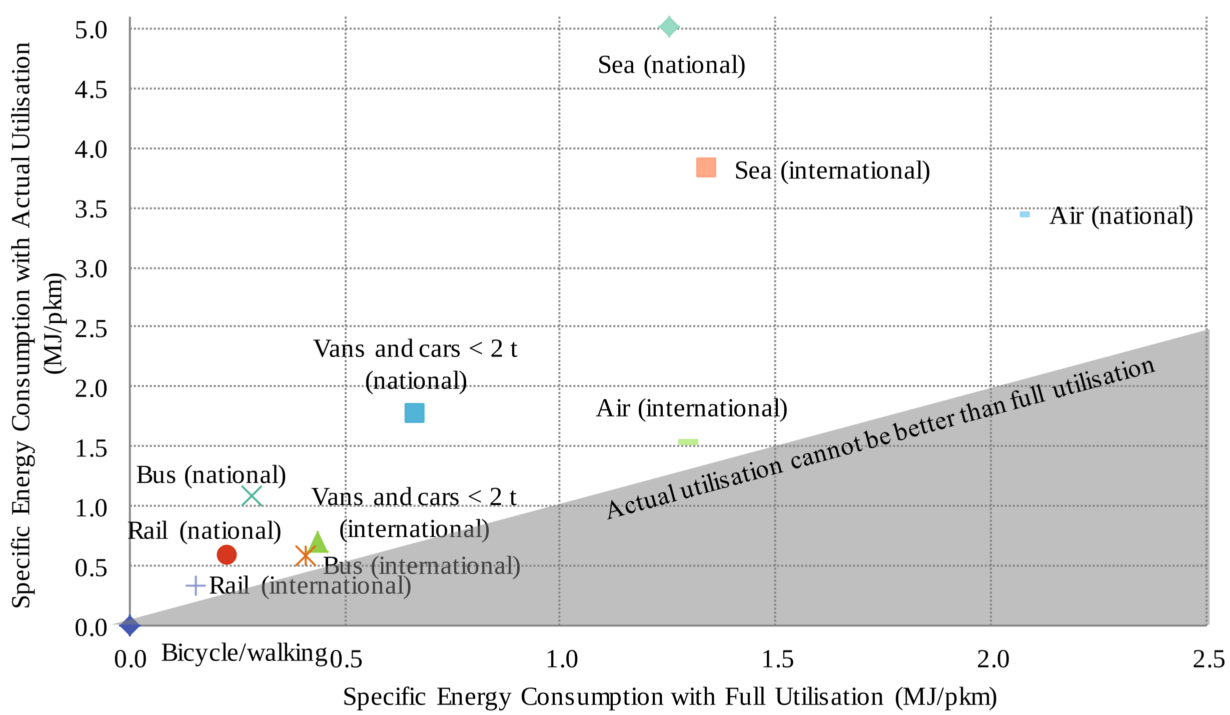

Figure 19: Specific energy consumption for passenger transport technologies in the 2010 *reference model* using actual 2010 utilisation statistics (load factors) and hypothetical full utilisation statistics.

3.1.2 Freight transport

For freight, the transport and energy demands vary considerably by mode. As displayed in Figure 20, vans account for almost half of the energy consumed by freight transport, but only 5% of the transport demand. Similarly, trucks consume almost half of the energy consumed and approximately 25% of the transport demand, while aviation requires 7% of the energy to provide 0.7% of the transport demand. The reason for these statistics is international sea transport: it accounts for 67% of the transport demand, but only 5% of the energy demand, which is due to the very low specific energy consumption required for sea freight.

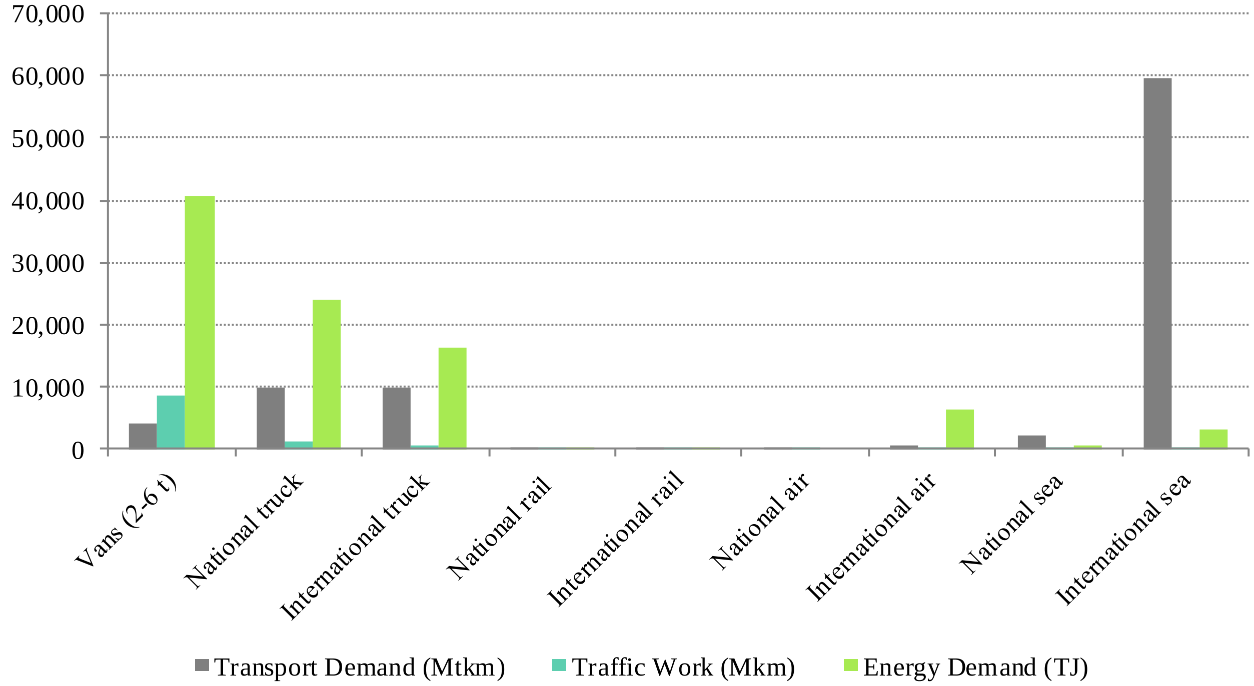

Figure 20: Transport demand, traffic work, and energy demand for each mode of freight transport in the 2010 *reference model*.

As illustrated in Figure 21 and Figure 22, in 2010 international sea transport was approximately 100 times more efficient than vans and aviation, and 20 times more efficient than trucks. It could be argued that this is due to the high utilisation of international shipping compared to other modes. However, the results in Figure 21 and Figure 22 also indicate that even if each mode was fully utilised, shipping would be similarly more efficient than the comparison under actual 2010 load factors. Although this could lead to the conclusion that more freight should be moved to ships, it is important to acknowledge that shipping goods also leads to a corresponding demand for trucks and vans i.e. the goods still need to be distributed to and from the harbour. Therefore, there are chain effects that need to be considered when creating alternatives for freight transport. Furthermore, vans are sometimes used to transport passengers as well as freight, so the final specific energy consumption for vans could be overestimated.

Similar to passenger transport, rail is once again a very efficient form of transport which is not utilised very much. As displayed in Figure 21, the efficiency of rail is similar to shipping, so it too consumes approximately 20-100 times less energy than the other modes. However, in contrast to shipping, rail is only used for 0.7% of the transport demand. In line with passenger transport, this suggests that there is significant scope to expand the rail network for freight transport.

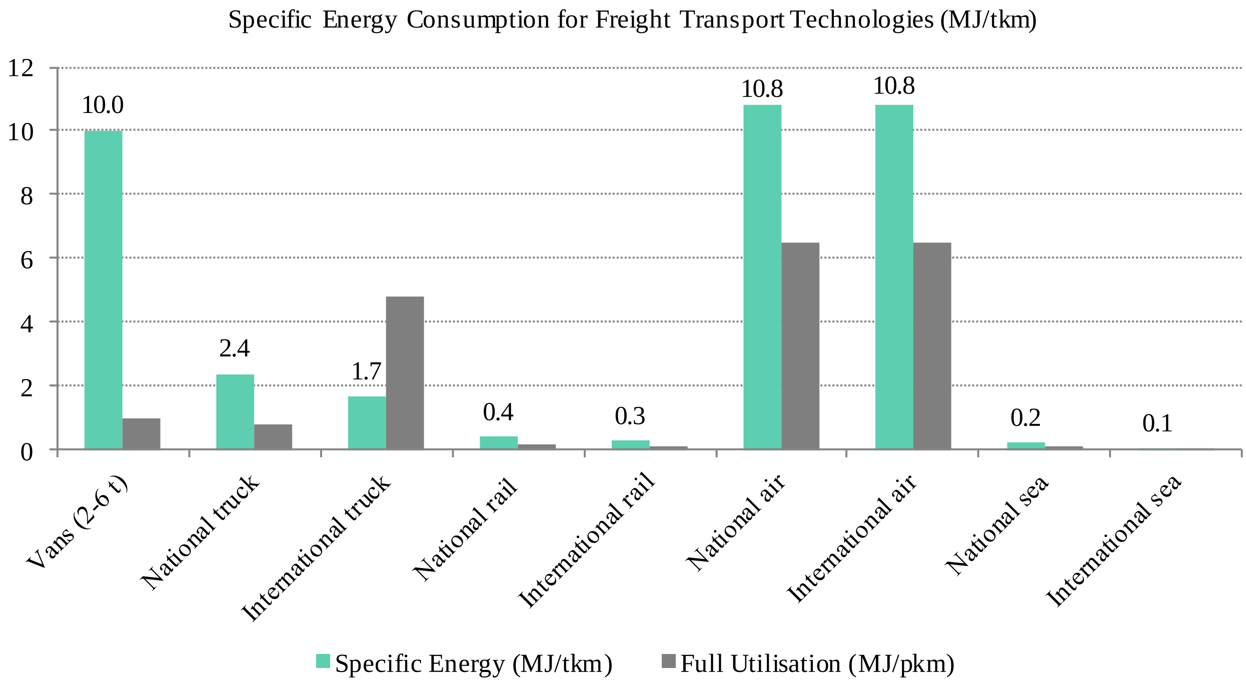

Figure 21: Specific energy consumption for freight transport technologies in the 2010 *reference model* using actual 2010 utilisation statistics (load factors) and hypothetical full utilisation statistics.

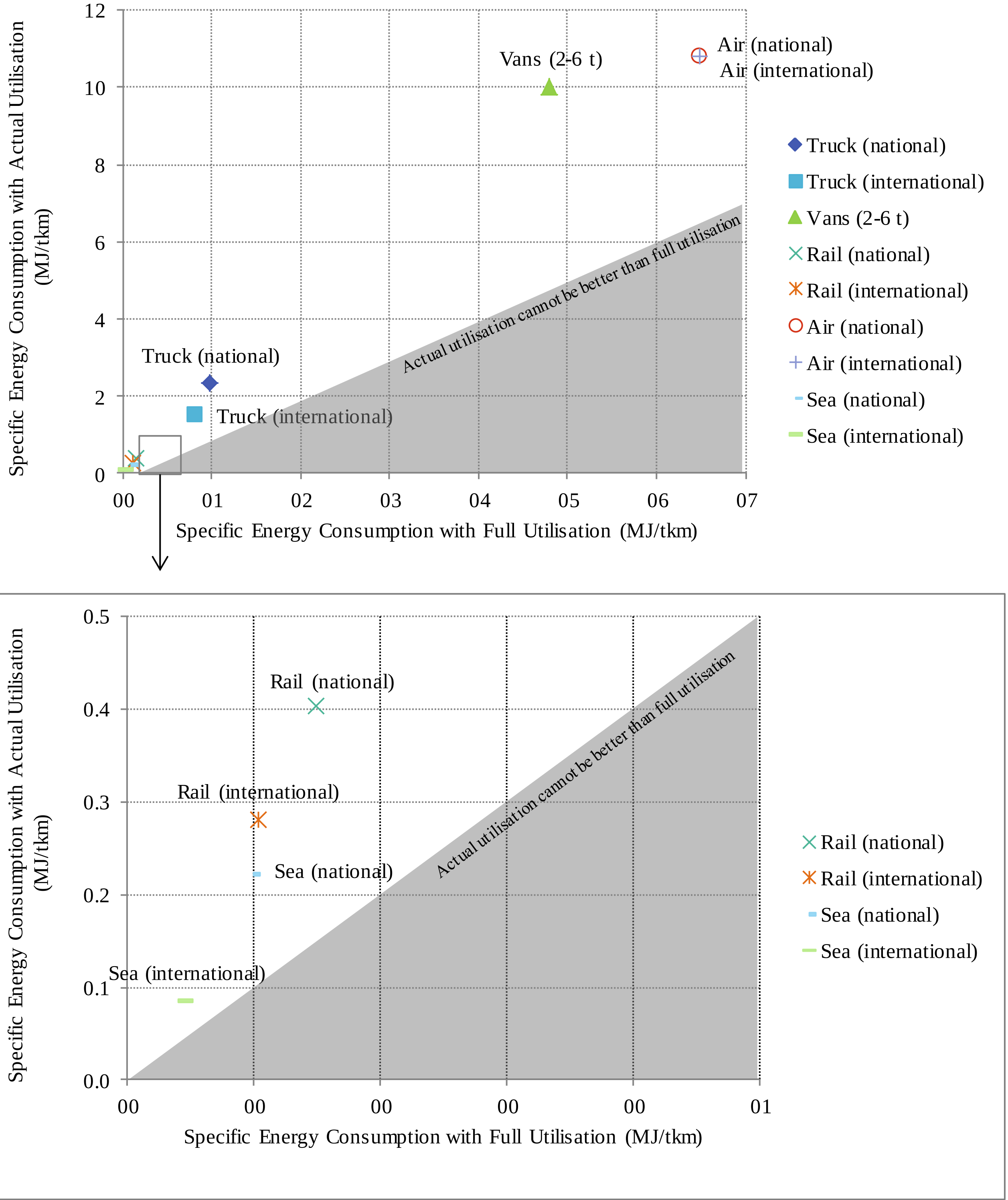

Figure 22: Specific energy consumption for freight transport technologies in the 2010 *reference model* using actual 2010 utilisation statistics (load factors) and hypothetical full utilisation statistics.

Finally, the high efficiency and capacities of sea transport are also evident when comparing national and international transport. Figure 23 indicates that international transport represents 80% of the transport demand, but only 6% of the traffic work. This reflects that bulk point-to-point movement of goods which takes place on an international level and the dispersed movement of goods at a national level. In line with this, national transport accounts for 70% of the total energy consumed for freight transport in Denmark, which is 65 PJ/year.

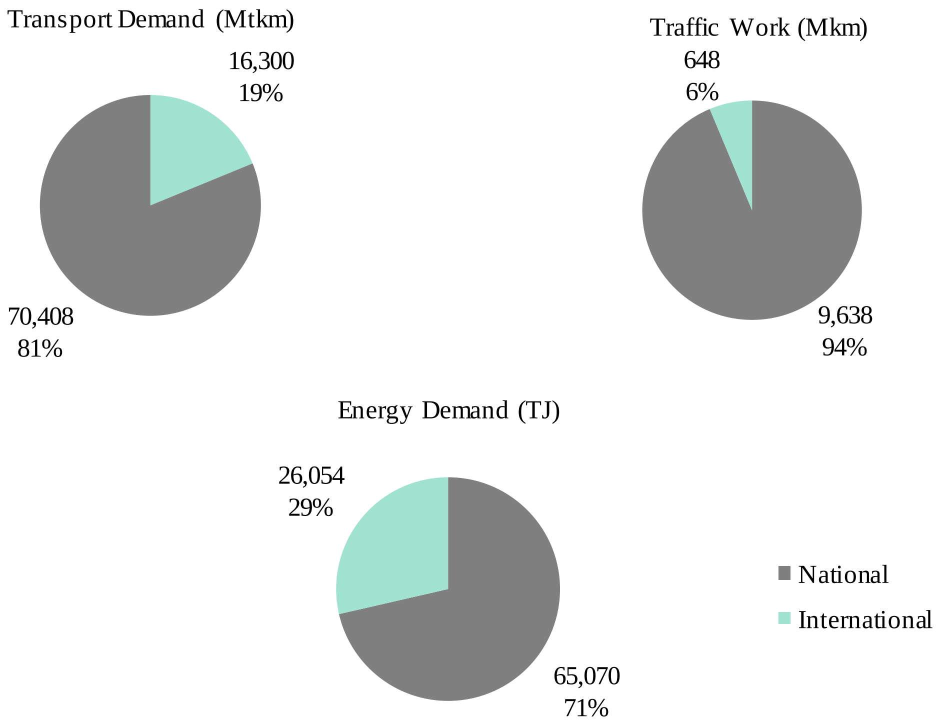

Figure 23: National and international transport demand, traffic work, and energy demand for freight transport in the 2010 *reference model*.

3.2 Reference Scenario for the Danish Transport Sector from 2010 to 2050

The *reference model* provides a detailed breakdown of the existing transport sector in Denmark. In CEESA, this is projected forward to the year 2050 to create a *reference scenario*, before a 100% renewable energy pathway is created. Due to the nature of future projections relating to the transport sector, there is no single correct forecast for these projections. Hence, the *reference scenario* is based on a number of statistics available in various databases and reports from organisations such as the Danish Energy Agency, the Infrastructure Commission, and StatBank Denmark [10,19,20,22,25–27]. These statistics are interpreted and aligned as much as possible in order to create a business-as-usual scenario of the Danish transport sector between 2010 and 2050. Two intermediate years are also considered, which are 2020 and 2030, while 2040 results are included as an interpolation between 2030 and 2050. A detailed description of the assumptions used to create the *reference scenario* is provided in Appendix C. Here a brief overview of the results is provided to illustrate how the Danish transport sector is expected to develop in terms of transport and energy demands.

3.2.1 Passenger Transport

The transport demands for passenger transport in the *reference scenario* are displayed in Figure 24. Overall, transport demands are estimated to increase by approximately 80% over the period 2010-2050, from 89,000 Mpkm in 2010 to 163,000 Mpkm in 2050. The highest growth rates are found for cars and aviation, which are also the modes with the largest transport demands for passengers. The general composition of the passenger transport demand remains similar in 2010 and 2050: cars make up 60% of the demand in both years, although there is a reduction for buses which is compensated for by an increase in aviation (corresponding to 5% of the total).

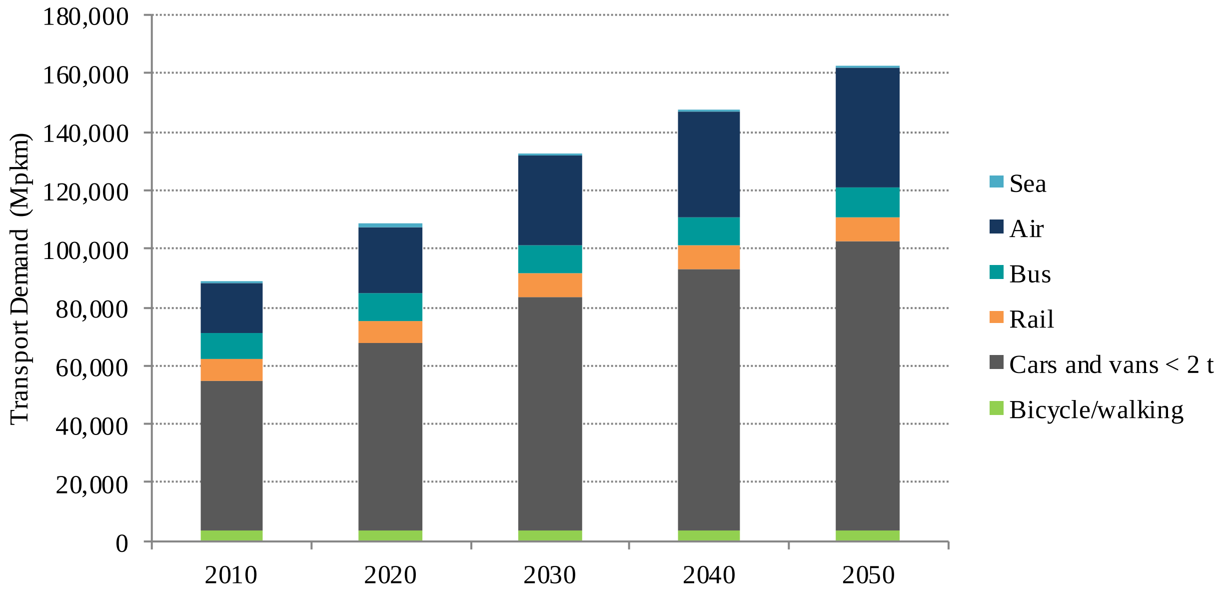

Figure 24: Transport demands by mode for passenger transport in the *reference scenario*.

The transport demands forecasted for passenger transport are connected to the corresponding energy demands based on the specific energy consumption of the different modes of transport. These are illustrated in Figure 25, where it is evident that rail is still the most efficient mode of passenger transport in 2050. It is evident from the reductions between 2010 and 2050 in Figure 25 that there are significant energy efficiency improvements assumed in the *reference scenario*. This reflects future concerns relating to the availability and price of fuel for conventional vehicles. However, even with these efficiency improvements, Figure 26 indicates that the overall demand for energy for passenger transport still increases by approximately 20% over the period 2010-2050. This is due to the high growth rates assumed for transport in the *reference scenario*, which counteract the energy efficiency improvements illustrated in Figure 25.

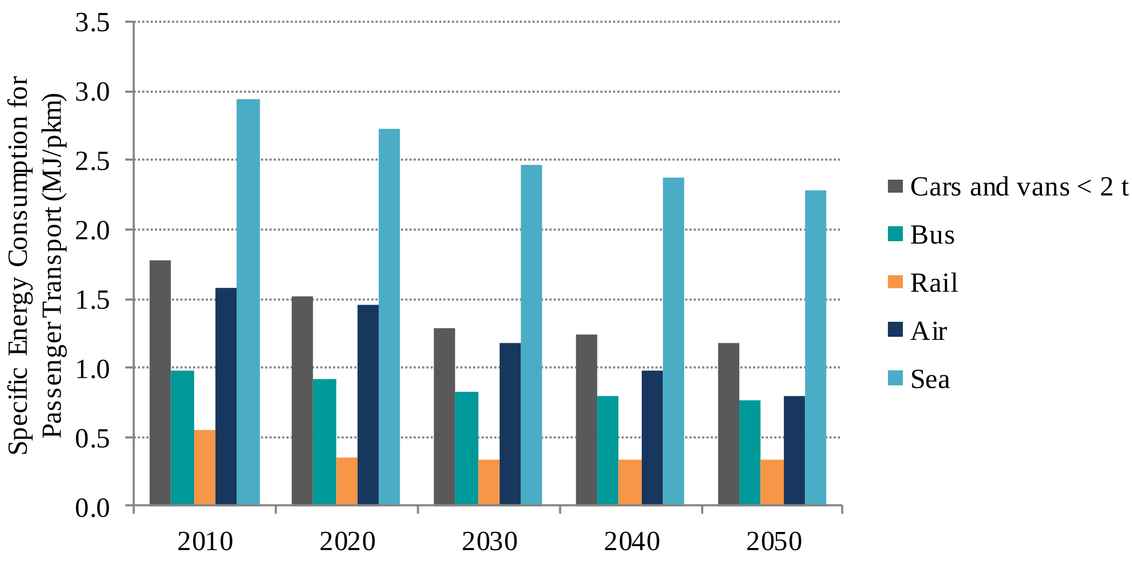

Figure 25: Specific energy consumption for the different modes of passenger transport in the *reference scenario*.

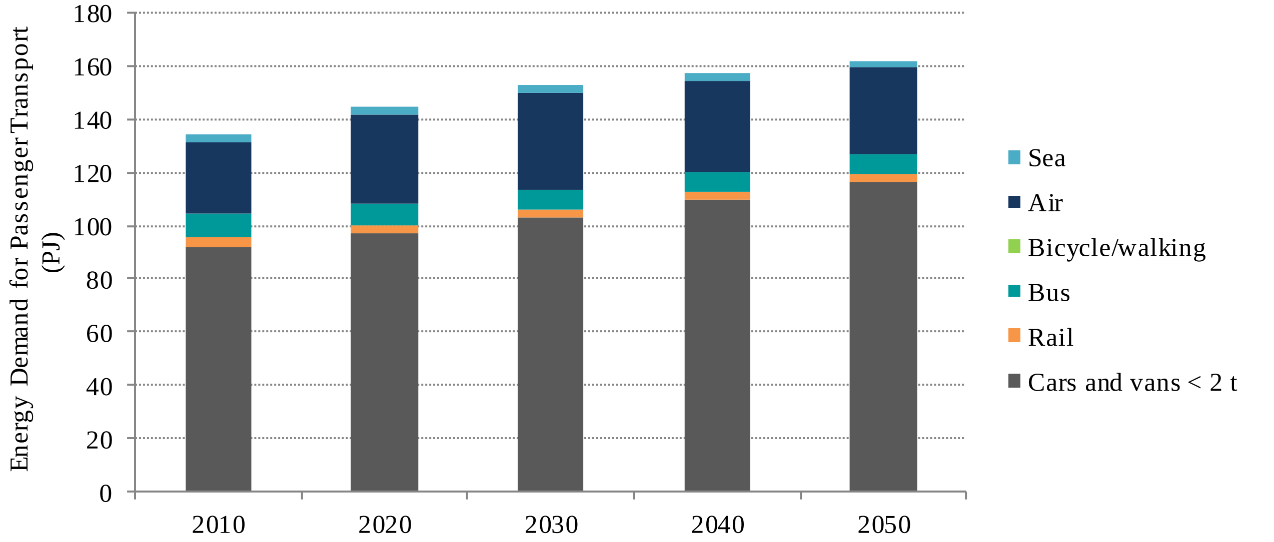

Figure 26: Energy demand by mode for passenger transport in the *reference scenario*.

3.2.2 Freight Transport

As outlined in Figure 27, freight transport will also increase rapidly between 2010 and 2050, with an overall growth of almost 90% from 87,000 Mtkm to 164 Mtkm. There is a clear difference in the modes that are expected to grow for both national and international freight. International rail, aviation, and sea will almost double by 2050, but these modes show little and even no growth over the same period for national freight transport. Instead, it is vans and trucks which create the growth at a national level, with both forms of transport increasing by over 90% between 2010 and 2050. The composition of freight transport is practically unchanged from today with sea freight continuing to provide approximately 70% of all demands, followed by trucks (20%) and vans (5%) in 2050.

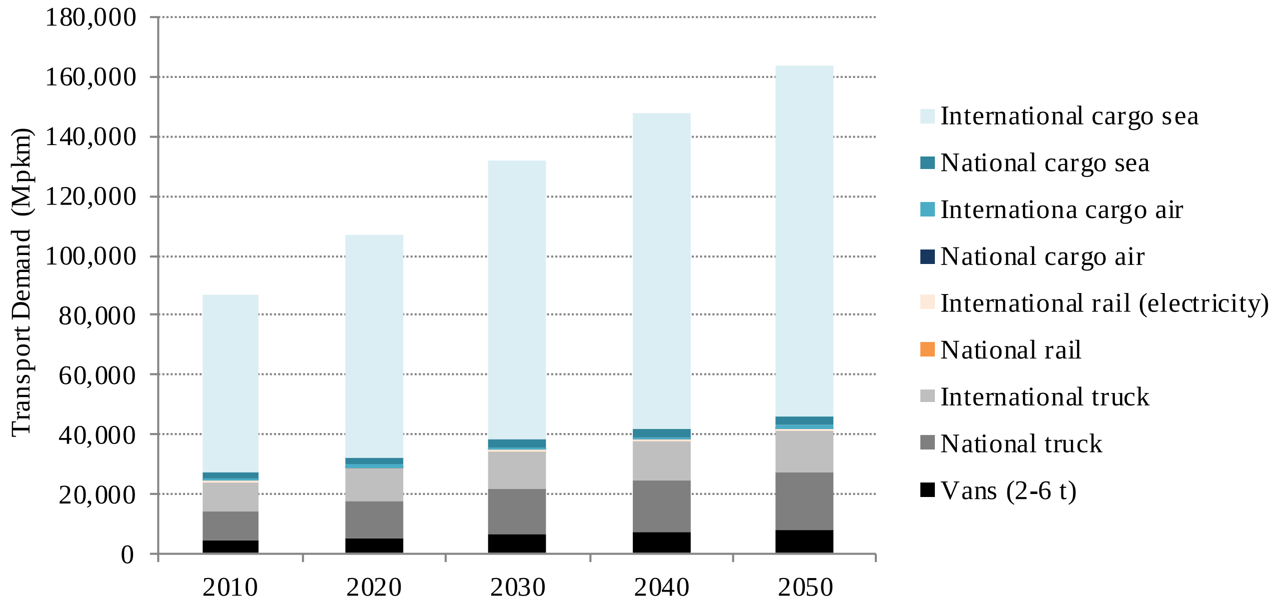

Figure 27: Transport demands by mode for freight transport in the *reference scenario*.

Once again, the freight transport demands are connected to the corresponding energy consumption using the specific energy consumption of the different modes of transport illustrated in Figure 28.

Surprisingly, the resulting energy demands presented in Figure 29 show a very small growth of only 4% between 2010 and 2050, even though the transport demands in Figure 27 grow by 90% over the same period. This is primarily due to the very low specific energy consumption of international sea freight. This high growth in this mode of transport reflects an increased trend in globalisation, but since sea freight is so efficient, the resulting growth in energy demands is not very large. It is important to recognise however, that with increased international sea freight, there is often a corresponding increase in the transport demands relating to national trucks. The goods delivered from port-to-port need to be subsequently transferred to their final destination, so even though international sea freight itself does not create a large increase in energy demands, it indirectly does through national trucks.

Another key reason for the relatively low growth in transport-energy demands for freight are the energy efficiency improvements included in the *reference scenario*. As outlined in Figure 28, all modes of transport reduce their specific energy consumption between 2010 and 2050. For example, vans and trucks account for 75% of the energy consumed for freight transport and these modes alone are expected to reduce their specific energy consumption by approximately one-third over the next 40 years. Hence, energy efficiency has a significant role to play in the business-as-usual *reference scenario*.

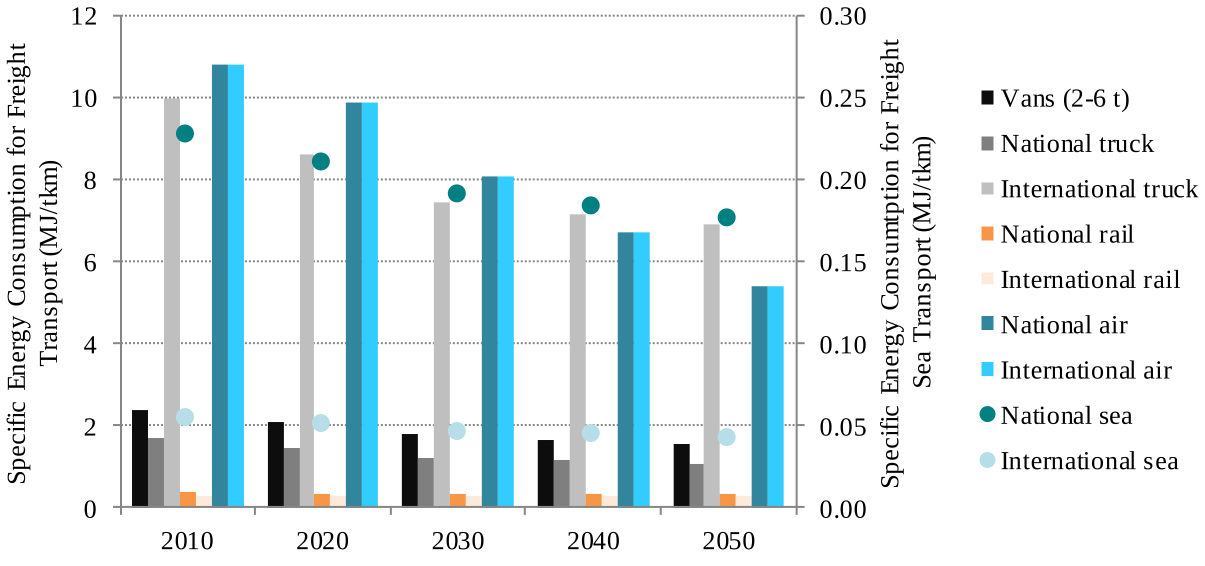

Figure 28: Specific energy consumption for the different modes of freight transport in the *reference scenario*.

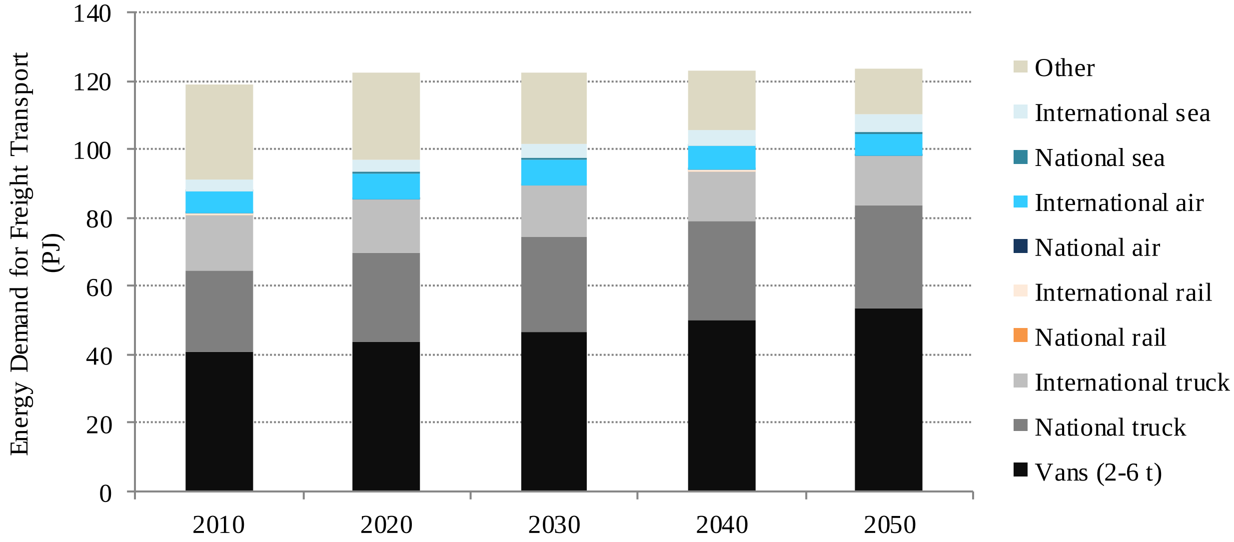

Figure 29: Energy demand by mode for freight transport in the *reference scenario*.

3.3 Summary

The final total energy demands for the *reference scenario* are displayed in Figure 30. These indicate that Denmark's transport-energy demands will increase under a business-as-usual development, even with the significant energy efficiency improvements displayed in Figure 25 and Figure 28 previously. In fact, if these energy efficiency improvements are not included, then the total energy demand for transport would be approximately 430 PJ in 2050 and not the forecasted 285 PJ. Furthermore, in 2050 oil will still account for approximately 95% of the energy used in the transport sector if current trends are followed. Once again, these trends demonstrate the challenge and urgency for new solutions in the transport sector. In CEESA, different 100% renewable energy scenarios have thus been created for the Danish transport sector for the year 2050, in order to overcome these challenges and meet overall ambitions of the Danish government [28].

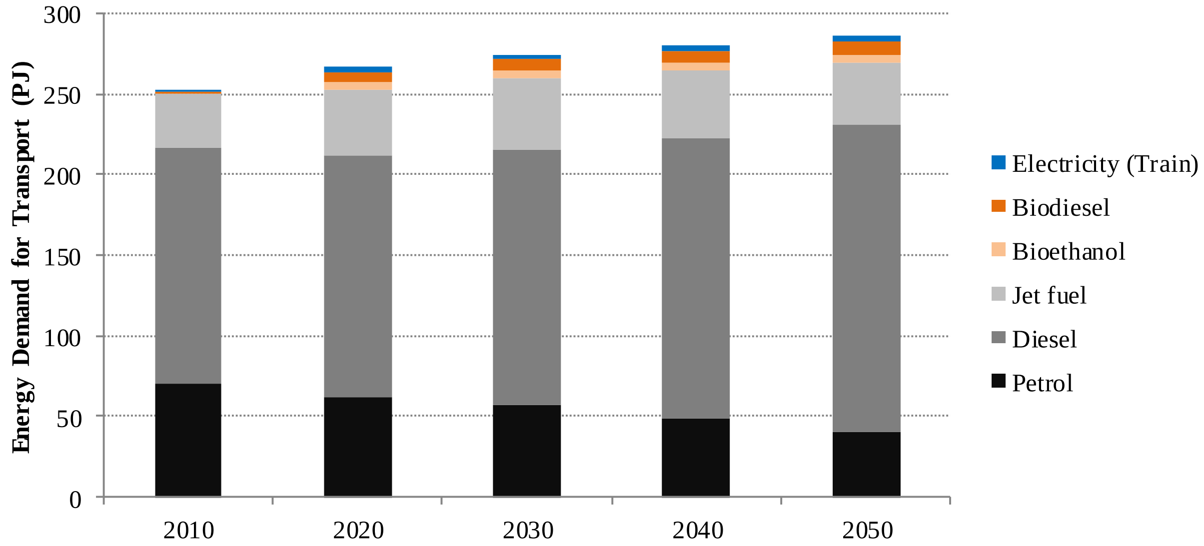

Figure 30: Energy demand by fuel for transport in the *reference scenario*.

4 New Renewable Energy Technology Scenarios

It is difficult to forecast the technical capabilities of new technologies in 2050, especially since 100% renewable energy systems are only beginning to evolve. However, by evaluating the role of new technologies based on the resources they use, the fuels they consume, the efficiency of producing these fuels, and the efficiency of the vehicles that use them, it is possible to make general conclusions about the mix of technologies required in a 100% renewable transport sector. The three technology scenarios chosen in CEESA are designed to evaluate extreme variations of these technology mixes instead of one specific pathway. In this section, the evaluation process used to choose the technologies analysed in CEESA is described along with the 'technology scenarios' which were subsequently modelled. The key conclusion is that technologies alone will not reduce the bioenergy demands in Denmark sufficiently i.e. below the residual bioenergy resource identified in CEESA [1]. Hence, the forecasted *high increase* in the Danish transport demand will need to be reduced to achieve a 100% renewable transport sector by 2050, which is subsequently investigated in section 5.

4.1 Comparison between Renewable Energy Resources

Although the transport sector utilises a wide range of fuels, only two resources were identified as the base materials in the context of a 100% renewable energy transport sector: bioenergy and electricity generated from renewable sources. By comparing these, it is evident that Denmark has a much larger renewable electricity resource than bioenergy resource. For example, the wind and solar energy potential in Denmark alone is approximately 1200 PJ/year and 250 PJ/year respectively [29], while in CEESA, the residual bioenergy resource identified for Denmark in the Technical Background Report 1 of this study is ~240 PJ/year [1] (see Figure 31). Since the total energy consumption in Denmark in 2010 was approximately 800 PJ [17], bioenergy will clearly be a limited and valuable resource in a 100% renewable energy system.

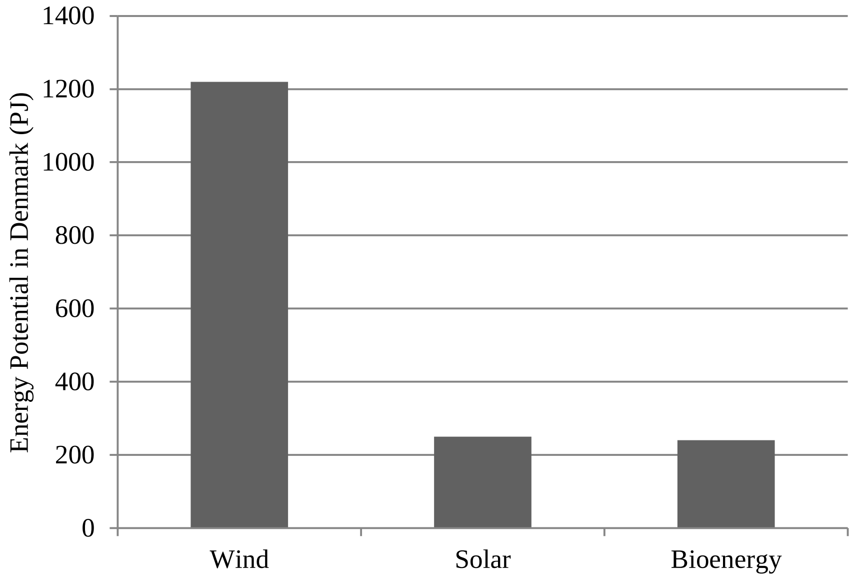

Figure 31: Energy potential in Denmark for wind, solar, and bioenergy [1,29]**.**

In addition, the bioenergy resource is still subject to numerous uncertainties including: how much does it affect food production, where should it be prioritised in the energy system, and how will bioenergy combustion impact the environment? Some of these issues are evident when comparing the average direct land-use requirements for bioenergy and renewable electricity. For example, it is evident in Figure 32 that wind power requires an average of 600 times less gross-land to produce the same amount of energy (1 PJ) compared to biofuels, with extremes of 130-1770 depending on the specific biofuel considered. Like oil in existing energy systems, bioenergy can exist in many forms depending on the type of transport demand which needs to be met and so, the various biofuels included in the gross-land area statistics in Figure 31 are outlined in Table 2.

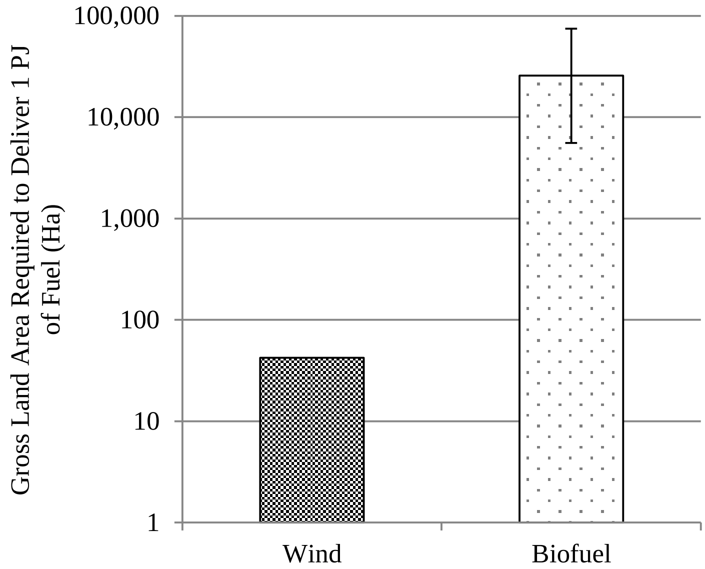

Figure 32: Gross land-area required to produce 1 PJ of wind generated electricity [30] **and biofuel. The error bars for biofuel illustrate the variation between the different forms of bioenergy considered, which are outlined in Table 2. Wind turbines require ~45 Ha/PJ while the average biofuel requires ~25,000 Ha/PJ.**

Table 2: Biofuel pathways included in the biofuel land-use calculations.

Biogas to methane	Grass on marginal land
	Grass on arable land
	Maize on arable land
Willow to bio-methanol	Fresh willow on marginal land
	Fresh willow on arable land
	Dried willow on marginal land
	Dried willow on arable land
Willow to FT liquids (i.e. biodiesel)	Fresh willow on marginal land
	Fresh willow on arable land
	Dried willow on marginal land
	Dried willow on arable land
Straw to ethanol (C5+C6)	Straw allocated to feed
	Straw allocated to other
Rapeseed to biodiesel	Arable land
Straw to ethanol (C6)	Straw allocated to feed
	Straw allocated to other

Based on these figures, the total land area required to produce 200 PJ of energy is illustrated in Figure 33. This proxy is used since approximately 200 PJ was consumed by the Danish transport sector in 2010 (see Figure 9). The results here indicate that approximately 0.3% of the Danish agricultural land area would be required if 200 PJ of electricity is produced by onshore wind farms in Denmark. In contrast, biofuels would require between 40% and 575% of the Danish agricultural land area.

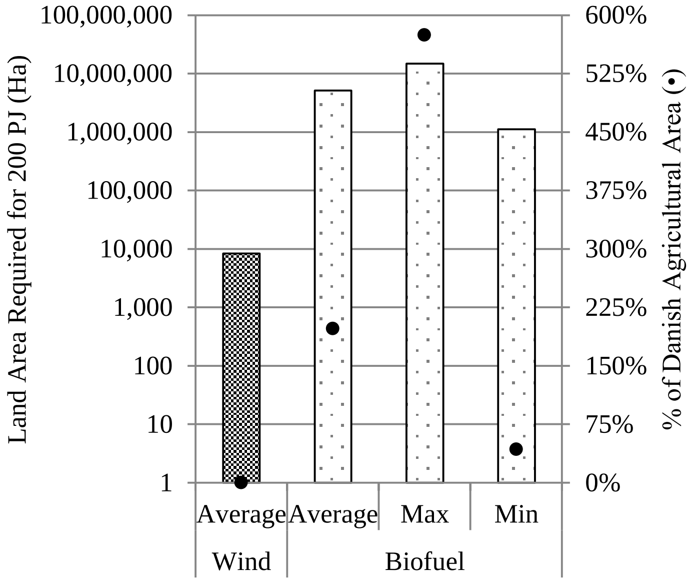

Figure 33: Gross land-area required to produce 200 PJ from wind generated electricity and biofuels. It was assumed that the Danish agricultural area was 26,000 km^2, which is 60% of the total land area in Denmark.

It is worth noting that 'gross' land-use compared in Figure 31 refers to the physical area required for the crops to produce this energy. Since some biofuels are by-products of existing crops, their corresponding 'direct' land-use (i.e. the land which needs to be converted from other uses to produce these fuels) may be much lower than the gross land-use presented here. However, in a 100% renewable Denmark, it is likely that all residual resources will be used in the energy system [1] and so, the resources used for the transport sector would represent the gross figures. For example, if 1 PJ of biofuel above the residual resource is necessary, this will then require at least 5000 Ha of additional land whereas the same area of land would enable 100 PJ of electricity from onshore wind turbines. This illustrates the risk associated with prioritising biofuels ahead of electricity for transport based on existing knowledge. Therefore, since the wind resource potential is four times larger than for bioenergy (Figure 31), and the gross land-use required for wind energy is much less than for biofuels (Figure 32), electricity is prioritised as a fuel in the transport sector over biofuels.

This conclusion is further vindicated when comparing the Danish bioenergy resource with the global bioenergy potential. As outlined in Figure 34, on a per capita basis the global bioenergy resource estimated for the rest of the world is less than the bioenergy resource estimated for Denmark in CEESA. If Denmark is going to be part of a 100% renewable energy world, the bioenergy resource may even be less than that identified in CEESA, since other countries may experience shortfalls. Once again, this supports a preference for electricity based transport in the future. Based on these foundations, the scenarios in CEESA are constructed with the prioritisation of electricity in mind.

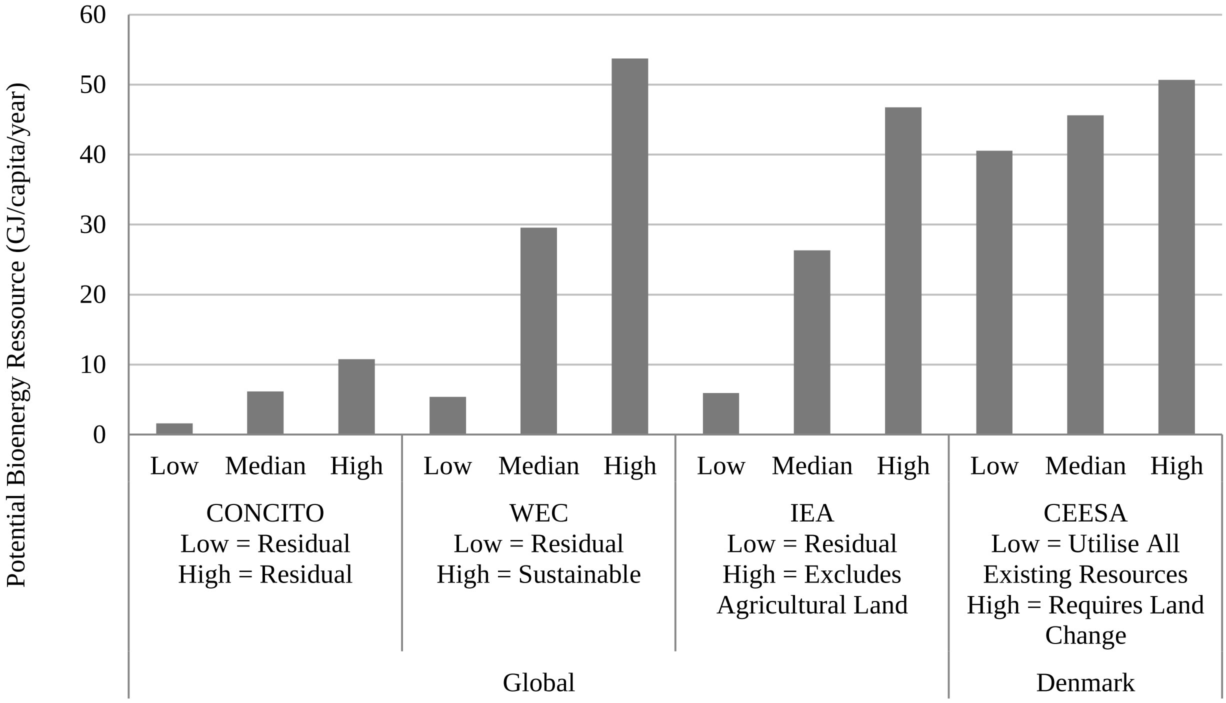

Figure 34: Comparison between the global and Danish [1] **bioenergy resource available for energy production. The global estimates are from CONCITO** [31]**, the World Energy Council** [32]**, and the International Energy Agency** [33]**.**

4.2 Renewable Energy Transport Fuel Pathways

Considering the renewable resources available in Denmark to produce electricity and the limitations associated with bioenergy, maximising the use of electricity and minimising the use of bioenergy in the transport sector is a key consideration in the CEESA project. Overall, five distinct pathways are analysed in detail here (see Table 3): electrification, fermentation, bioenergy hydrogenation (includes biomass and biogas), CO_2 hydrogenation, and co-electrolysis. These pathways are described in detail below along with an overall comparison. A separate energy flow diagram is available for each pathway outlining the electricity and bioenergy required to produce 100 PJ of the primary fuel.

Table 3: Transport fuel pathways considered in CEESA and their principal objective.

Pathway Considered	Principal Objective
Electrification	Use electricity as the primary transport fuel.
Fermentation	Convert straw to a fuel suitable for transport (i.e. ethanol) using a fermenter.
Bioenergy Hydrogenation	Gasify a biomass resource OR use anaerobic digester to produce biogas. Afterwards boost its energy potential as a transport fuel using hydrogen from steam electrolysis.
CO_2 Hydrogenation (CO_2Hydro)	Create a fuel without any direct bioenergy consumption using hydrogen from steam electrolysis and sequestered carbon dioxide.
Co-electrolysis	Create a fuel without any direct bioenergy consumption by co-electrolysing steam and sequestered carbon dioxide.

To create the pathways which lead to a liquid, the final fuel had to be defined in order to identify the conversion losses. It is assumed here that methanol is the preferred **liquid** fuel in a 100% renewable energy system. Methanol is the simplest alcohol with the lowest carbon content and the highest hydrogen content of any liquid fuel [34–36]. Furthermore, methanol can be used in internal combustion engines (ICE) as a replacement for petrol with relatively few modifications [37]. The suggested conversion costs for adaptation of petrol vehicles to methanol flexi-fuel are as low as 700 DKK (€90-260) per vehicle [38]. The use of methanol as a fuel is not a novelty, in the USA approximately 20,000 methanol cars and 100 refuelling stations were in use in the mid-1990s [39]. Today in China there are different methanol blends including M100 available on the market and also development of dedicated vehicles by Chinese automobile manufactures is rising [40]. Interestingly, the use of methanol as a marine fuel is in full swing in Sweden, where a ferry on methanol is going to be tested [41]. It is worth noting though that dimethyl ether (DME) could also be used since it is the first derivative of methanol and it is very suitable as an alternative to conventional diesel [42]. The efficiency lost when comparing DME to methanol can be gained due to the higher efficiencies of diesel engines compared to petrol engines. Therefore, the transport demands which are displayed in the flow diagrams are similar for both methanol and DME from a well-to-wheel perspective.

It is assumed that methanol/DME can be used directly in all modes of transport except aviation. At present, it is unclear how aviation fuel will be developed in the future, particularly due to the very specific criteria necessary for an adequate jet fuel. As outlined in detail in Appendix F, these requirements include a high specific energy requirement, rapid evaporation, low viscosity, low explosion risk, and good thermal stability. After assessing three different fuel options for aviation in Appendix F (i.e. hydrogen, alcohols, and electrofuels), it was concluded that electrofuels have the highest potential to be implemented in the future aviation systems because the changes needed in infrastructure and technologies are insignificant. In Appendix F, the term “synthetic fuels” refers to fuels which are produced by the combination of CO_2 (from sources such as biomass, carbon capture, and ambient air) and hydrogen. This is the same method used in the pathways below to create methanol/DME. Therefore, it is assumed that jet fuel can be produced from the methanol/DME produced in the pathways described in this section (i.e. by refining the methanol/DME fuel [43]). Although bio [44] and synthetic [45,46] based aviation fuel has already been demonstrated in jet engines, it was not possible in CEESA to identify the exact losses that occur when aviation fuel is created instead of methanol/DME. However, to account for this, a proxy of 20% is assumed for the additional losses when refining methanol/DME into jet fuel based on discussions within the expert group meetings.

For some of the pathways, a separate methane pathway is also considered, since **gas** based transport is often proposed as an alternative renewable energy in the future [47,48]. Furthermore, natural gas based vehicles are already well-established, with over 10 million vehicles, 250 models, and 50 manufacturers worldwide [49,50]. It is important to emphasise here that the 'optimum' choice of electrofuel is not defined in this study, but instead the impact of large amounts of electrofuels is quantified by implementing one potential electrofuel. Therefore, methane is only included here to establish the scale of the difference between a 'liquid' and 'gas' based transport system rather than to define the optimum type of electrofuel. This should be investigated in more detail in future research.

For all fuels, a passenger transport demand (pkm) and a freight transport demand (tkm) are displayed, since it can be used for either in all cases except one (i.e. battery electrification). The specific energy consumptions (see Table 4) used to estimate the transport demands are average fleet efficiencies from the 2010 *reference model* (described in section 3 and Appendix B) and vehicle efficiencies by the Danish Energy Agency [26]. By assessing the energy losses from production to consumption, it is then possible to compare each of the pathways in terms of the resources they require and the transport demand they meet. The following sections describe each pathway individually and afterwards, these are compared to one another.

Table 4: Specific energy consumptions used to estimate the transport demand which can be met from the transport fuels produced, which is based on data from the 2010 reference and vehicle efficiency estimates by the Danish Energy Agency [26]**.**

	Passenger Transport		Freight Transport	
Fuel	Load Factor (p/vehicle)	Specific Energy Consumption (MJ/pkm)	Load Factor (t/vehicle)	Specific Energy Consumption (MJ/tkm)
Electric Rail	84	0.34	278	0.31
Electric Car	1.5	0.32	n/a	n/a
Methanol/DME	1.5	1.15	12	1.9
Methane	1.5	1.57	12	2.65
Ethanol	1.5	1.5	12	3.3

4.2.1 Electrification

Electricity can be used as a direct transport fuel in two ways: by delivering it to the end-user or by using batteries as a storage medium. To date, rail and buses (i.e. trolleybuses) are the only forms of transport where electricity is delivered directly to the end user. The key limitation is the infrastructure required since a cable must be available to the end user at all times. This requires high initial investment costs and also restricts the routes feasible. However, once the infrastructure is in place, due to the high efficiency of rail a relatively large transport demand of 300 Gpkm or 325 Gtkm can be met when 100 PJ of electricity is available (see Figure 35).

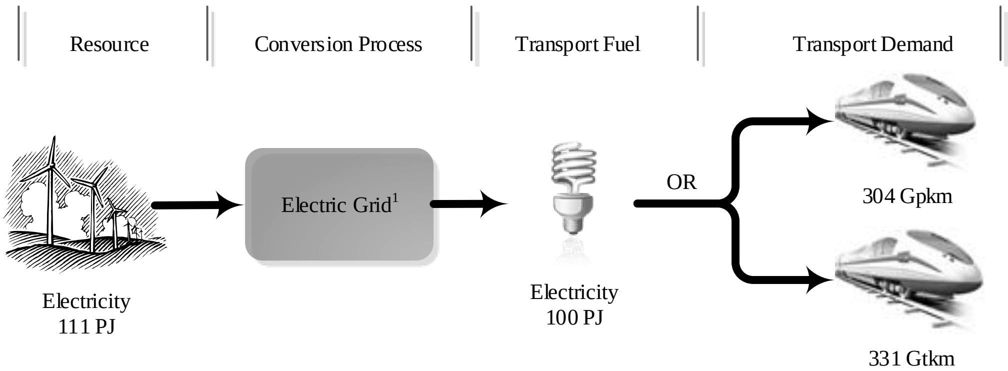

Figure 35: Direct use of electricity by the end-user for transport. [1]Assuming 10% losses for the electric grid [17] **.**

To increase the route flexibility of electrification, batteries can be used. Several electrical and hybrid electrical vehicle technologies are already commercially available today [11]. It thus seems to be realistic to implement these technologies in the near future from a technical point of view. As outlined in Figure 36, this is also a very efficient pathway. However, batteries come with a number of key limitations, particularly their energy density.

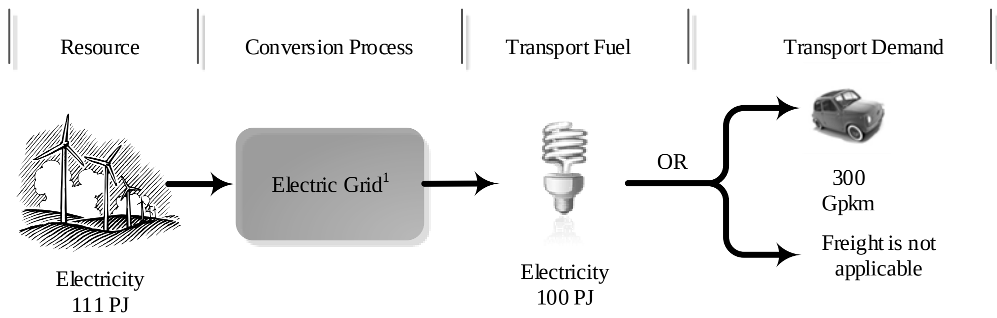

Figure 36: Direct use of electricity for transport using battery storage. [1]Assuming 10% losses for the electric grid [17]**.**

In comparison to liquid fuels, batteries can store very little energy relative to their weight. For example, Figure 37 indicates that the energy densities for conventional fossil fuels are approximately 85 times larger and for biofuels approximately 40-70 times larger compared to the lithium-ion battery (which is the battery of choice for many electric vehicles [11]). This can be reduced when the higher efficiency of electric vehicles is taken into account (see the weight efficiency in Figure 37), but the difference is still extreme: all biofuels and fossil fuels have a weight efficiency of at least >1000% more than lithium-ion batteries. Therefore, even though batteries create more flexibility in terms of the routes and modes of transport that can be electrified, it is still considerably restricted by the energy density limitations of the battery. In addition, as part of this work, a number of detailed, generic and transparent analyses of current state-of-the-art battery electrical vehicles have been conducted under realistic conditions (Appendix E). Such analyses show that the present technology has challenges to overcome before it can meet the general expectations as presented in most literature. Consequently, it should be stressed that the present technology needs further development in order to be able to fulfil the preconditions behind the future scenarios. Direct electrification is thus not suitable for all modes of transport such as trucks, aviation, and marine transport. In a 100% renewable energy system, some form of high energy-density fuel (such as methanol) will also be necessary to supplement direct electrification and so, a variety of liquid and gaseous fuel pathways are also developed in CEESA.

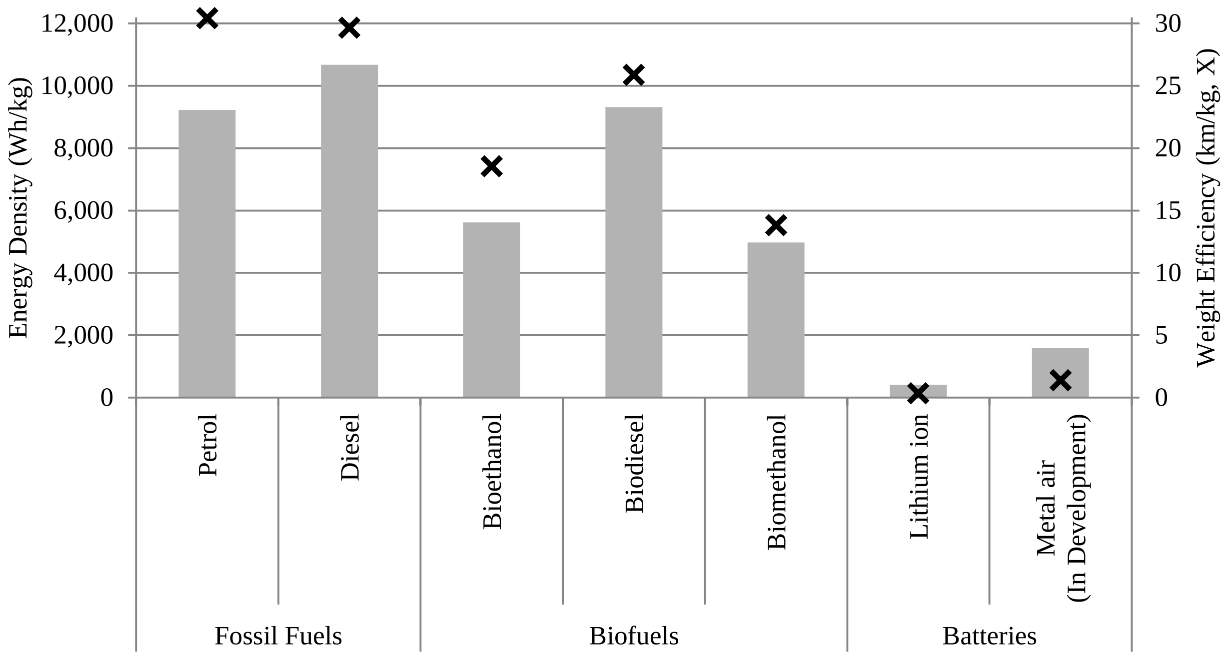

Figure 37: Energy density and weight efficiency for a selection of fossil fuels, biofuels, and batteries [51,52]**. It is assumed that petrol and bioethanol cars have an efficiency of 1.9 MJ/km, for diesel, biodiesel, and bio-methanol it is assumed to be 1.6 MJ/km, while electric vehicles have an efficiency of 0.5 MJ/km.**

4.2.2 Fermentation

The principal objective in the fermentation pathway is to convert straw to ethanol by use of a fermenter. Even though this process itself is only approximately 25% efficient as only the cellulose is fermented, there are a number of by-products produced from hemicellulose and lignin which can subsequently be used to create other fuels. Since there are a variety of options available, two distinct pathways are presented here.

The first fermentation pathway in Figure 38 is the 'fuel optimised' option, since it is designed to create the maximum amount of useful fuel with the minimum input. For example, in this pathway the lignin and residual sugars from the fermenter are hydrogenated to create an 'oil slurry' which is well suited as a fuel for marine diesels. In addition, the C5 sugars can be converted to conventional diesel and so they can be used for trucks. From the hydrogenation process, there are also by-products of coke and inorganic materials, which can be utilised in a number of ways such as:

- Gasified and hydrogenated to produce more fuel such as methanol/DME (as in Figure 38).
- Burned in a power plant to produce electricity.

At present it is unclear which option would be most suitable in a 100% renewable energy system. However, since the supply of fuel will be a key limitation for the transport sector in the future, it is assumed here that the coke and inorganics are used to create methanol/DME. Due to the very high salt content in this by-product and its technological immaturity, the gasification should be approached with caution. No figures are available for the conversion losses that occur when coke and inorganics are gasified and hydrogenated and so, it is assumed that the losses are equivalent to those for wood gasification (see section 4.2.3), which is an optimistic assumption. The CO_2 emitted from the fermenter can also be hydrogenated to create additional fuel such as methanol/DME. It is assumed that the CO_2 is exhausted from the fermenter without any notable energy penalty. The reaction and conversion losses assumed are discussed in section 4.2.4.

The second fermentation pathway in Figure 39 is the ‘energy optimised’ option, since it is designed to maximise the energy available in the fuels created. In this process, the CO_2 from the fermenter is hydrogenated in the same way as in the ‘fuel optimised’ process in Figure 38. However, the lignin and residual sugars are gasified instead of being hydrogenated. Due to the high salt content present in all agricultural residues, it is assumed here that this will require both a low and high temperature gasifier. Once again, the losses associated with wood gasification are assumed for both the low and high temperature gasifiers, which are optimistic assumptions (see section 4.2.3) [31]. After gasification, the gas is hydrogenated to produce syngas which can be converted to methanol/DME using chemical synthesis. The final energy flows for the energy-optimised fermentation process are displayed in Figure 39.

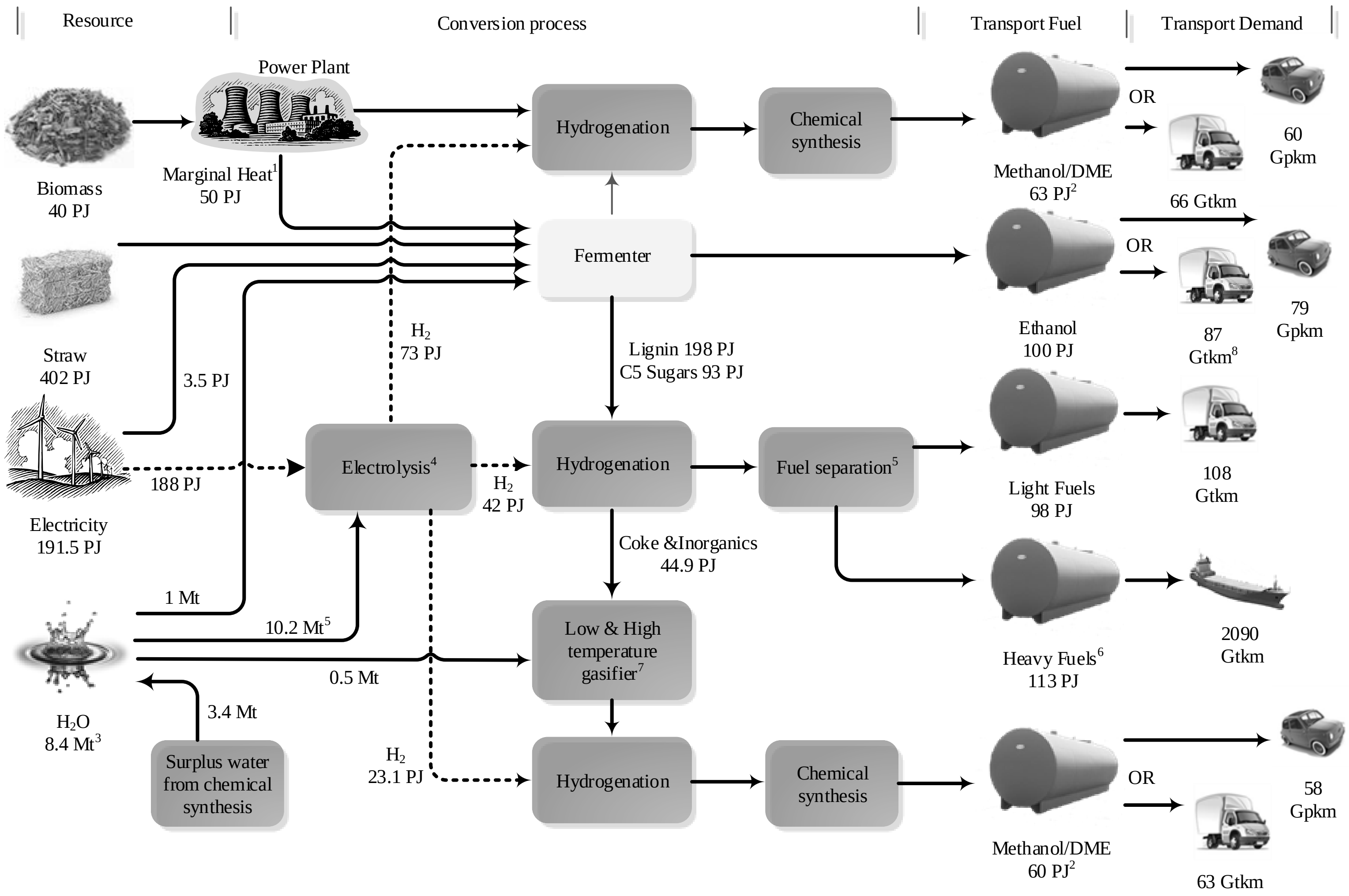

Figure 38: Fuel optimised fermentation pathway with gasified by-products. [1]Assuming a marginal efficiency of 125% and a steam share of 12.5% relative to the straw input. [2]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage. [3]This is the net demand for water i.e. it is reduced by the water recycled from chemical synthesis. [4]Assuming an electrolyser efficiency of 73% for the steam electrolysis [16]. **[5]The specific techniques used for fuel separation are confidential. [6]Heavy fuels are suitable for ships and it is unlikely they will be further refined due to the associated losses. [7]Assuming the same conversion process and losses as for cellulous gasification** [31]. **[8]Asumed that ethanol trucks require approximately 25% more fuel than the diesel equivalents based on the difference between ethanol and diesel cars. The abbreviation Mt here refers to million metric tons.**

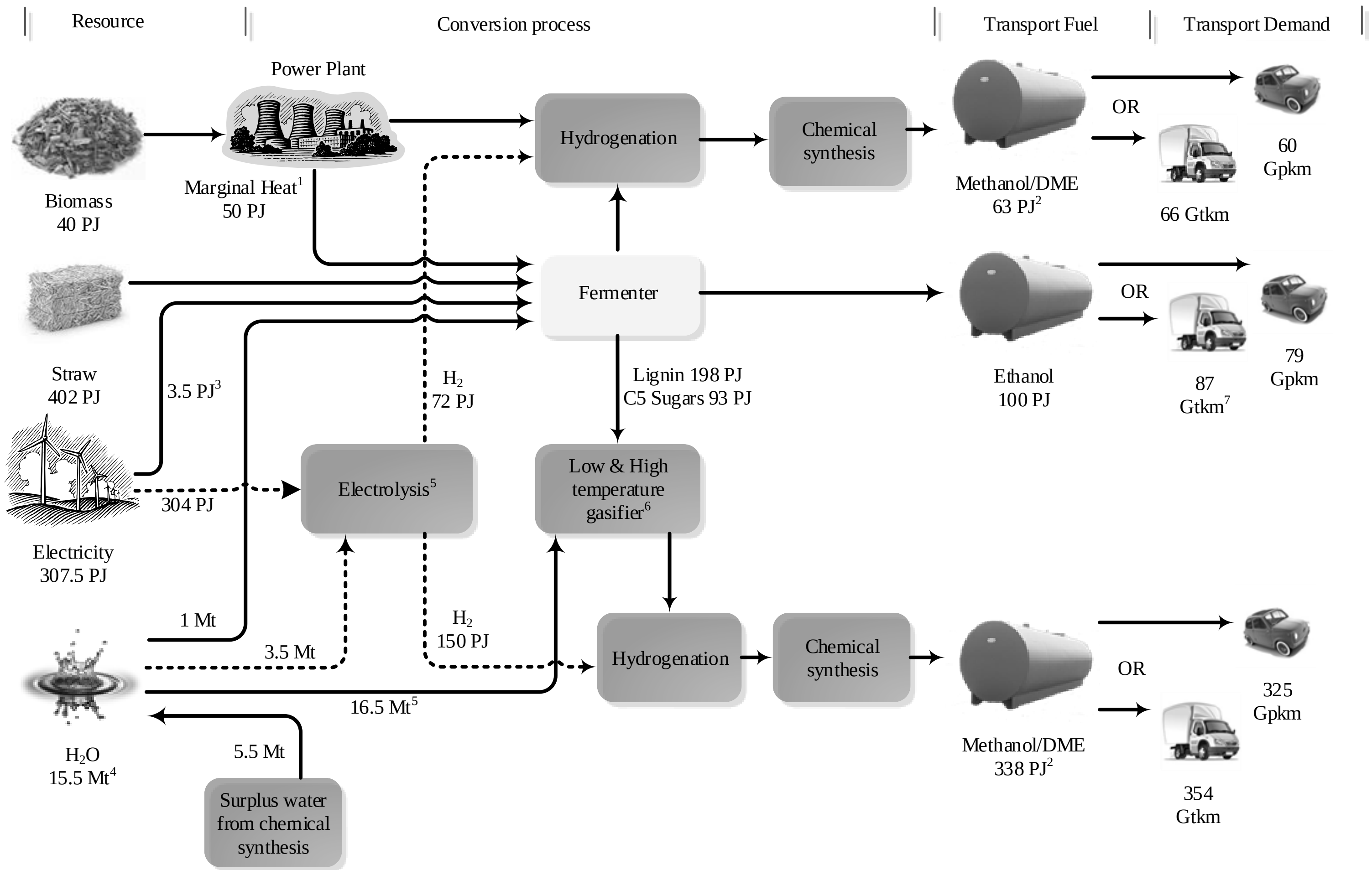

Figure 39: Energy optimised fermentation pathway. [1]Assuming a marginal efficiency of 125% and a steam share of 12.5% relative to the straw input. [2]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage. [3]Assuming an electricity demand of 0.8% relative to the straw input. [4]This is the net demand for water i.e. it is reduced by the water recycled from hydrogenation. [5]Assuming an electrolyser efficiency of 73% for the steam electrolysis [16]. **[6]Assuming the same conversion process as for cellulous gasification and hydrogenation to methanol, but the round-trip losses have been doubled since there are two gasifiers here (low and high temperature) and there is uncertainty in relation to the gasification of lignin and C5 sugars** [31]. **[7]Asumed that ethanol trucks require approximately 25% more fuel than diesel equivalents, based on the difference between ethanol and diesel cars. The abbreviation Mt here refers to million metric tons.**

4.2.3 Bioenergy Hydrogenation

The principal objective in the bioenergy hydrogenation pathway is to create a transport fuel from bioenergy, which is boosted by hydrogen from steam electrolysis. In this way, the energy potential of the bioenergy resource is maximised. Here, three different bioenergy pathways have been considered:

- Biomass hydrogenation to methanol
- Biomass hydrogenation to methane
- Biogas hydrogenation to methane

A variety of biomass feed stocks can be used in this process: wood gasification is already being commercialised on a large scale [5] while the gasification of biomass from energy crops and straw is currently at the demonstration phase [53,54]. As outlined in Figure 40, once biomass is gasified, it is then hydrogenated using hydrogen from steam electrolysis. Hydrogenating the biomass increases the energy content and the energy density of the original biomass, thus reducing the need for biomass [31]. The resulting syngas is then transformed into a transport fuel using chemical synthesis, which is already a well-established technique by the fossil fuel industry for converting coal [45] and natural gas [55] to liquid fuels.

In this study, the energy and mass balance assumed for biomass hydrogenation is based on the hydrogenation of cellulous to both methanol and methane. The resulting energy flow diagrams are outlined in Figure 40 and Figure 41 respectively. In practice, additional conversion procedures could also be necessary for biomass gasification, since there is a wide variety of different technologies which can be utilised [3]. For example oxygen could be used to gasify the biomass [56] and it is also assumed here that all of the carbon is utilised in the reaction, so if this is not possible in practice further losses may occur. However, the overall demand for biomass and hydrogen per unit of methanol produced is indicative of those necessary if the pathway is utilised in the future.

Energy and mass balance for biomass hydrogenation to methanol

$C_6(H_2O)_5$	+	$6H_2$	+	H_2O	$\longrightarrow$	$6CH_3OH$
Biomass (Cellulous)		Hydrogen		Water		Methanol
2823 kJ		1452 kJ		0 kJ		3778 kJ
162 g		12 g		18 g		192 g

Energy and mass balance for biomass hydrogenation to methane

$C_6(H_2O)_5$	+	$12H_2$	$\longrightarrow$	$6CH_4$	+	$5H_2O$
Biomass (Cellulous)		Hydrogen		Methane		Water
2823 kJ		2904 kJ		kJ		0 kJ
162g		24g		96g		90g

Biogas hydrogenation is also included here based on two reactions: firstly the gasification of glucose which occurs in an anaerobic digester, followed by the hydrogenation of the resulting CO_2. When glucose is gasified, it results in a gas which contains approximately 50% methane and 50% CO_2 by volume, as outlined in the stoichiometric equation below. In practise the mix is usually 55-70% methane, 30-45% CO_2, and 1-2% of other elements [57,58], since the feedstock is never pure glucose. Hence, the estimates here assume a slightly higher CO_2 output than typically obtained from anaerobic digesters. Since methane is typically the major component in the biogas from the anaerobic digester, the CO_2 contained in the biogas is hydrogenated to methane. The resulting flow diagram for biogas hydrogenation is presented in Figure 42.

Energy and mass balance for biogas hydrogenation to methane

$C_6H_{12}O_6$	$\longrightarrow$	$3CO_2$	+	$3CH_4$	+	(+ NH_3 + H_2S)
Biomass (Glucose)		Carbon Dioxide		Methane		Contaminants
2882 kJ		0 kJ		kJ		0 kJ
180 g		132 g		48 g		

$3CO_2$	+	$12H_2$	$\longrightarrow$	$3CH_4$	+	$6H_2O$
Carbon Dioxide		Hydrogen		Methane		Water
0 kJ		2904 kJ		kJ		0 kJ
132 g		24 g		48 g		108 g

It is possible to convert the resulting methane to methanol by reforming it to a synthetic gas and then synthesising the synthetic gas to methanol using a high pressure. The reforming step is a very energy intensive process since it is a strongly endothermic reaction and needs a large external energy supply [59]. Although there are variations in the efficiencies reported, they are all within a range of approximately 70-80% [60]. The second phase of converting from syngas to methanol is negligible, since it only requires a suitable catalyst. However, overall approximately 20-30% of the fuel is lost during the transition from methane to methanol and hence this has not been included in the analysis here.

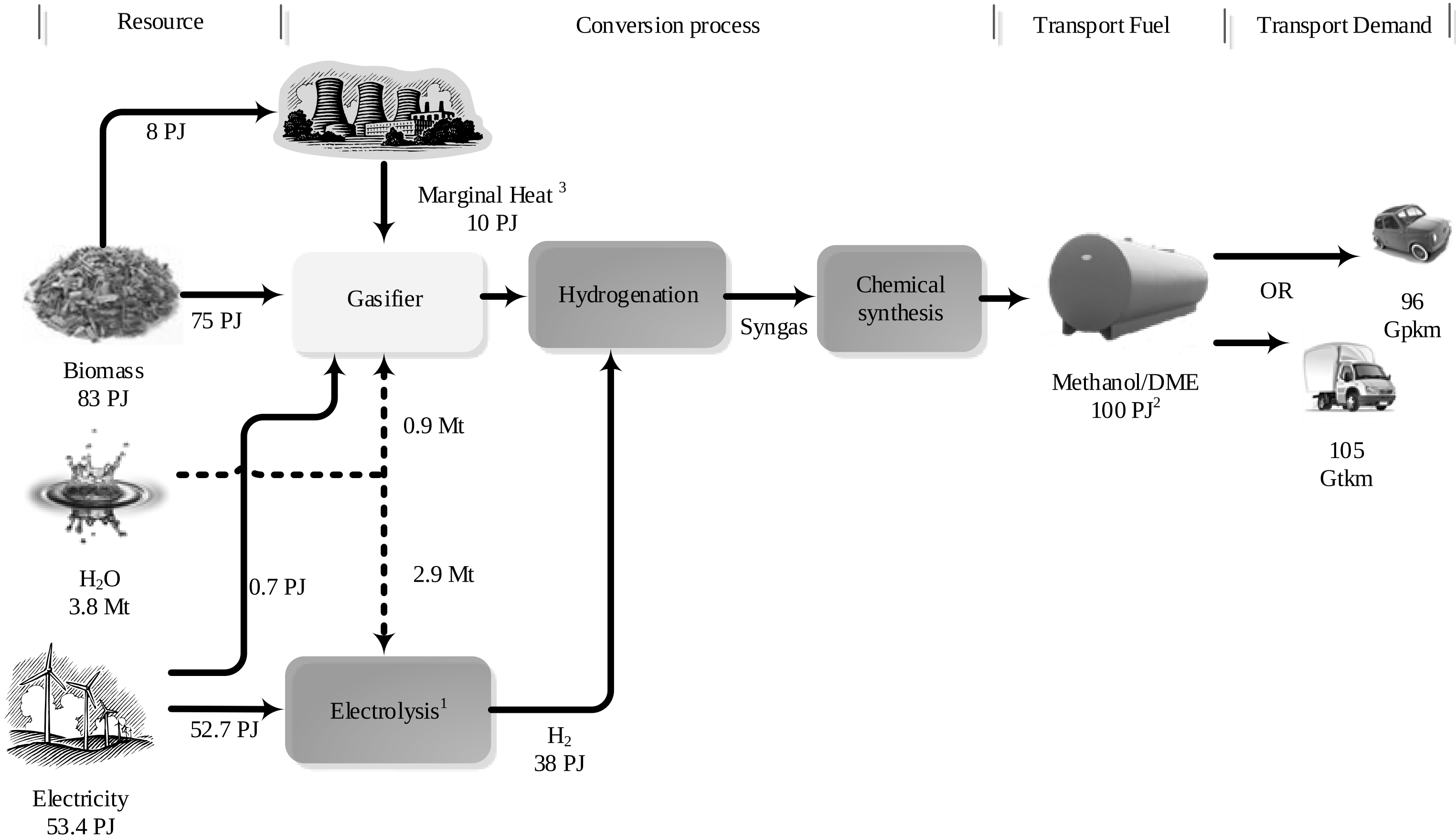

Figure 40: Steam gasification of biomass which is subsequently hydrogenated. [1]Assumed an electrolyser efficiency of 73% for the steam electrolysis [16]. **[2]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. [3]Assuming a marginal efficiency of 125% and a steam share of 13% relative to the biomass input. The abbreviation Mt here refers to million metric tons.**

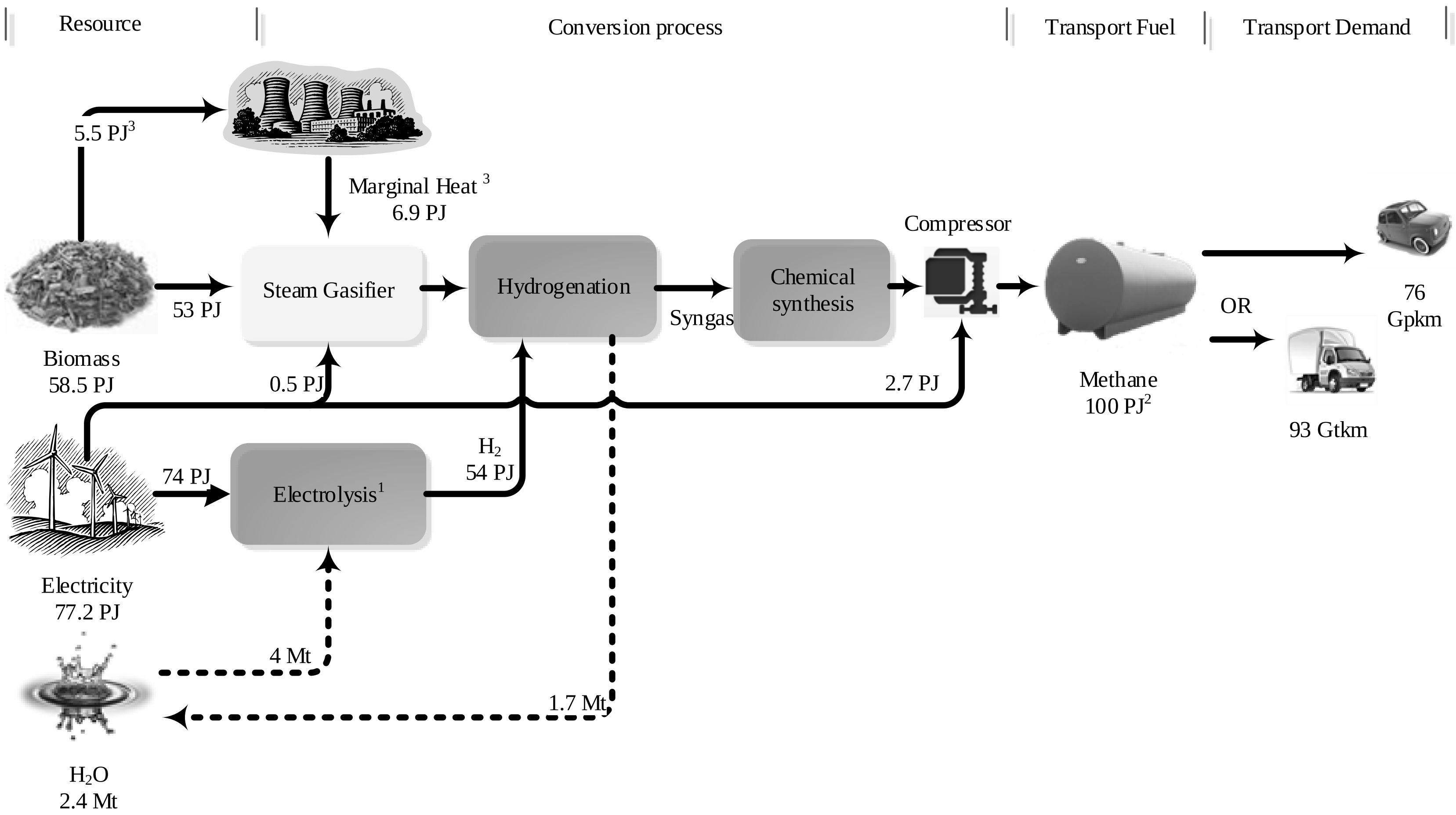

Figure 41: Steam gasification of biomass which is subsequently hydrogenated to methane. [1]Assumed an electrolyser efficiency of 73% for the steam electrolysis [16] **. [2]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. [3]Assuming a marginal efficiency of 125% and a steam share of 13% relative to the biomass input. The abbreviation Mt here refers to million metric tons.**

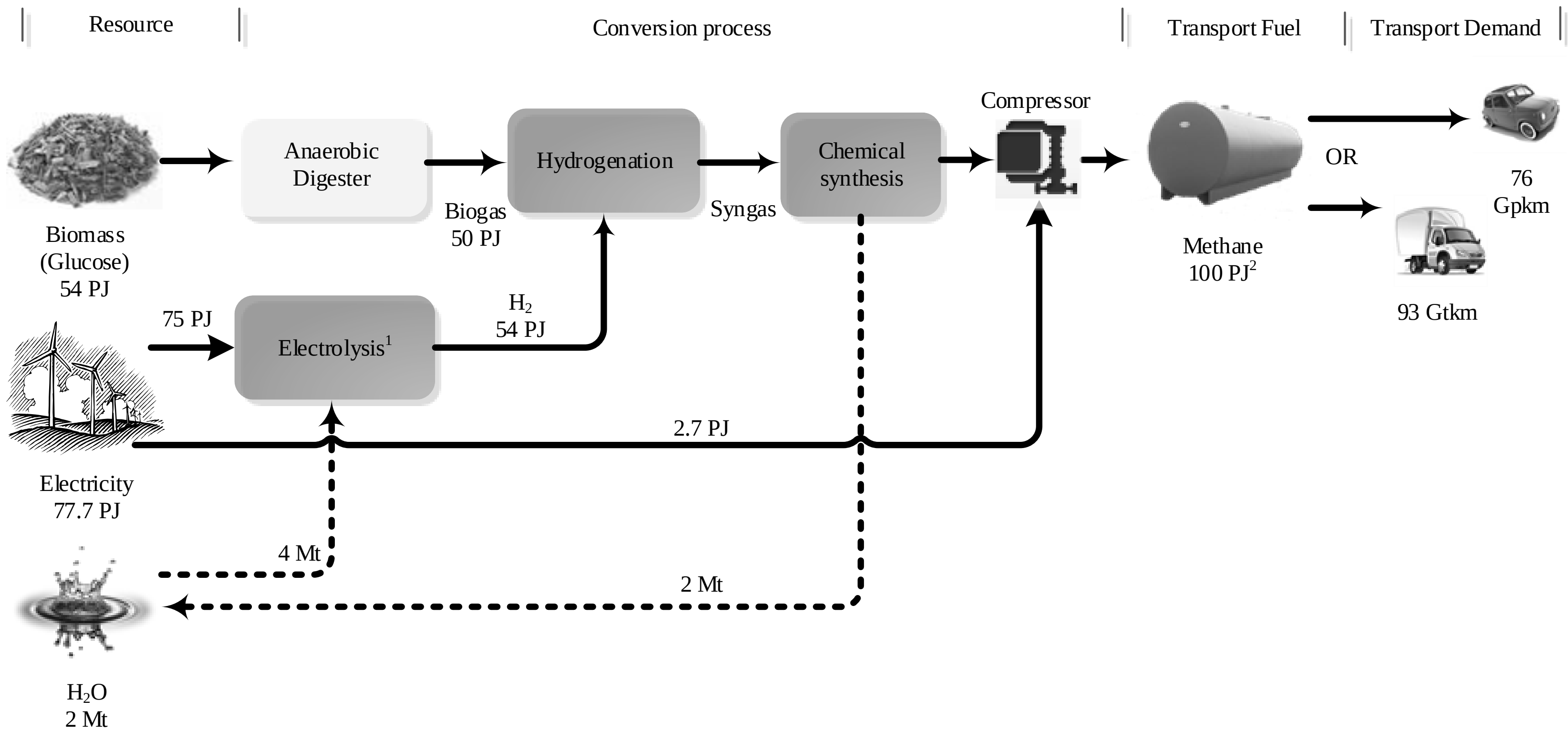

Figure 42: Production of biogas from biomass which is subsequently hydrogenated to produce methane. [1]Assumed an electrolyser efficiency of 73% for the steam electrolysis [16]. **[2]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

4.2.4 CO_2 Hydrogenation

The CO_2 hydrogenation (CO_2Hydro) pathways considered here combine carbon dioxide and hydrogen gases together, followed by chemical synthesis to produce a fuel for transportation. The principal objective in these pathways is to create a fuel which does not require any direct biomass input by using steam electrolysis and sequestered carbon dioxide. Separate pathways are included for methanol/DME and methane based on these energy and mass balances:

Energy and mass balance for CO_2 hydrogenation to methanol

CO_2	+	$3H_2$	$\longrightarrow$	CH_3OH	+	H_2O
Carbon Dioxide		Hydrogen		Methanol		Water
0 kJ		726 kJ		630 kJ		0 kJ
44 g		6 g		32 g		18 g

Energy and mass balance for CO_2 hydrogenation to methane

CO_2	+	$4H_2$	$\longrightarrow$	CH_4	+	$2H_2O$
Carbon Dioxide		Hydrogen		Methane		Water
0 kJ		968 kJ		kJ		0 kJ
44 g		8 g		16 g		36 g

The hydrogen can be produced by steam electrolysis, which requires electricity and water. There is currently a CO_2Hydro to methane demonstration plant being developed in Germany [61]. To collect the carbon dioxide, two primary options are considered in CEESA: carbon capture and recycling (CCR) from biomass power plants [62] and carbon trees [63]. Therefore, in total four pathways are considered here:

- CO_2 hydrogenation to methanol/DME using CCR (Figure 43)
- CO_2 hydrogenation to methanol/DME using carbon trees (Figure 44)
- CO_2 hydrogenation to methane using CCR (Figure 45)
- CO_2 hydrogenation to methane using carbon trees (Figure 46)

According to the latest research [62,63], there is only a 5% difference in the electricity demand required to sequester the carbon dioxide in these two pathways. The key difference is that carbon trees do not require any combustible fuel in the energy system. However, since biomass is already used in the power plants in CEESA [1], these two pathways are almost identical from in terms of energy consumption. The only key difference between the two carbon sequestration options is the cost: currently, the estimated cost for CCR is approximately 225 DKK/tCO_2 (i.e. €30/tCO_2) [62] while for carbon trees it is approximately 1120 DKK/tCO_2 (i.e. \$200/tCO_2) [63].

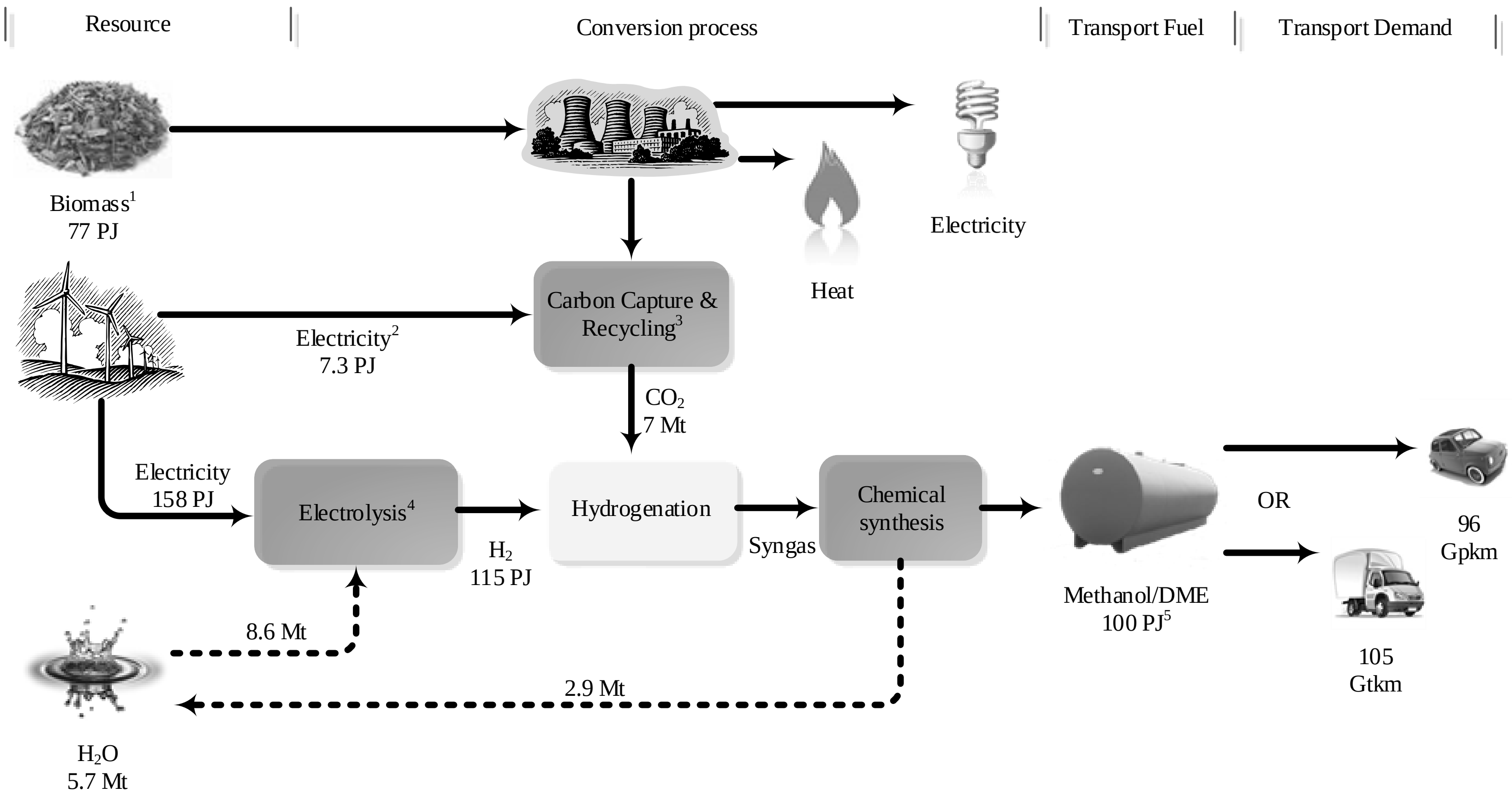

Figure 43: Hydrogenation of carbon dioxide sequestered using CCR to methanol/DME. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO_2 for capturing carbon dioxide from coal power plants [64]**. [3]Carbon capture & recycling (CCR) is used in CEESA since it is currently a cheaper alternative to carbon trees** [62,63]**. If carbon trees were used here, they would require approximately 5% more electricity** [63]**. [4]Assuming an electrolyser efficiency of 73% for the steam electrolysis** [16]**. [5]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

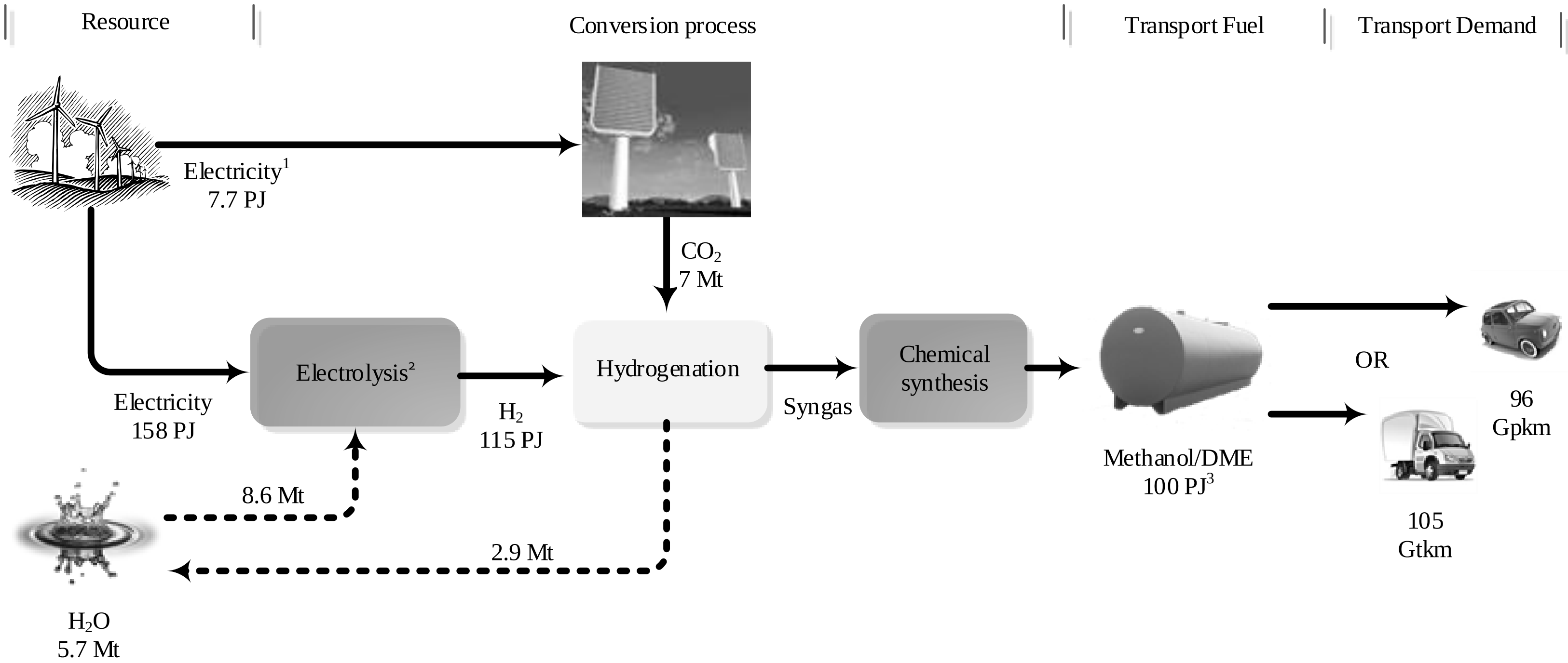

Figure 44: Hydrogenation of carbon dioxide sequestered using carbon trees to methane. [1]Based on an additional electricity demand of 1.1 MJ/tCO_2 for capturing carbon dioxide using carbon trees [63]. [2]Assuming an electrolyser efficiency of 73% for the steam electrolysis [16]. [3]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.

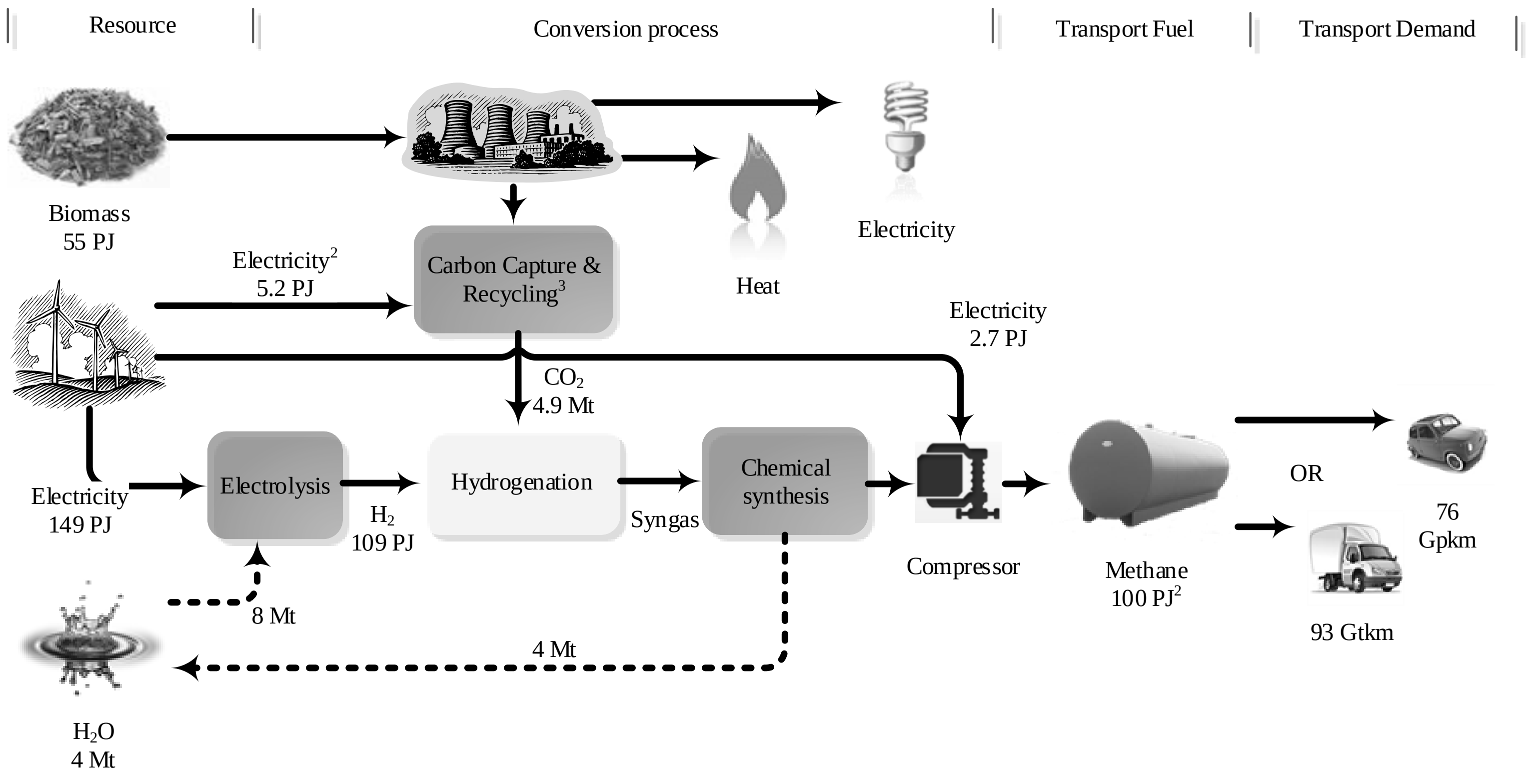

Figure 45: Hydrogenation of carbon dioxide sequestered using CCR to methane. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO$_2$ for capturing carbon dioxide from coal power plants [64]. **[3]Carbon capture & recycling (CCR) is used in CEESA since it is currently a cheaper alternative to carbon trees** [62,63]. **If carbon trees were used here, they would require approximately 5% more electricity** [63]. **[4]Assuming an electrolyser efficiency of 73% for the steam electrolysis** [16]. **[5]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

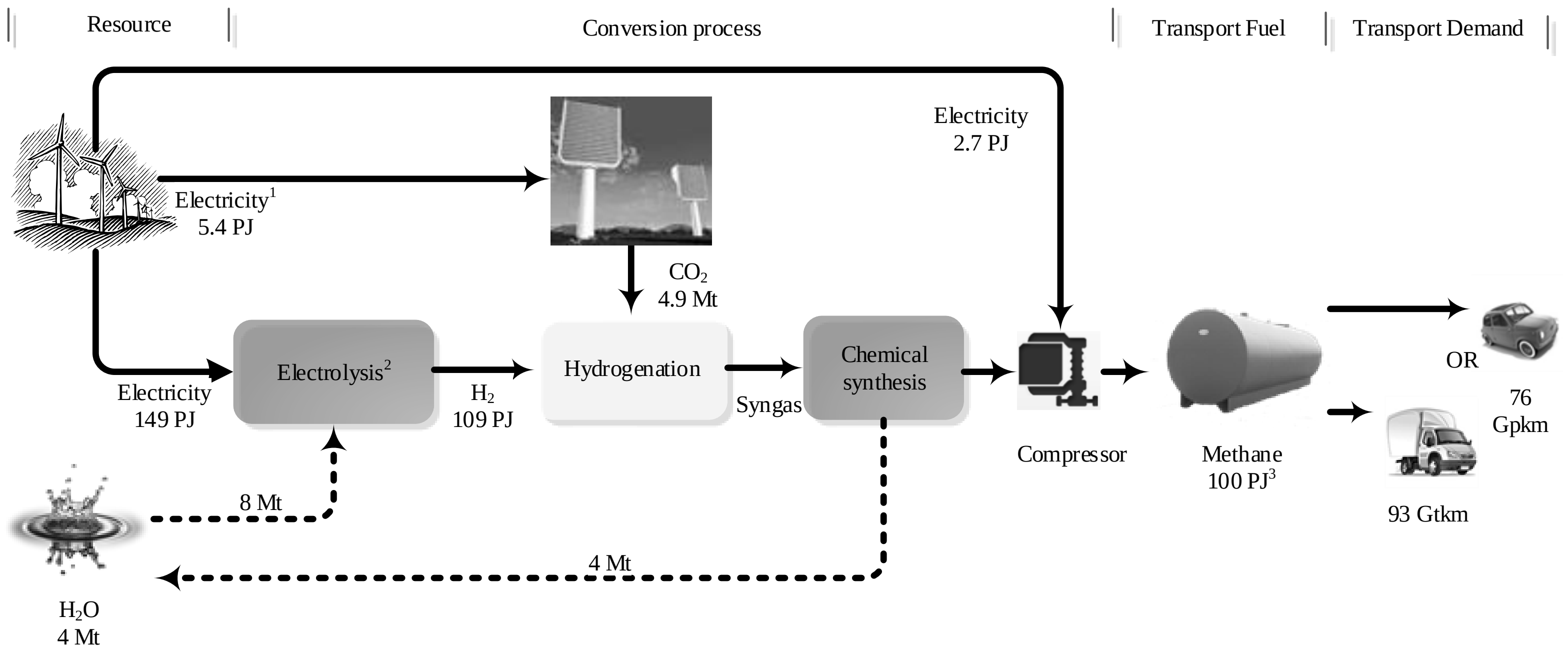

Figure 46: Hydrogenation of carbon dioxide sequestered using carbon trees to methane. [1]Based on an additional electricity demand of 1.1 MJ/tCO_2 for capturing carbon dioxide using carbon trees [63]**. [2]Assuming an electrolyser efficiency of 73% for the steam electrolysis** [16]**. [3]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

4.2.5 Co-electrolysis

The co-electrolysis pathways are quite similar to the CO_2Hydro pathways since the principal objective is to create a fuel which does not require any direct bioenergy input. However, instead of using carbon dioxide, this pathway combines hydrogen with carbon monoxide gas followed by chemical synthesis to produce either methanol/DME or methane. To do so, steam and carbon dioxide are both broken down at the same time in one electrolyser unit and hence the name co-electrolysis. The energy and mass balances for the pathways considered here are:

Energy and mass balance for co-electrolysis to methanol

$4H_2O$	+	$2CO_2$	→	$4H_2$	+	$2CO$	+	$(3O_2)$	→	$2CH_3OH$	+	$(3O_2)$
Water		Carbon Dioxide		Hydrogen		Carbon Monoxide		Oxygen		Methanol		
				968 kJ		kJ				1259 kJ		
72g		88g		8g		56g		96 g		64g		96 g

Energy and mass balance for co-electrolysis to methane

$3H_2O$	+	CO_2	→	$3H_2$	+	CO	+	$(2O_2)$	→	CH_4	+	H_2O	+	$(2O_2)$
Water		Carbon Dioxide		Hydrogen		Carbon Monoxide		Oxygen		Methane		Water		Oxygen
				726 kJ		kJ				kJ				
54 g		44 g		6 g		28 g		64 g		16 g		18 g		64 g

Like the CO_2Hydro pathway, the carbon dioxide can be obtained using either CCR or carbon trees, so again there are four pathways in total here:

- Co-electrolysis to methanol/DME using CCR (Figure 47)
- Co-electrolysis to methanol/DME using carbon trees (Figure 48)
- Co-electrolysis to methane using CCR (Figure 49)
- Co-electrolysis to methane using carbon trees (Figure 50)

Once again, since biomass is being utilised in the electricity and heat sectors already in CEESA, the key difference between these two forms of carbon sequestration is the cost. In comparison to the CO_2Hydro pathway, co-electrolysis requires a lower water input than, but there is no excess water from the reaction. Hence, the net water demand is the same for both pathways.

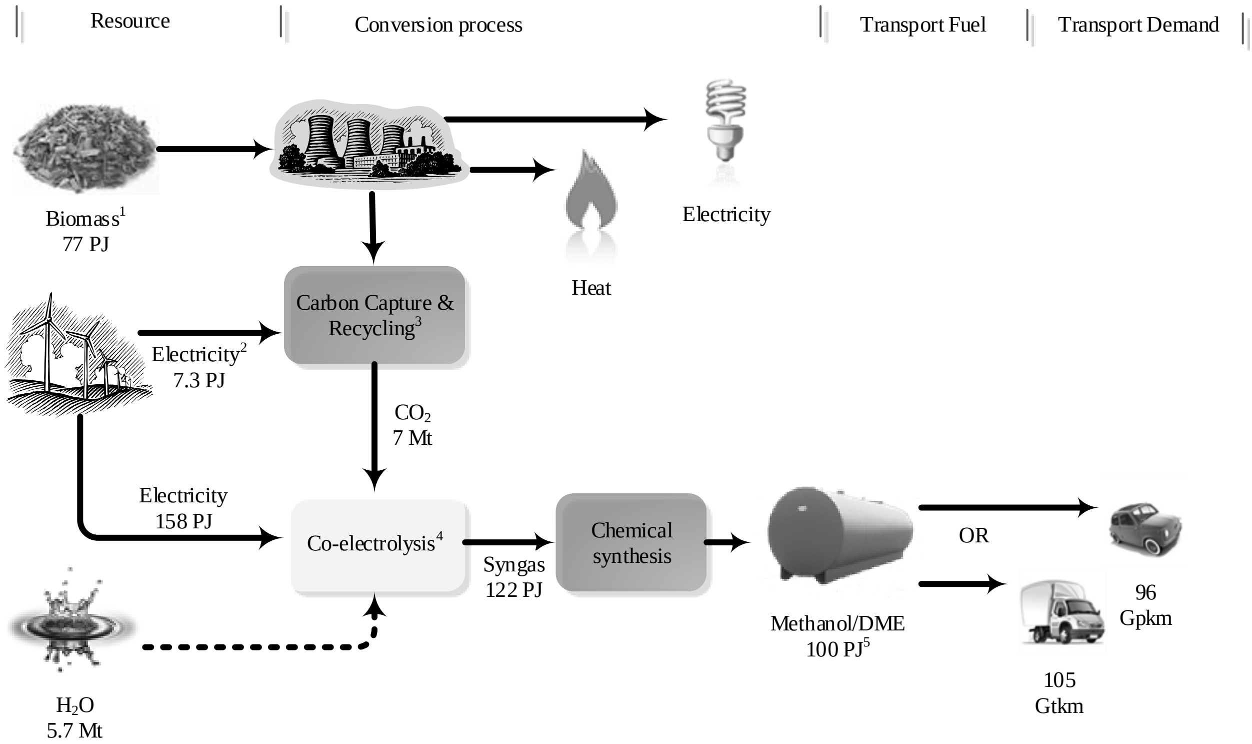

Figure 47: Co-electrolysis of steam and carbon dioxide which is obtained using CCR to methanol/DME. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO_2 for capturing carbon dioxide from coal power plants [64]. **[3]Carbon capture & recycling (CCR) is used in CEESA since it is currently a cheaper alternative to carbon trees** [62,63]. **If carbon trees were used here, they would require approximately 5% more electricity** [63]. **[4]Assuming a co-electrolyser an efficiency of 78%: 73% for steam and 86% for carbon dioxide** [16]. **[5]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

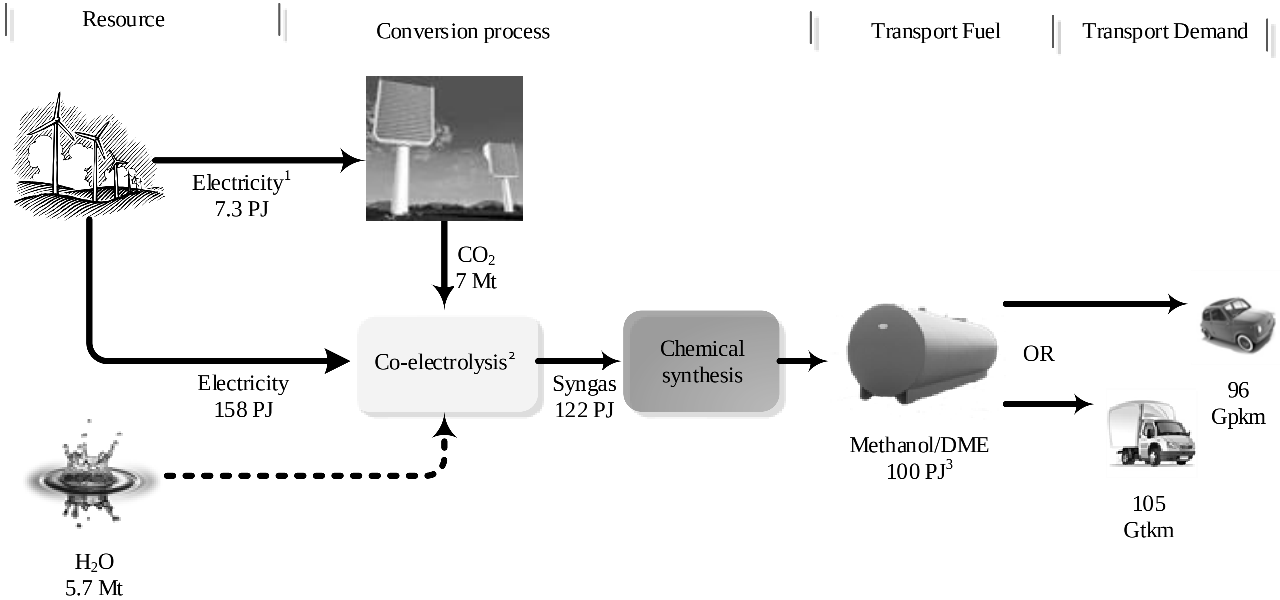

Figure 48: Co-electrolysis of steam and carbon dioxide which is obtained using carbon trees to methanol/DME. [1]Based on an additional electricity demand of 1.1 MJ/tCO_2 for capturing carbon dioxide using carbon trees [63]**. [2]Assuming a co-electrolyser an efficiency of 78%: 73% for steam and 86% for carbon dioxide** [16] **. [3]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

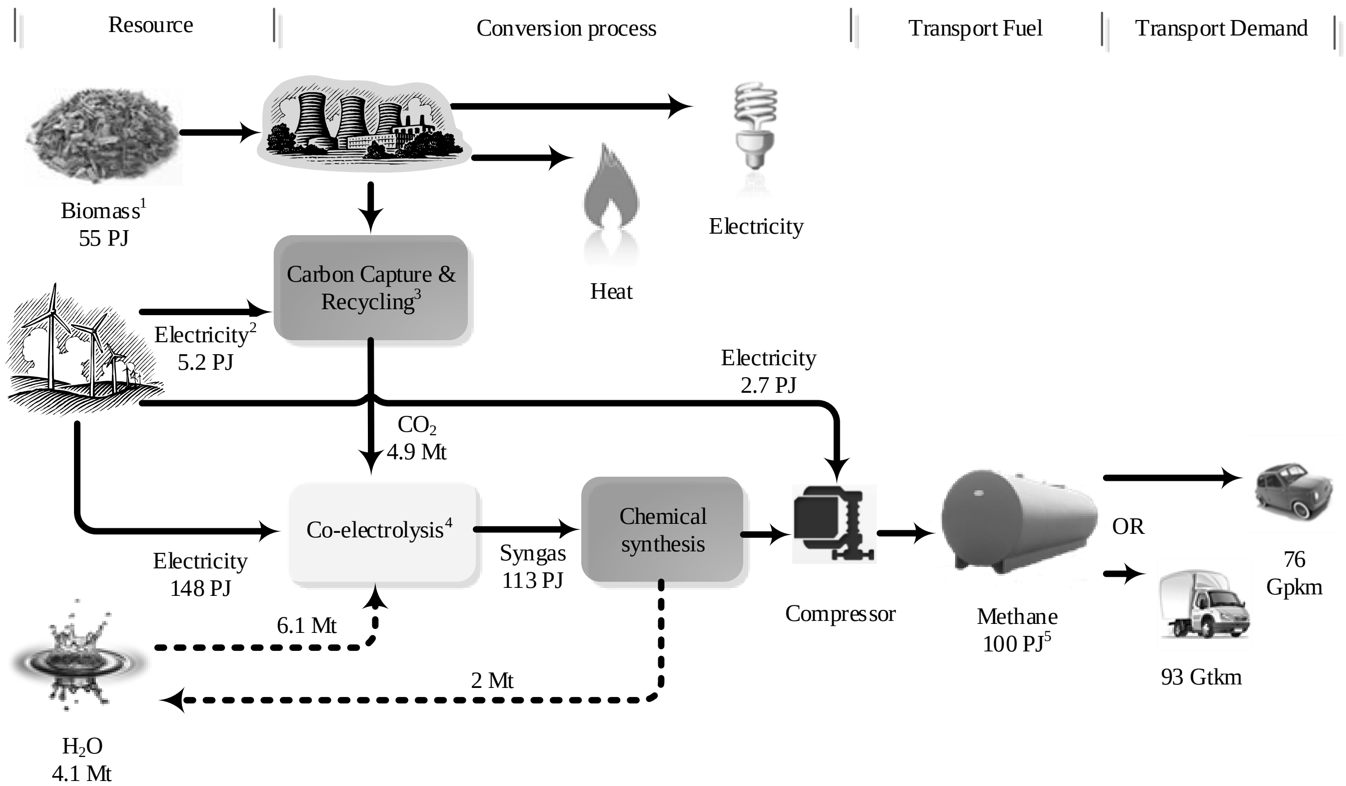

Figure 49: Co-electrolysis of steam and carbon dioxide which is obtained using CCR to methane. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO_2 for capturing carbon dioxide from coal power plants [64]. **[3]Carbon capture & recycling (CCR) is used in CEESA since it is currently a cheaper alternative to carbon trees** [62,63]. **If carbon trees were used here, they would require approximately 5% more electricity** [63]. **[4]Assuming a co-electrolyser efficiency of 78%: 73% for steam and 86% for carbon dioxide** [16]. **[5]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

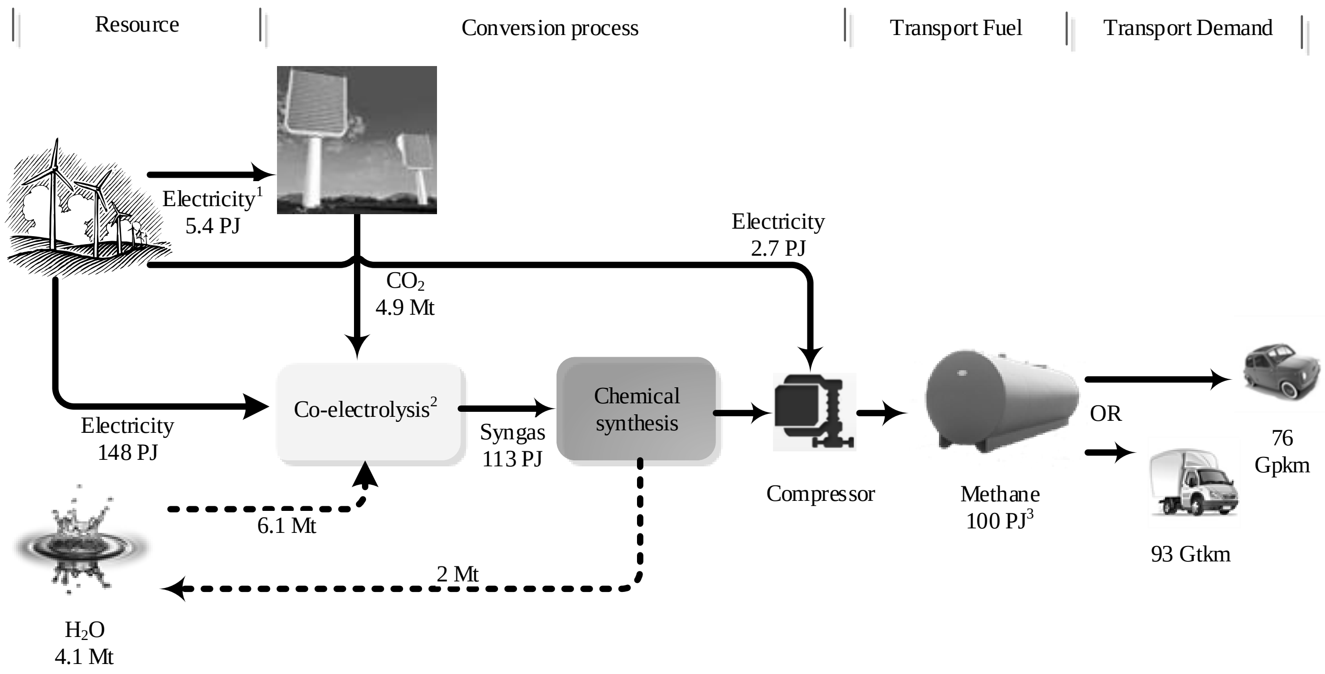

Figure 50: Co-electrolysis of steam and carbon dioxide which is obtained using carbon trees to methane. [1]Based on an additional electricity demand of 1.1 MJ/tCO_2 for capturing carbon dioxide using carbon trees [63]**. [2]Assuming a co-electrolyser an efficiency of 78%: 73% for steam and 86% for carbon dioxide** [16]**. [3]A loss of 5% was applied to the fuel produced to account for additional losses in the chemical synthesis and fuel storage. The abbreviation Mt here refers to million metric tons.**

4.2.6 Comparison

Using the energy flow diagrams presented in Figure 35 to Figure 50, it is possible to compare each of the pathways by identifying the electricity and bioenergy required to produce 100 Gpkm for passenger transport and 100 Gtkm for freight transport, as presented in Figure 51 and Figure 52 respectively.

The results confirm that direct electrification is the most sustainable form of transportation in terms of the resources consumed. It requires the lowest amount of electricity compared to all of the pathways and it does not require any direct bioenergy consumption. Battery electrification is also a very efficient pathway, but as mentioned previously, in a 100% renewable energy system both electrification scenarios will need to be supplemented by some form of high energy-density fuel.

The results in Figure 51 and Figure 52, suggest that methanol/DME is more efficient than those with methane as the final fuel. However, there is still a lot of uncertainty surrounding many of the assumptions about the technological development required in the pathways here. Even though the current calculations suggest that methanol/DME is more efficiency, there may be significant changes as the technologies develop in the future, especially the efficiency of the vehicles that are required for each fuel. In this study, methanol/DME is assumed so that the impact of electrofuels can be assessed, but in the future a more detailed comparison will be necessary between the impact of a 'liquid' or 'gas' based transport sector to establish the most efficiency and cost-effective end fuel. It is important to emphasise here that it is very unclear at present which final fuel will eventually be chosen in practice: methanol/DME or methane. This is due to the numerous uncertainties relating to vehicle efficiencies, infrastructure costs, and forecasted technological development. However, since the final fuel only alters the chemical synthesis at the end of the pathways, the principal of 'boosting' biomass or 'hydrogenating' CO_2 is common for both methanol/DME and methane. Hence the importance of including these principals in a future 100% renewable system is the key focus in the CEESA scenarios, rather than the specific choice of end fuel itself.

Focusing now solely on the methanol/DME results in Figure 51 and Figure 52, it is difficult to compare the 'fuel optimised' fermentation process with the others since the heavy fuels can only be used as marine diesels. The freight demand met using these ships cannot be directly compared with the freight demand met by trucks in the other pathways, so it is not included in the comparison. However, it is possible to compare the 'energy optimised' fermentation process to the other options. Firstly, the 'energy optimised' fermentation process can be compared to biomass hydrogenation, since these both use a combination of electricity and biomass. By doing so quantitatively, it is clear that biomass hydrogenation requires slightly less electricity and biomass. The difference between the two is not sufficient to make a conclusive decision on the future pathway that will be utilised, which is similar to the conclusions drawn in previous research in Sweden [65]. However, from a qualitative perspective, the difference between these two pathways is much more significant. Both the 'fuel optimised' and 'energy optimised' fermentation processes are very complex and include numerous conversions which are very uncertain, especially the gasification of coke and the gasification of lignin. Since the conversion losses for the gasification of coke and lignin are currently not available, the conversion losses for cellulose gasification were assumed here, which is an optimistic assumption. In addition, the fermentation processes includes an array of interactions between different sub-pathways for its by-products (i.e. hydrogenation and gasification). In comparison, the biomass hydrogenation process consists of one principal (i.e. gasification of biomass). Also, the biomass hydrogenation process finishes with chemical synthesis, meaning the choice of fuel produced is likely to be more flexible, whereas the fermentation pathway will always be partially restricted to ethanol and more specifically, for the 'fuel optimised' process to marine diesels. Both pathways still need a lot of development before they can be implemented at the scale necessary for a 100% renewable energy system. However, based on this assessment of the current knowledge, the authors of this study concluded that biomass hydrogenation seems more likely to achieve its technological development targets. This is of course subject to debate and change, so like the discussion around methane vs. methanol, this should not be viewed as a concrete recommendation for the long-term, but rather an assessment of what is likely to happen in the future based on today's information. In conclusion, the biomass hydrogenation pathway is utilised in CEESA when defining the energy flows and costs for bio-methanol/DME.

The remaining pathways, CO_2Hydro and co-electrolysis, do not require any direct biomass input. From Figure 51 and Figure 52, it is evident that both pathways require the same amount of electricity. However, the CO_2Hydro pathway uses steam electrolysis which is already a well-established technology whereas co-electrolysers are still under development. Therefore, CO_2Hydro is used in CEESA when simulating liquid fuel which does not require any direct biomass input and so the output methanol/DME is referred to as **CO_2-methanol/DME**. Both the CO_2Hydro and co-electrolysis pathways represent the same principal, which is the use of electricity and captured CO_2 to create liquid fuel. Therefore, although the CO_2Hydro pathway is used in CEESA, the results are indicative of those that would be achieved with co-electrolysis also.

It is critical to recognise that biomass hydrogenation and CO_2Hydro have been chosen to represent two uniquely different methods in the future transport sector: one which boosts a biomass resource and one which uses captured CO_2. This does not mean that the biomass hydrogenation pathway will be used instead of bioethanol or that CO_2Hydro will be used instead of co-electrolysis. In the future, the ultimate decision will depend on the technological development and demonstration of these facilities on a large-scale. It is clear that these two principals will need to be applied in some way to achieve a 100% renewable energy system in Denmark, depending on the residual bioenergy resource available. Throughout this study the abbreviation 'bio' is placed before a fuel if it comes directly from a bioenergy resource (i.e. biomass hydrogenation) and the abbreviation 'CO_2' is placed before the name of a fuel to signify that it is produced directly from an electrolyser as an CO_2 electrofuel (i.e. CO_2Hydro). Using these principals, three different technology scenarios are created in CEESA, as discussed in the following section.

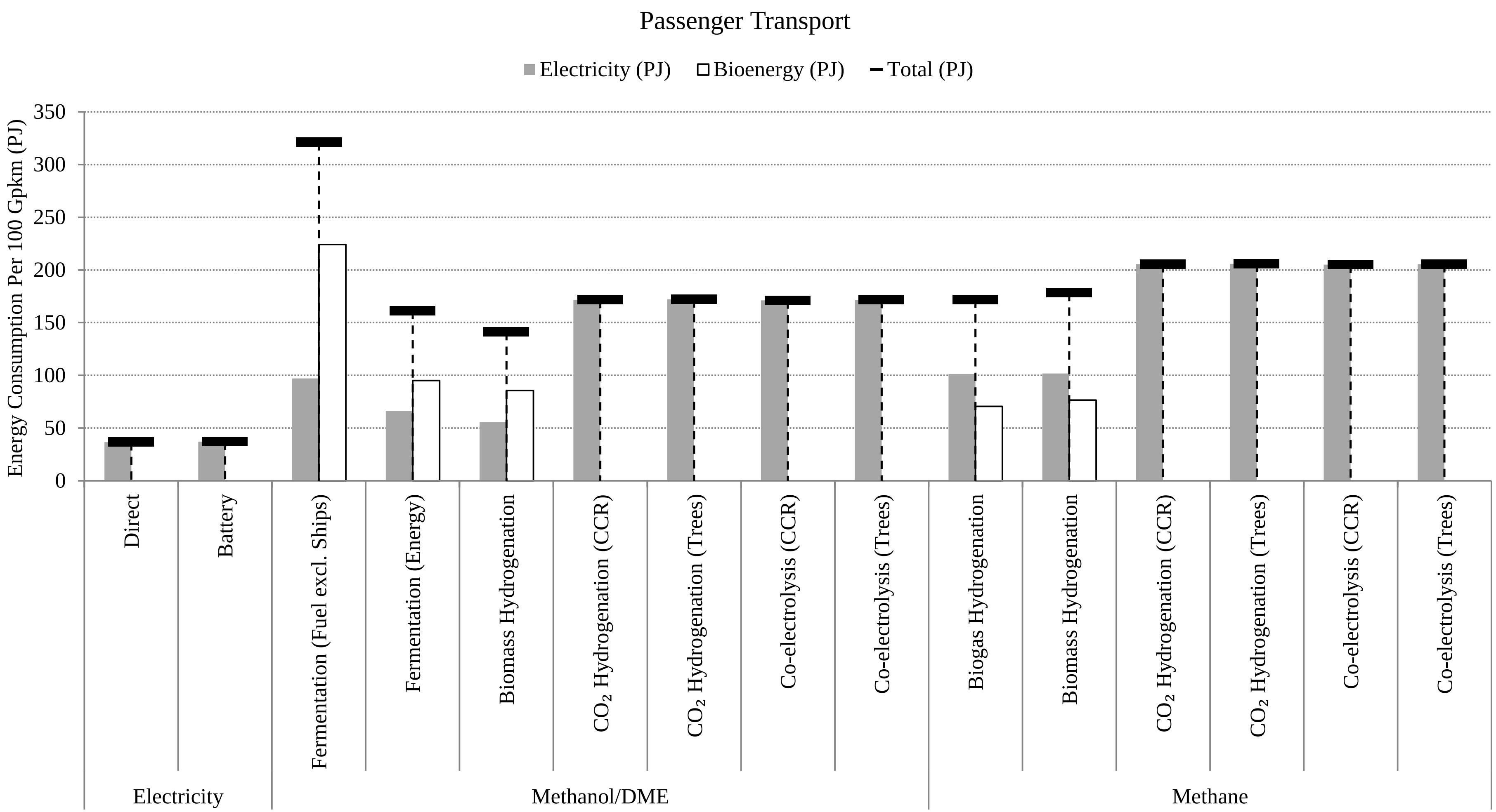

Figure 51: Electricity and bioenergy required for each transport fuel pathway to provide 100 Gpkm of passenger transport.

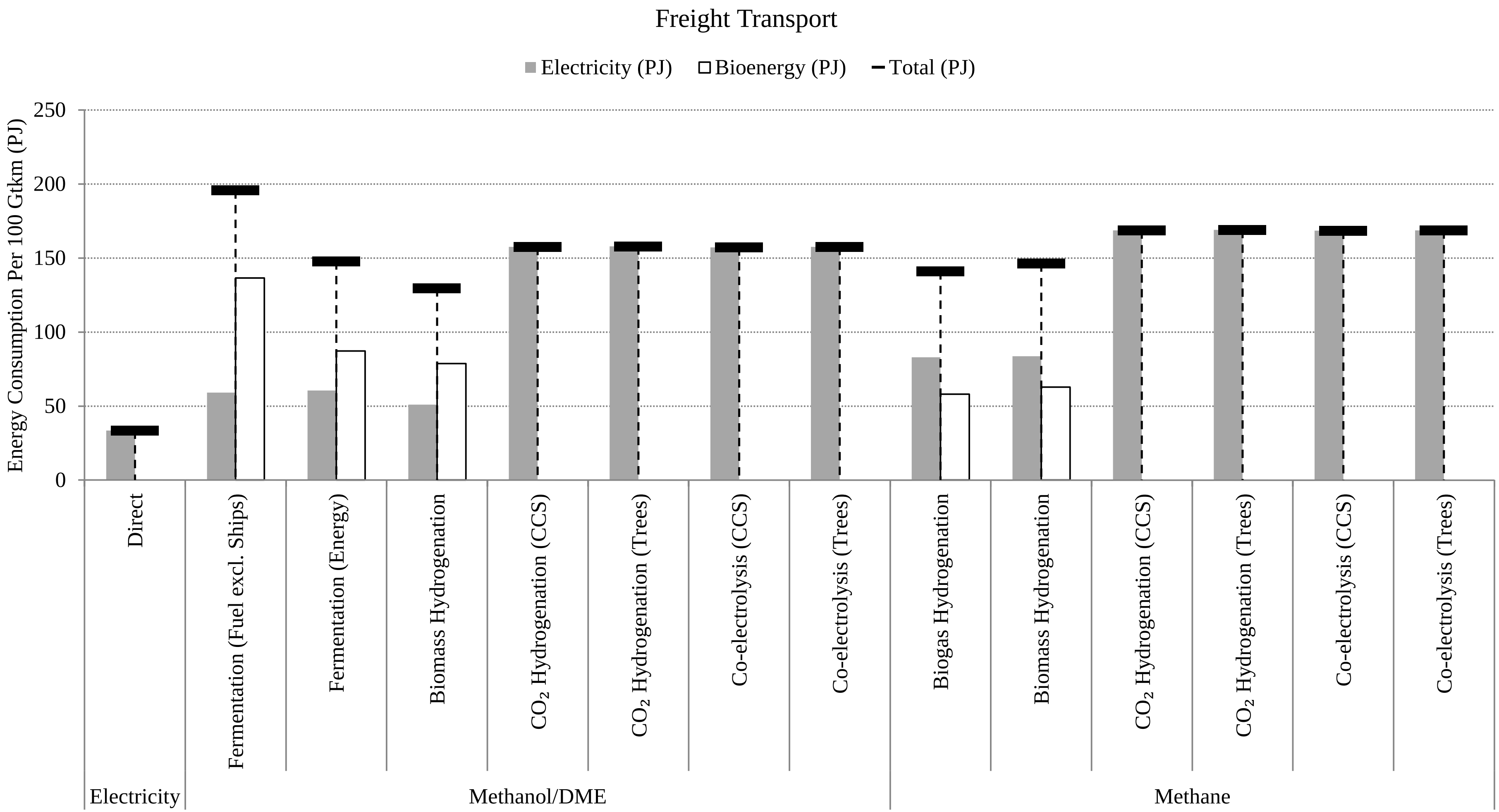

Figure 52: Electricity and bioenergy required for each transport fuel pathway to provide 100 Gtkm of freight transport.

4.3 CEESA Technology Scenarios

In CEESA, three technology scenarios were designed which fit the following criteria: a *conservative* scenario is based on known technologies, an *ideal* scenario uses technologies which are currently under development, and a *recommendable* scenario is a "realistic and recommendable" scenario based on a balanced assessment of realistic and achievable technology improvements. The technologies included in each scenario are described here, which have been chosen based on the pathways designed in section 4.2.

4.3.1 Conservative

The first scenario is called the '*conservative*' scenario. It is based on the assumption that the forecasted transport demands in the *reference scenario* will occur for the year 2050 and it only uses technologies which are very likely to develop. Where possible, direct electrification of the transport sector is prioritised using either rail or batteries, but as mentioned previously, some form of liquid fuel is still required. To meet this demand, bio-methanol/DME is utilised in the *conservative* scenario. This is due to the fact that several different technology options already exist for gasification and bio-methanol/DME [66]: there are even many demonstration and commercial plants in countries such as Denmark [3], Japan [4], Sweden [5,6], and China [7]. In contrast, only one demonstration plant in Iceland [67] and one proposed plant in Canada [68] have been identified for CO_2-methanol/DME. By making this division, the *conservative* scenario also represents a situation where the Danish energy system relies on a bioenergy-based energy sector, since bio-methanol/DME is based on biomass hydrogenation.

The mix of different technologies utilised in the transport sector for the *conservative* scenario is displayed in Table 5. For passenger transport in 2050, 35% of the transport demand for private cars is met by electric vehicles and 40% is met by ICE bio-methanol vehicles. The remaining 25% is provided by a mix of electricity and bio-methanol/DME using 15% hybrid bio-methanol/DME vehicles and 10% plug-in hybrid bio-methanol/DME vehicles. Considering that over 90% of private car journeys are below 100 km and the range of commercially available electric vehicles is already above 160 km, the *conservative* scenario assumes a modest electrification of the private car fleet over the next 40 years. This is supplemented by a relatively straightforward transition from conventional petrol and diesel ICEs to bio-methanol/DME ICE vehicles. For buses, it is assumed that 10% of the transport demand is provided by electric buses and 15% by ICE bio-methanol/DME hybrid buses. Once again this is a relatively conservative electrification of the bus fleet considering that 54% of the forecasted bus transport demand in 2050 is made up of journeys below 50 km (see Appendix C). The remaining 75% of the bus transport demand is met by ICE bio-methanol/DME vehicles. No alternations are made to rail transport since it is already assumed in the *reference scenario* that all passenger rail transport will be electrified in Denmark by 2050. Finally, for passenger transport, both the aviation and marine sectors use bio-based fuels, in the form of bio-jetfuel and bio-methanol/DME respectively.

In relation to freight transport in 2050, Table 6 indicates that 20% of 2-6 t vans are electric vehicles, 55% are ICE bio-methanol/DME, and 25% are ICE hybrid bio-methanol/DME. The national transport demand for trucks is provided by 85% ICE bio-methanol/DME vehicles and 15% by hybrid bio-methanol/DME vehicles. The hybrid vehicles are preferred for shorter journeys, but since 8% are below 50 km and 32% between 50-200 km, 15% hybrid vehicles are deemed conservative for national trucks. For international trucks, 100% of the fuel is bio-methanol/DME and 100% of the vehicles are ICEs. Only 3% of the transport demand for international trucks is forecasted to be below 250 km in

2050, so it is assumed that hybrid vehicles will not be suitable. Once again no changes are made to rail since the *reference scenario* already expects it to be 100% electric by 2050. Finally, similar to passenger transport, aviation is supplied entirely by bio-jetfuel and sea transport using bio-methanol/DME.

Table 5 and Table 6 also indicate the 'technology transition' that must occur in the *conservative* scenario between 2010 and 2050. For both passenger and freight transport, it is essential that battery electric, ICE bio-methanol/DME, and hybrid vehicles are developed and implemented. In the *conservative* scenario here, 5% of private cars, 1% of buses, and 5% of 2-6 t vans are electric by 2020 to begin this development. Bio-methanol/DME is assumed to develop faster by 2020, since bio-methanol/DME vehicles are similar to conventional fossil-fuel vehicles. Therefore, in 2020 5% of private cars, 5% of vans, 10% of buses, and 10% of trucks are bio-methanol/DME, while 5% of private cars, vans, buses and national trucks are hybrid bio-methanol/DME vehicles. In addition, 5% of private cars, vans, and buses are hybrid diesel vehicles by 2020, which increases the overall energy efficiency of the fleets. Biodiesel and bioethanol are phased out by 2020, due to their relatively large land-use requirements, which have been outlined previously in Figure 32. For these roadmaps, historical data is used to estimate the proportion of vehicles which are replaced in a decade. The statistics from StatBank indicate that 63% of the private car fleet in Denmark was less than 10 years old in 2010, while 70% of the truck fleet was less than 10 years old [22]. Hence, the scenarios here are developed assuming that the same proportion of cars and trucks will be less than 10 years old in 2020 also. For example, only 20% of the private car fleet is replaced with new technologies in 2020, thus leaving approximately 40% to be replaced with conventional petrol and diesel vehicles and assuming that the remaining 40% is made up of vehicles more than 10 years old.

As outlined in Figure 53, the *conservative* transport scenario will lead to a heavy dependence on bioenergy since approximately 189 PJ of biofuel is necessary in 2050. More specifically there is a large dependence of 149 PJ on bio-methanol/DME in 2050 as it can be utilised in road, rail, and sea transport, while there is also a demand of 39 PJ on bio-jetfuel. Therefore, for the *conservative* scenario, approximately 395 PJ/year of bioenergy is necessary by 2050: approximately 169 PJ/year in the transport sector and 226 PJ/year for the rest of the energy system. Since the total residual bioenergy resource available in Denmark for 2050 is approximately 240 PJ/year [1], it is clear that moving to a 100% renewable energy using mainly existing technologies will mean that Denmark is heavily dependent on bioenergy, which is not a sustainable solution.

Table 5: New passenger transport technologies as a percentage of the vehicle fleet for the *conservative* and *ideal* scenarios from 2010 to 2050.

Vehicle	Type of technology	*Conservative*					*Ideal*				
	Year	*2010*	*2020*	*2030*	*2040*	*2050*	*2010*	*2020*	*2030*	*2040*	*2050*
Cars and vans < 2 t	Battery electric vehicles	-	2%	15%	25%	35%	-	15%	40%	58%	75%
	ICE Bio-methanol/DME	-	5%	20%	30%	40%	-	-	-	-	-
	ICE hybrid vehicle Bio-methanol/DME	-	2%	5%	10%	15%	-	-	-	-	-
	ICE Plug-in hybrid vehicle Bio-methanol/DME	-	-	5%	8%	10%	-	-	-	-	-
	ICE CO_2-methanol/DME	-	-	-	-	-	-	-	5%	5%	5%
	ICE hybrid vehicle CO_2-methanol/DME	-	-	-	-	-	-	-	5%	8%	10%
	ICE Plug-in hybrid vehicle CO_2-methanol/DME	-	-	-	-	-	-	-	5%	8%	10%
	ICE hybrid vehicle Diesel	-	2%	5%	3%	-	-	10%	10%	5%	-
	ICE Plug-in hybrid vehicle Diesel	-	-	-	-	-	-	10%	15%	8%	-
Rail	No shift in technology*	-	-	-	-	-	-	-	-	-	-
Bus	Battery electric busses	-	1%	5%	8%	10%	-	5%	20%	23%	25%
	ICE Bio-methanol/DME	-	10%	20%	48%	75%	-	-	-	-	-
	ICE Hybrid Bio-methanol/DME	-	5%	10%	13%	15%	-	-	-	-	-
	ICE CO_2-methanol/DME	-	-	-	-	-	-	1%	5%	15%	25%
	ICE Hybrid CO_2- methanol/DME	-	-	-	-	-	-	-	5%	18%	30%
	Fuel cell hybrid busses CO_2-methanol/DME	-	-	-	-	-	-	1%	5%	13%	20%
	ICE Hybrid Diesel	-	5%	10%	5%		-	25%	30%	15%	-
Air	Gas-turbines Bio-jetfuel	-	-	5%	53%	100%	-	-	-	-	-
	Gas-turbines CO_2-jetfuel	-	-	-	-	-	-	1%	10%	55%	100%
Sea	Bio-methanol/DME	-	1%	10%	55%	100%	-	-	-	-	-
	CO_2-methanol/DME	-	-	-	-	-	-	1%	10%	55%	100%

*It is assumed in the *reference scenario* that rail in Denmark is electrified.

Table 6: New freight transport technologies as a percentage of the vehicle fleet for the *conservative* and *ideal* scenarios from 2010 to 2050.

Vehicle	Type of technology	*Conservative*					*Ideal*				
	Year	*2010*	*2020*	*2030*	*2040*	*2050*	*2010*	*2020*	*2030*	*2040*	*2050*
Vans (2-6t)	Battery electric vehicles	-	2%	10%	15%	20%	-	10%	20%	28%	35%
	ICE Bio-methanol/DME	-	5%	15%	35%	55%	-	-	-	-	-
	ICE hybrid vehicle Bio-methanol/DME	-	2%	10%	18%	25%	-	-	-	-	-
	ICE CO_2-methanol/DME	-	-	-	-	-	-	-	5%	23%	40%
	ICE hybrid vehicle CO_2-methanol/DME	-	-	-	-	-	-	-	5%	8%	10%
	ICE Plug-in hybrid vehicle CO_2-methanol/DME	-	-	-	-	-	-	-	5%	10%	15%
	ICE hybrid vehicle Diesel	-	2%	10%	5%	-	-	5%	5%	3%	-
	ICE Plug-in hybrid vehicle Diesel	-	-	-	-	-	-	5%	5%	3%	-
National Trucks	ICE Bio-methanol/DME	-	10%	20%	53%	85%	-	-	-	-	-
	ICE hybrid vehicle Bio-methanol/DME	-	5%	10%	13%	15%	-	-	-	-	-
	ICE CO_2-methanol/DME	-	-	-	-	-	-	1%	5%	28%	50%
	ICE Hybrid CO_2- methanol/DME	-	-	-	-	-	-	1%	5%	18%	30%
	Fuel cell hybrid truck CO_2-methanol/DME	-	-	-	-	-	-		1%	11%	20%
	ICE Diesel Hybrid	-	-	5%	3%	-	-	20%	20%	10%	-
International Trucks	ICE Bio-methanol/DME	-	10%	20%	60%	100%	-	-	-	-	-
	ICE CO_2-methanol/DME	-	-	-	-	-	-	1%	5%	50%	95%
	Fuel cell hybrid truck CO_2-methanol/DME	-	-	-	-	-	-	-	1%	3%	5%
Rail	No shift in technology	-	-	-	-	-	-	-	-	-	-
Air	Gas-turbines Bio-jetfuel	-	-	5%	53%	100%	-				
	Gas-turbines CO_2-jetfuel	-	-	-	-	-	-	1%	10%	55%	100%
Sea	Bio-methanol/DME	-	1%	10%	55%	100%	-				
	CO_2-methanol/DME	-	-	-	-	-	-	1%	10%	55%	100%
Other*	Bio-methanol/DME	-	5%	15%	58%	100%	-	-	-	-	-
	Bio-jetfuel	-	-	5%	53%	100%	-	-	-	-	-
	CO_2-methanol/DME	-	-	-	-	-	-	1%	5%	53%	100%
	CO_2-jetfuel	-	-	-	-	-	-	1%	5%	53%	100%

*Other includes the agricultural, fishery/gardening/forestry, and the military sectors.

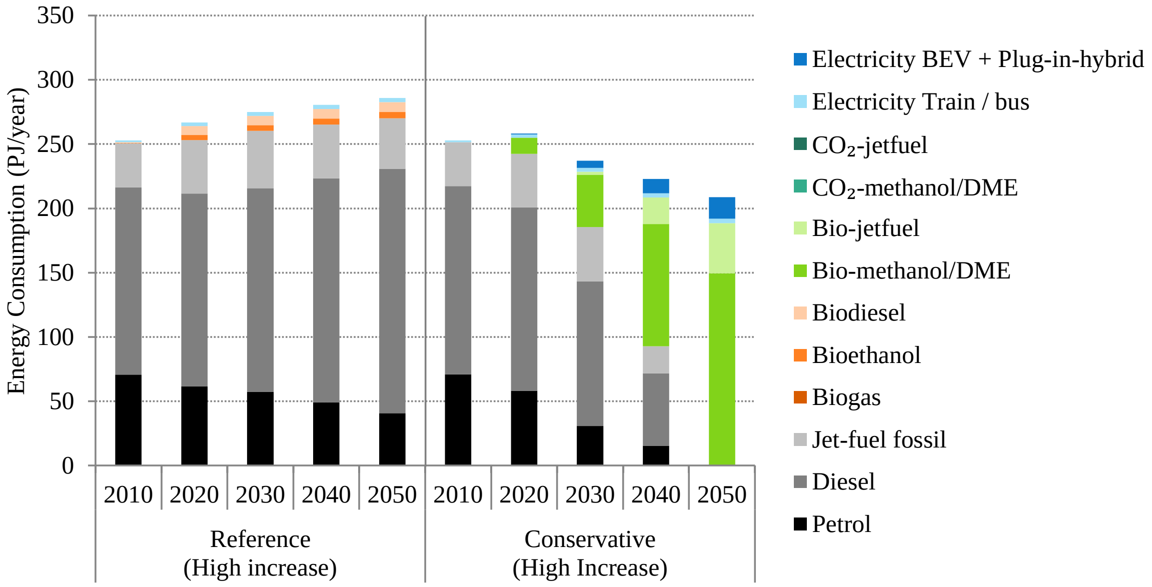

Figure 53: Energy consumed by fuel type for the *reference* and *conservative* scenarios between 2010 and 2050 for a *high increase* (business-as-usual) in the transport demand.

4.3.2 Ideal

To reduce Denmark's dependence on bioenergy, an '*ideal*' scenario is also analysed here. It is assumed in the *ideal* scenario that all expected new technologies which can reduce the consumption of bioenergy will be fully developed, particularly electrolysers and carbon trees. The resulting breakdown of technologies for passenger transport in 2050 is outlined in Table 5. For private cars, 75% of the transport demand is supplied by electric vehicles, since 65% of the transport demand is made up of trips below 50 km and 95% of the demand by trips below 100 km. The remaining 35% is met by a combination of 5% ICE CO_2-methanol/DME vehicles, 10% ICE CO_2-methanol/DME hybrids, and 10% ICE CO_2-methanol/DME plug-in hybrids. Fuel-cell vehicles using electrofuels are not implemented as it is assumed that ICE CO_2-methanol/DME cars will be a more economical alternative [26] and also, that fuel cells will not develop for small vehicles with the large-scale implementation of direct electric vehicles. Considering that buses have limited time to charge, it is assumed that 25% of the passenger transport demand is powered by electricity even though approximately 75% of the bus transport demand is made up of trips below 50 km. However, considering the large number of short trips, hybrid vehicles are extensively used: 30% of the passenger bus transport demand is met by hybrid ICE vehicles and 20% by fuel-cell hybrids, both using CO_2-methanol/DME as the liquid fuel. Unlike the assumption for cars, it is assumed here that fuel cells will develop for larger vehicles such as buses, primarily due to the scale and weight of these larger vehicles. The final 25% of the bus transport demand is met using ICE CO_2-methanol/DME vehicles. Passenger rail is already 100% electric in 2050 under the *reference scenario* so no alternations are made in the *ideal* scenario. Passenger aviation and passenger sea transport are both supplied by 100% CO_2 electrofuel, as in an *ideal* world the demand for bioenergy is reduced to a minimum.

As displayed in Table 6 for freight transport in 2050, 35% of the demand for vans (2-6 t) is met by electric vehicles, which accounts for all journeys under 50 km. The remaining 65% is supplied by 15% plug-in ICE CO_2-methanol/DME hybrids, 10% ICE CO_2-methanol/DME hybrids, and 40% ICE CO_2-methanol/DME vehicles. Like cars, it is assumed that fuel cell vehicles will not develop for smaller vans with the large-scale implementation of direct electrification. For national trucks, 20% is supplied by CO_2-methanol/DME fuel-cell hybrid vehicles and 30% by hybrid ICE CO_2-

methanol/DME vehicles. Hybrids are used for 50% of the transport demand since 50% of it is made up of journeys below 200 km. The remaining 50% of the transport demand is supplied by ICE CO_2-methanol/DME vehicles. International trucks travel very long distances (>250 km) and hence hybrid vehicles are not very suitable. Therefore, 5% of the international truck transport demand is supplied by CO_2-methanol/DME fuel-cell hybrid vehicles in 2050, which corresponds to the proportion of the transport demand made up of journeys below 250 km. Fuel cell vehicles also account for a small proportion of the international truck fleet which accounts for vehicles which require auxiliary power for applications such as refrigeration. The remaining 95% is supplied by ICE CO_2-methanol/DME vehicles since all remaining journeys are above 250 km (i.e. approximately 43% of journeys are between 250 km and 1000 km, and approximately 52% of journeys are over 1000 km). Freight rail is already 100% electric in the *reference scenario* so no changes have been added here. All aviation and sea fuel for freight is supplied by CO_2-jetfuel and CO_2-methanol/DME respectively in the *ideal* scenario, once again to reduce the bioenergy demands. Finally, the transport demand in the 'other' sector (which includes fishery, gardening, forestry, military, and agricultural) is 100% CO_2-methanol/DME for road transport and 100% CO_2-jetfuel for air transport.

As outlined in Table 5 and Table 6 for the transition between 2010 and 2050, the key challenge to reach this *ideal* scenario by 2050 is the development of electrofuels, since their development is subject to considerable uncertainties [69]. Considering this, even in the *ideal* scenario it is assumed that CO_2-methanol/DME will not be available for small vehicles until 2030. However, for large vehicles such as trucks and buses, 1% of the fleets are provided by both hybrid and plug-in hybrid CO_2-methanol/DME vehicles in 2020, to encourage the development of these technologies. Similarly, it is assumed that 1% of sea transport will be CO_2-methanol/DME and 1% of aviation will be CO_2-jetfuel by 2020. After such a slow initial penetration, electrofuels are increased significantly between 2020 and 2030 to begin the push for a 100% renewable scenario in 2050. Overall approximately 15% of cars and vans, 10% of trucks, and 15% of buses use some form of CO_2-methanol/DME fuelled vehicle by 2030. Similarly, 10% of aviation fuel is CO_2-jetfuel and 10% of marine fuel is CO_2-methanol/DME by 2030, which forms the basis for the final push towards 100% electrofuels in these sectors by 2050.

As displayed in Figure 54, there is no bioenergy required for transport in the *ideal* scenario, so the demand for bioenergy is reduced to approximately 180 PJ/year for the entire energy system. However, the transition from the current fossil-fuel based transport sector to an *ideal* 100% renewable energy based transport sector using electrofuels demonstrates the significant challenges facing transport. If biofuels are not available, then electrofuels must be developed so they can begin to penetrate the transport market as early as 2020 and provide a significant proportion of the transport demand (approximately 11%) by 2030. However, at present the *ideal* development seems unlikely due to the uncertainties surrounding electrofuels, particularly in relation to the development of economical electrolysers and carbon capture technologies. Therefore, although it is an *ideal* scenario from a sustainability perspective (provided that the energy system is based on renewable energy), the uncertainties associated with electrofuels make it too unrealistic to make it the foundations of a future energy strategy.

In summary, the *conservative* scenario uses an unsustainable consumption of bioenergy and the *ideal* scenario is subject to too much uncertainty in relation to the development, capabilities and the cost of future technologies. Therefore, to present a more sustainable and realistic pathway, a *recommendable* transport scenario has also been created in the CEESA project.

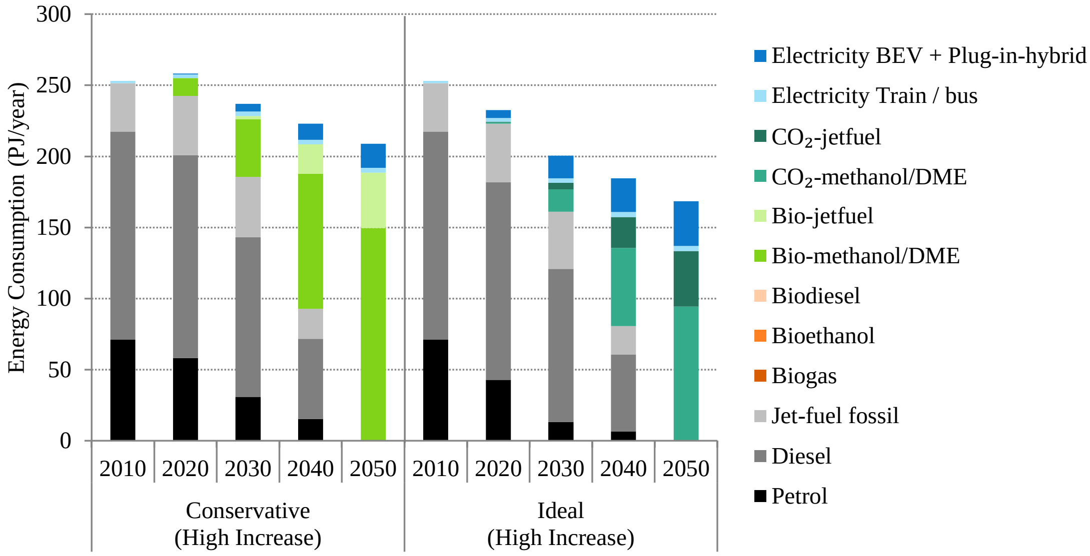

Figure 54: Energy consumed by fuel type for the *conservative* and *ideal* scenarios between 2010 and 2050 for a *high increase* (business-as-usual) in the transport demand.

4.3.3 Recommendable

In the '*recommendable*' scenario the objective is to form a "realistic and recommendable" scenario based on a balanced assessment of realistic and achievable technology improvements. For 2050, the first priority is once again to use as much direct electrification in the transport sector as possible. This is supplemented by less biofuels than in the *conservative* scenario and less electrofuel than in the *ideal* scenario. As outlined in Table 7, in 2050 the *recommendable* scenario assumes that 75% of the private car transport demand is met by electric vehicles and the remaining 25% is met by a mix of bio- and CO_2-methanol/DME vehicles: 10% are ICEs, 10% are plug-in hybrids, and 5% are hybrids. Hence, there is the same amount of direct electrification as in the *ideal* scenario for smaller vehicles, which is supplemented by an even mix of bio and CO_2 fuel. In relation to busses, 15% are electric, 47.5% are CO_2-methanol/DME, and 37.5% are bio-methanol/DME in 2050. As already outlined, passenger rail is completely electrified in the *reference scenario* by 2050 so no changes are necessary. For aviation, 50% of the fuel is bio-jetfuel and 50% CO_2-jetfuel, while for marine transport 50% is bio-methanol/DME and 50% is CO_2-methanol/DME. Bio-methanol/DME and CO_2-methanol/DME are utilised equally in passenger aviation and passenger sea transport in order to reduce the overall demands on bioenergy. However, this mix will ultimately be determined by the technological development in key technologies such as biomass gasification, electrolysers, and carbon capture.

For freight in 2050, it is assumed that vans will also use a considerable amount of direct electrification. As outlined in Table 8, 35% of the fleet is assumed to be battery electric vehicles by 2050. The remaining 65% is composed of 40% ICE, 15% ICE hybrid, and 10% ICE plug-in hybrid vehicles which are powered by an even mix of bio- and CO_2-methanol/DME. Like in the *ideal* scenario, it is assumed here that fuel cells will not be developed in small vehicles due to the large-scale implementation of electric vehicles from an early stage. National trucks use 37.5% ICE and 15% ICE hybrid bio-methanol/DME vehicles in the *recommendable* scenario along with 37.5% ICE, 10% ICE hybrid, and 5% fuel-cell hybrid CO_2-methanol/DME vehicles. Similarly, international trucks are 45% ICE bio-methanol/DME, 45% ICE CO_2-methanol/DME, and 5% fuel-cell hybrid CO_2-methanol/DME vehicles. There is a higher percentage of hybrid vehicles in the national truck fleet due to the larger proportion of shorter trips. A small fraction (i.e. 5%) of both is assumed to be fuel cell vehicles since some trucks require auxiliary power. Freight rail is completely electrified in the *reference scenario* by 2050 so no changes are implemented here. Finally, the air, sea, and 'other' sectors all use a mix of 50% bio- and 50% CO_2-based fuel by 2050 in the *recommendable* scenario.

Table 7: New passenger transport technologies as a percentage of the vehicle fleet for the *recommendable* scenario from 2010 to 2050.

Vehicle	Type of technology	*Recommendable*				
Year		*2010*	*2020*	*2030*	*2040*	*2050*
Cars and vans < 2 t	Battery electric vehicles	-	5%	25%	50%	75%
	ICE Bio-methanol/DME	-	10%	20%	12.5%	5%
	ICE hybrid vehicle Bio-methanol/DME	-	2%	5%	3.8%	2.5%
	ICE Plug-in hybrid vehicle Bio-methanol/DME	-	-	10%	7.5%	5%
	ICE CO_2-methanol/DME	-	-	-	2.5%	5%
	ICE hybrid vehicle CO_2-methanol/DME	-	-	-	1.3%	2.5%
	ICE Plug-in hybrid vehicle CO_2-methanol/DME	-	-	-	2.5%	5%
	ICE hybrid vehicle Diesel	-	2%	5%	2.5%	-
	ICE Plug-in hybrid vehicle Diesel	-	1%	10%	5%	-
Rail	No shift in technology*	-	-	-	-	-
Bus	Battery electric busses	-	1%	10%	12.5%	15%
	ICE Bio-methanol/DME	-	10%	15%	21.3%	27.5%
	ICE Hybrid Bio-methanol/DME	-	5%	10%	10%	10%
	ICE CO_2-methanol/DME	-	-	1%	14.3%	27.5%
	ICE Hybrid CO_2-methanol/DME	-	-	1%	5.5%	10%
	Fuel cell hybrid busses CO_2-methanol/DME	-	-	1%	5.5%	10%
	ICE Hybrid Diesel	-	20%	20%	10%	-
Air	Gas-turbines Bio-jetfuel	-	1%	10%	30%	50%
	Gas-turbines CO_2-jetfuel	-	-	1%	25.5%	50%
Sea	Bio-methanol/DME	-	1%	10%	30%	50%
	CO_2-methanol/DME	-	-	1%	25.5%	50%

*It is assumed in the *reference scenario* that rail in Denmark is electrified.

Table 8: New freight transport technologies as a percentage of the vehicle fleet for the *recommendable* scenario from 2010 to 2050.

Vehicle	Type of technology	*Recommendable*				
Year		*2010*	*2020*	*2030*	*2040*	*2050*
Vans (2-6t)	Battery electric vehicles	-	5%	20%	27.5%	35%
	ICE Bio-methanol/DME	-	10%	20%	20%	20%
	ICE hybrid vehicle Bio-methanol/DME	-	2%	5%	6.3%	7.5%
	ICE Plug-in hybrid vehicle Bio-methanol/DME	-	-	-	2.5%	5%
	ICE CO_2-methanol/DME	-	-	-	10%	20%
	ICE hybrid vehicle CO_2-methanol/DME	-	-	-	3.8%	7.5%
	ICE Plug-in hybrid vehicle CO_2-methanol/DME	-	-	-	2.5%	5%
	ICE hybrid vehicle Diesel	-	2%	5%	2.5%	-
	ICE Plug-in hybrid vehicle Diesel	-	1%	10%	5%	-
National Trucks	ICE Bio-methanol/DME	-	15%	20%	28.8%	37.5%
	ICE hybrid vehicle Bio-methanol/DME	-	5%	10%	10%	10%
	ICE CO_2-methanol/DME	-	-	1%	19.3%	37.5%
	ICE Hybrid CO_2-methanol/DME	-	-	1%	5.5%	10%
	Fuel cell hybrid truck CO_2-methanol/DME	-	-	1%	3%	5%
	ICE Diesel Hybrid	-	5%	5%	2.5%	-
International Trucks	ICE Bio-methanol/DME	-	15%	25%	36.3%	47.5%
	ICE CO_2-methanol/DME	-	-	5%	26.3%	47.5%
	Fuel cell hybrid truck CO_2-methanol/DME	-	-	1%	3%	5%
Rail	No shift in technology	-	-	-	-	-
Air	Gas-turbines Bio-jetfuel	-	1%	10%	30%	50%
	Gas-turbines CO_2-jetfuel	-		1%	25.5%	50%
Sea	Bio-methanol/DME	-	1%	10%	30%	50%
	CO_2-methanol/DME	-	-	1%	25.5%	50%
Other*	Bio-methanol/DME	-	1%	10%	30%	50%
	Bio-jetfuel	-	1%	10%	30%	50%
	CO_2-methanol/DME	-	-	1%	25.5%	50%
	CO_2-jetfuel	-	-	1%	25.5%	50%

***Other includes the agricultural, fishery/gardening/forestry, and the military sectors.**

Overall, the *recommendable* scenario uses 71 PJ of electrofuel compared to 133 PJ in the *ideal* scenario. More significantly though, the *recommendable* scenario does not expect electrofuels to be utilised until 2030 and even then, it is only used in small quantities: 3% of buses, 3% of national trucks, 6% of international trucks, 1% of aviation, and 1% of marine transport. However, since bio-methanol/DME and bio-jetfuel seem more technological advanced at present, these are introduced in 2020. As already mentioned, there are already demonstration bio-methanol/DME plants in operation [3–6,66] and commercial flights using bio-jetfuel [44]. This enables methanol/DME vehicles to develop while electrolysers and carbon capture technologies for electrofuels are also developing. Therefore, after 2030 the share of bio-methanol/DME begins to stabilise considerably as more CO_2-methanol/DME is introduced into the energy system. This also fits with the assumption that only alkaline electrolysers are used until 2030, after which the more efficient solid oxide electrolysers are utilised for electrofuel production. The objective here is to ensure that the peak demand for biofuels in the transport sector does not surpass the residual bioenergy resources available in the Danish energy system. However, even with these efforts, the *recommendable* scenario requires approximately 70 PJ/year of bio-methanol/DME and bio-jetfuel for the transport sector in 2050 if the BAU *high increase* in the transport demand occurs. This is still 20-30 PJ/year (~60%) more than the forecasted bioenergy resource available for transport in Denmark in 2050. Hence, technological changes only are unlikely to result in a sustainable 100% renewable transport sector by 2050, so other measures will also be necessary to reduce the overall energy demand for transport. These are considered in the next section by developing a '*medium increase*' scenario for the transport demand instead of the business-as-usual *high increase* scenario.

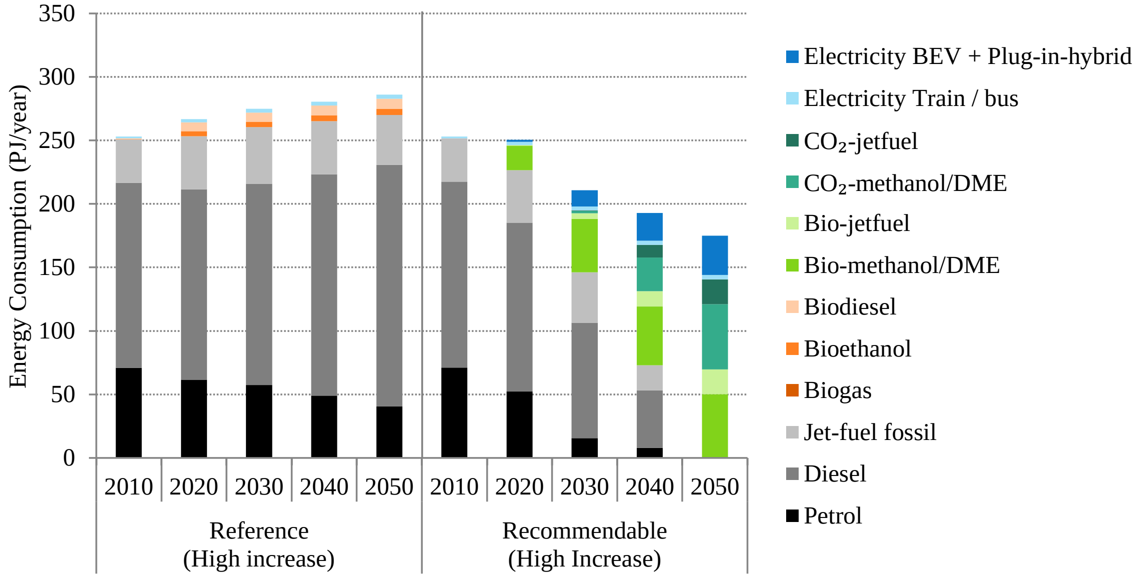

Figure 55: Energy consumed by fuel type for the *reference* and *recommendable* scenarios between 2010 and 2050 for a *high increase* (business-as-usual) in the transport demand.

5 Scenarios with a Medium Increase in the Transport Demand and Some Modal Shift

To reduce the energy required in the transport sector and correspondingly reduce the bioenergy consumption necessary for transport, the following key changes can be made:

1. The high forecasted increase can be reduced. Under a business-as-usual scenario passenger transport demands are expected to increase by 50% between 2010 and 2050, while freight transport is expected to almost double.
2. The efficiency of conventional transport vehicles can be increased. For example, the IEA has outlined how road vehicle efficiencies can be doubled by 2030 [70].
3. Vehicles can be utilised more. In the *reference model* it is evident that the existing transport sector has very poor utilisation factors. For example, in 2010 national trucks only utilise approximately 42% of their capacity. By increasing this utilisation, the transport sector can reduce its overall energy demand.
4. Different modes of transport which are more efficient and use more sustainable fuels can be utilised more. For example, rail is particularly suitable to replace long road journeys since it is very efficient and it can be completely electrified.

In practice, these changes can be implemented using a range of different measures such as new infrastructure, economic incentives, regulatory policies, and participatory programmes. New infrastructure would encourage the use of more efficient transport modes such as public transport, walking, and cycling. It could also encourage intermodal freight transport which would increase the utilisation figures in national and international trucks. Economic incentives include road pricing, congestion charging, removing travel subsidies for private cars, restructuring car tax to reflect the distance travelled and the efficiency of the vehicle used, reducing the subsidy on company cars, introducing a CO_2 tax, and reducing taxes on public transport. These measures could contribute to all four of changes outlined above. Regulatory changes could be long-term spatial planning which minimises the transport demand required, energy efficiency improvement regulations for vehicles, information technology systems which provide consumers with more information, and regulations which encourage local production of goods. Finally, participatory measures could be carpooling schemes and fuel-efficient driving courses. It is very difficult to model the consequences of these measures individually as many of them overlap with one another. For example, introducing a congestion charge will not encourage people to use public transport if the infrastructure necessary is not put in place. Therefore, these reductions are modelled as a group in the *medium increase* transport demand scenario by implementing the following measures in passenger transport:

- From 2010-2020 the increase in individual transport is reduced and the fall in public transport is reversed, so that its share is stabilised around 24% from 2010 to 2020. Also the total biking transport demand is increased by approximately 150% compared to 2010. The following actions are implemented in this period:
    - Currently bikes are used to meet approximately 3.8% of the transport demand. Between 1998-2003, for round trips below 22 km 21% of the transport demand was met using bicycles and 23% by walking [71]. In the *reference scenario* this level is expected to decrease to about 2% by 2050, as other types of transport are increasing. However, a study in Copenhagen has shown that the number of people cycling to work has increased from 30% in 1996 to 35% in 2010 [71]. The plan is to increase the market share of bicycling to 50% of the trips to work or education in Copenhagen in 2015, which is expected to cost between 0.2-0.7 billion DKK [71]. Hence, it is

assumed here that a number of modal shifts towards biking from shorter car and bus journeys are possible when the goal is to reduce the overall transport demand. 5% of leisure-related car journeys below 25 km are moved to biking/walking and 14% of work-related car journeys below 25 km are moved to biking. Also, 3% of national bus journeys are moved to biking.

  - The increase in work and leisure related transport in cars is reduced by 25% for all trips below 50 km. 7.5% of the transport demand for both work and leisure related car journeys above 50 km are moved to trains by 2020. The utilisation of cars will also increase with policies such as road pricing and tolls. The utilisation for work-related car trips less than 50 km is increased by 5% and for longer trips (i.e. > 50 km) by 10%. It is assumed that the utilisation will not increase for leisure related trips. Finally for cars, it is assumed that their efficiency improves at a rate of 2.9%/year instead of the 1.45%/year in the *reference scenario*. These additional reductions are predicted since EU policy is demanding further efficiency improvements [72] and there are a number of new technologies being developed such as 'Port Injection Spark Ignition' (PISI) engines, 'Direct Injection Spark Ignition' (DISI) engines, and 'Direct Injection Compression Ignition' (DICI) engines[3].
  - The growth in the national bus transport demand is increased to 1.5%/year for 5-25 km and to 0.5%/year for 25-50 km. The utilisation for buses is not increased, as it is assumed that this would be cancelled out by the introduction of new buses to meet the increased transport demand.
  - The transport demand for trains is increased by 40% in 2020. Therefore, the utilisation will also increase from 40% to 56% in 2020 since existing trains will be used more.
  - The increase in national aviation transport is reduced by 50% from 3.2%/year to 1.6%/year and international aviation growth is reduced by 33% from 3.2%/year to 2.13%/year. No additional energy efficiency improvements are assumed for aviation between now and 2020.
- Between 2020 and 2030, there are a number of modal shifts which increase the total biking transport demand by approximately 165% compared to 2010 and increase the use of public transport to 30.1% by 2030. Domestic aviation is almost eliminated with the electrification and expansion of the national rail system and international aviation is 17% less in 2030 than in the *reference scenario*. To do this, the following actions are implemented in this period:
  - The increase in the transport demand for short car trips (<50 km) is reduced by 50% for both work and leisure. The growth rate for work-related and leisure-related cars is reduced by 50% for all journeys below 50 km. 15% of the transport demand for leisure-related car journeys above 50 km and 25% of work-related car journeys above 50 km are moved to trains. 1% of leisure-related car journeys below 25 km are moved to biking/walking. 3% of work-related car journeys below 25 km are moved to biking and 1% of work-related car journeys above 25 km are moved to bikes. 5% of the international car transport demand is moved to international trains.
  - The growth rate for national buses is increased to 3%/year for 5-25 km journeys and 1%/year for 25-50 km. The national bus transport demand will increase to 3% for 5-25 km and to 1% for 25-50 km. Also, 1.5% of national bus journeys are moved to biking.
  - Domestic aviation continues to grow at the same rate as in 2010-2020 (i.e. 1.6%/year), but 95% of domestic aviation is then moved to national rail by 2030. International

[3] PISI engines offers advantages over DISI engines in the case of some particular fuelling options, including biogas and hydrogen. It is expected by automotive manufacturers that this technology will improve significantly over the next decade. The DICI engine is currently the most efficient in terms of fuel utilization but prospects are that PISI and DISI engines in the future will offer similar efficiencies due to improvements of the technologies and due to the fact that diesel particulate filters most likely will be compulsory.

aviation also continues to grow at the same rate as the previous decade at 2.13%/year. As outlined in Appendix F, the efficiency of aeroplanes can be improved in areas such as the engine, nacelle, propulsion system, materials, aerodynamic structure, manufacture processes, overall aircraft system and the operational procedures. However, no radical reductions are expected from technology development and hence, the energy efficiency improvements assumed in the reference 0.9%/year are maintained. The most promising solution for reducing the energy demand in aviation is to shift some of the aviation to other modes of transport with lower energy consumption. In line with this, 5% of all international air below 1000 km is moved to international rail. Further modal shifts are also made in the next two decades.

- From 2030 to 2050 the market share for public transport grows significantly to 38.9%, while at the same time the total biking transport demand doubles compared to 2010. Overall there is a 22% reduction in the total passenger transport demand in 2050 compared to the *reference*, but even with this reduction there is still a 16% increase in 2050 compared to 2010. The following changes are made in this period for passenger transport:
    - The annual change in transport demand is set to 0%/year for all cars, rail, cycling, bus, aviation, and sea transport.
    - 3% of leisure-related car journeys below 25 km are moved to biking/walking and 6% of work-related car journeys below 25 km are moved to biking. 1% of work-related car journeys above 25 km are moved to bikes. 25% of car journeys above 50 km are moved to trains for both leisure and work related trips. 10% of the international car transport demand is moved to international trains.
    - 2% of national bus journeys are moved to biking.
    - All of domestic aviation has been moved to rail by 2050.
    - 20% of all international air below 1000 km is moved to international rail.

As outlined in Figure 56, there is an overall reduction in the passenger transport demand of approximately 23% between the *high increase* (BAU) and *medium increase* scenarios. There is also a significant shift from private cars to public transport, which has a market share of approximately 40% by 2050. This along with the utilisation and energy improvement measures reduces the overall energy demand for the transport sector in the new *medium increase* scenario (which is discussed later).

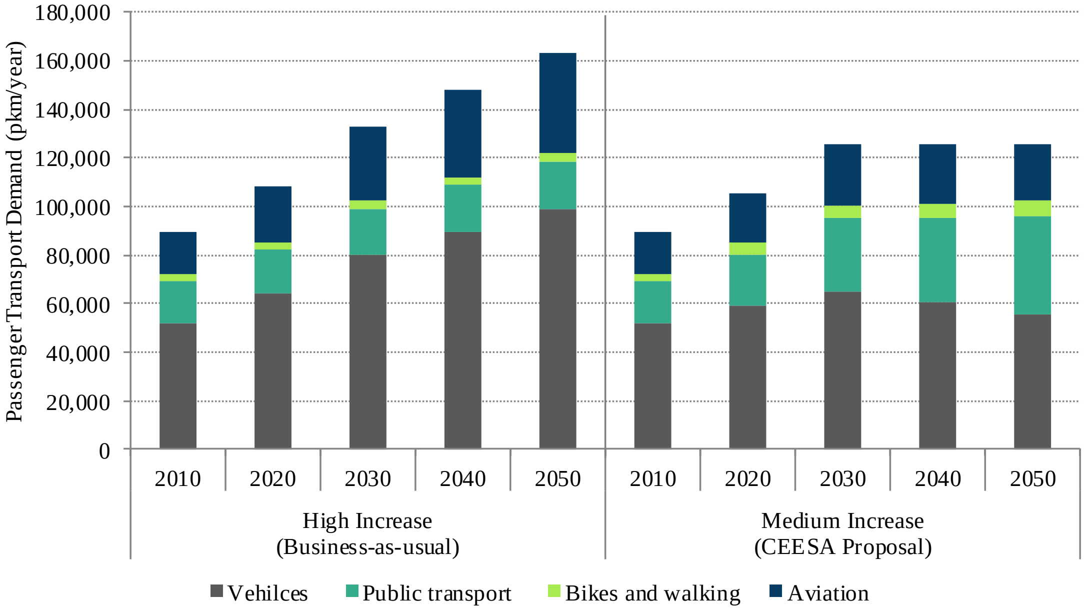

Figure 56: Passenger transport demand from 2010 to 2050 by mode for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

In addition to the actions for the passenger transport demand, the following changes are also included for freight transport:

- Vans:
  - Energy efficiency improvements for vans are the same as outlined above for cars.
  - The utilisation rate increases by 5% from 48% to 50% for all years.
- National Truck to National Rail:
  - No energy efficiency improvements are assumed for trucks, since the *reference* already includes significant improvements.
  - By 2020, 0.75% of the national truck transport demand is moved to rail. By 2030 1.5% is moved and by 2050 3% is moved.
- International truck to rail:
  - By 2020, 5% of international truck transport demand is moved to rail, by 2030 it is 30% and by 2050 it is 40%. This is based on the fact that 41% of the transport demand by international freight on trucks is over 1000 km in the *reference*. Also, at present the transit component of international rail is 1800 million tkm (i.e. trains going to/from Sweden from/to Germany) out of a total freight transport demand for rail in Denmark of 2240 million tkm. Hence, the infrastructure required for international freight transport in Denmark is already there.
  - The utilisation of national and international trucks is increased by 20% for all trip lengths, since it is 20% higher in Denmark in 1999 compared to 2009 [73]. Therefore, it is assumed that the historical highs could be achieved in the future.
- Aviation:
  - The energy efficiency improvements assumed for aviation are not changed: a 50% improvement between 2010 and 2050 is maintained in line with EU and industry targets.
  - The forecasted increase in demand is reduced by 50% between 2010 and 2020 to 1.15%/year. It is also reduced to 0%/year after 2020 from original values of 2.3%/year for 2020-2030 and 1.15%/year for 2030-2050.

As outlined in Figure 57, there is a negligible change (<1%) in the total freight transport demand in the *medium increase* and the *reference scenario*: there is still an increase of approximately 90% from 2010 to 2050. The modal shift actions here will have the most important role to play in the freight sector, as some demand is moved from road to rail which is a more energy efficient and sustainable mode of transport. Overall however, the demand for freight transport is not altered significantly and hence it could offer some further reductions in the future. It is important to note that the costs have been included here for the measures considered for both passenger and freight transport, which are provided in Appendix D.

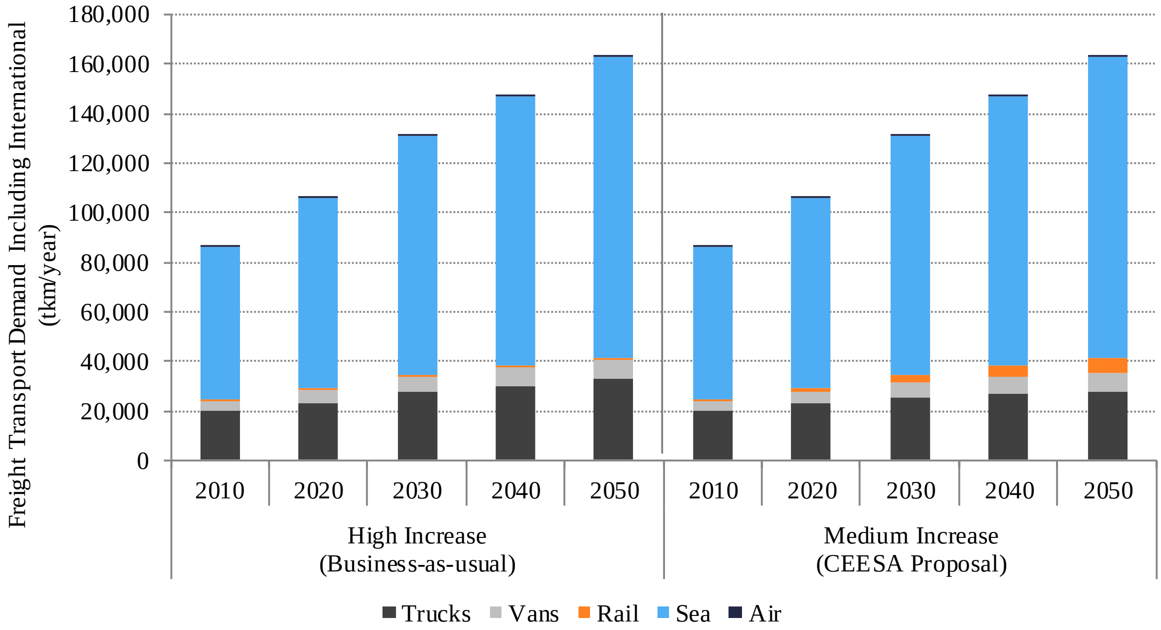

Figure 57: Freight transport demand including the international component from 2010 to 2050 by mode for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

By implementing the *medium increase* demand, the energy required for transport can be reduced for all scenarios considered. As displayed in Figure 58, the total energy required in the *reference scenario* is reduced by 30% to 198 PJ when the *medium increase* is considered. Similarly, there is an energy reduction of approximately 23% the *recommendable* scenario down to 135 PJ. More significantly though, the demand for bio-based fuels in the *recommendable* scenario is now reduced to 52 PJ in 2050, while the demand for electrofuels is 53 PJ. As discussed earlier, there is a total bioenergy resource of approximately 40-50 PJ/year available for the transport sector in Denmark in 2050, which is discussed in more detail in the CEESA 100% renewable energy system report [1]. However, even in the *recommendable* scenario with a *medium increase* in transport demand, the demand for bio-methanol/DME and bio-jetfuel is approximately 52 PJ/year. This is 2-12 PJ above the sustainable threshold identified in CEESA, so further improvements may need to be made. For example, freight transport demand could be reduced further considered since the reductions implemented here are almost negligible, as illustrated in Figure 57. The results here indicate that further research will be necessary in the future to gain a deeper understanding of the pros and cons associated with mixes of bio- and CO_2-based electrofuels. In CEESA, the *medium increase recommendable* has created the first assessment of this mix.

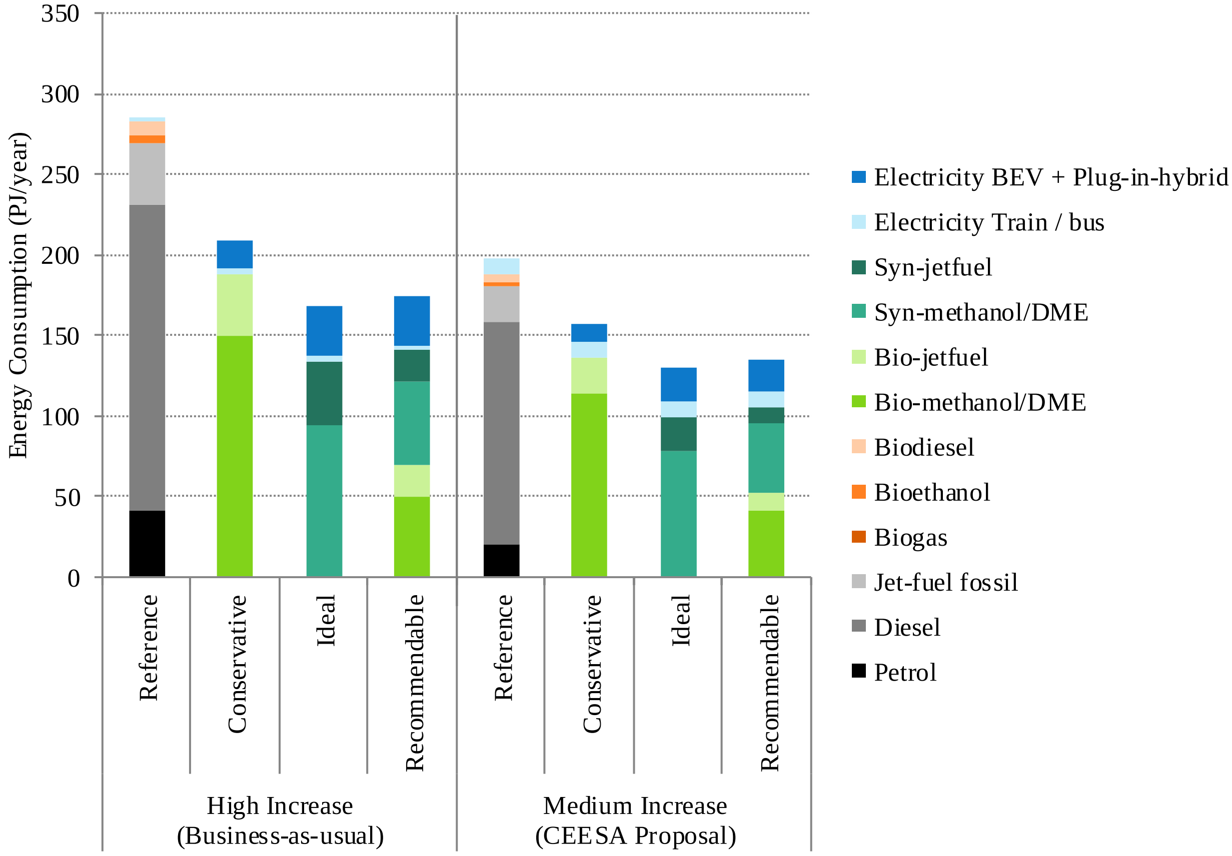

Figure 58: Energy consumed by fuel type in 2050 for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

Figure 59 presents the total annual costs for the transport sector for all the technology scenarios in 2050 for the *high increase* and the *medium increase* transport demands. Here it is evident that the total costs for all scenarios is lower if the *medium increase* transport demand is implemented than if the *high increase* is followed. There is a clear different in the mix of costs between the two: the *medium increase* scenario has lower energy-related costs, lower vehicle costs, and higher infrastructure costs. This is due to the a change in focus from a high number of underutilised individual vehicles in the *high increase* scenario to more public transport, more efficient vehicles, and better infrastructure in the *medium increase* scenario. This is also evident from the costs associated with infrastructure: in the *high increase* scenario road infrastructure is approximately twice as much as rail, whereas in the *medium increase* scenario it is the opposite. By moving the transport demand from road to rail, there are significant energy and cost savings. In summary, the results in Figure 58 and Figure 59 demonstrate two significant conclusions from the CEESA project:

- Reductions in the transport demands can be achieved using a wide variety of measures which will result in economic savings in the Danish energy system regardless of the scenario followed to 2050.
  &
- If a 100% renewable is to be realised in Denmark by 2050, it is essential that the energy demand is reduced in the transport sector to reduce the amount of bio-based fuels required to a sustainable level.

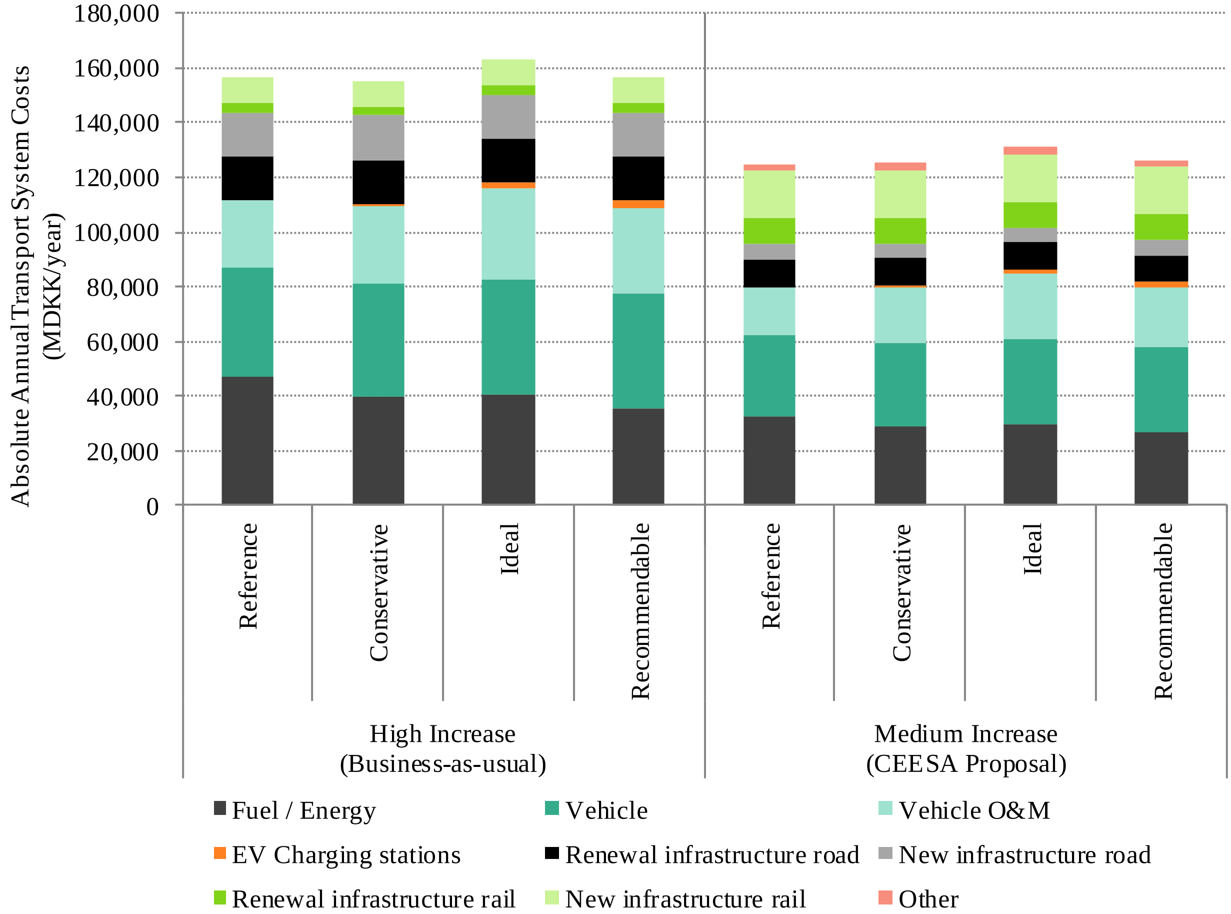

Figure 59: Transport system costs in 2050 for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

5.1 Sensitivity Analysis with a No Increase Scenario

Finally, as outlined earlier in Figure 56 and Figure 57, the transport demand is still increasing significantly in the '*medium increase*' scenario between now and 2050. To illustrate the significance of this, a 'no increase from 2020' scenario is also analysed here for the transport demand. In this scenario, both the passenger and freight transport demands continue to grow between now and 2020, as outlined in Figure 56 and Figure 57 respectively, but afterwards the growth is set to 0%/year. In addition, the other measures outlined in the *medium increase* scenario are also implemented, which includes modal shifts, new infrastructure, and energy efficiency improvements. As displayed in Figure 60, if transport demands are maintained at 2020 levels, then the *recommendable* scenario will only require 108 PJ/year for transport instead of 135 PJ/year in the *medium increase* scenario and 175 PJ/year in the *high increase* (BAU) scenario. In line with this total energy consumption drop, the *recommendable* scenario will require 42 PJ/year of bio-based fuels and 42 PJ/year of electrofuels in the '*no increase*' scenario, which is a reduction of 20% and 21% respectively compared to the *medium increase*. No additional costs have been added to account for the measures required to stop the growth in the transport demand after 2020 and hence, no concrete conclusions are available in relation to its feasibility. However, the results in Figure 60 verify that existing transport demands can be met using a sustainable level of bio-based and hence, further reductions in the forecasted increase for the transport demand should be considered. This will not only make it easier to reach 100% renewable transport sector in Denmark, but it will also benefit a fossil fuel based transport sector in Denmark by minimising the demand for imported oil.

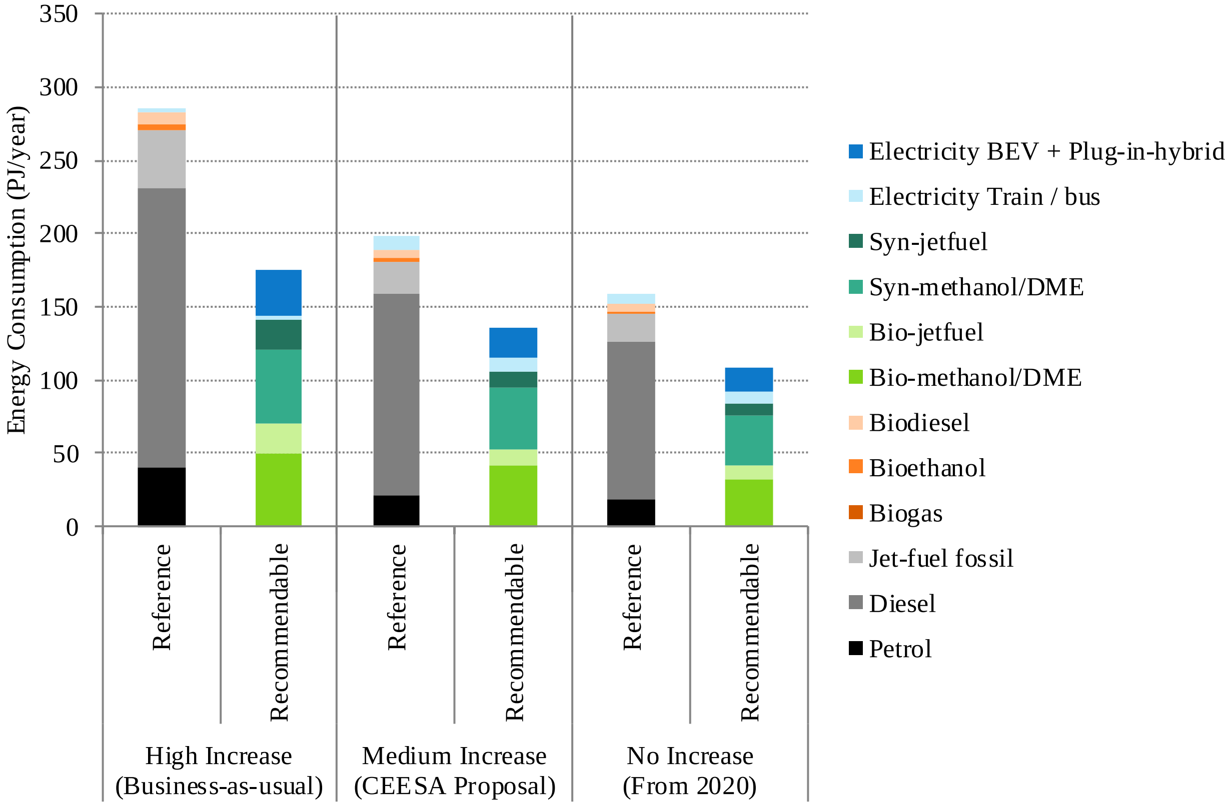

Figure 60: Energy consumed by fuel type in 2050 for the *reference* and *recommendable* scenarios with a *high increase*, *medium increase*, and *no increase* (from 2020) in the transport demand.

6 Recommended Scenario from the CEESA Project

Some results have already been presented for the *recommendable* scenario in previous chapters, when comparing it to the *conservative, ideal* and *high increase* alternatives. Here the focus is on the *medium increase recommendable* scenario only, since this is the final scenario recommended from the CEESA project. A detailed breakdown of the energy consumption and costs relating to the *medium increase recommendable* scenario is presented.

6.1 Energy Consumption

Figure 61 illustrates the energy demands for the *reference* and *recommendable* scenarios from 2010 to 2050 with the *medium increase* in the transport demand. Similar to the timeline presented in Figure 55 previously, it is clear from the results below that direct electrification and bio-methanol/DME should be introduced by 2020 to begin the transition to a 100% renewable transport sector. As CO_2-methanol/DME production develops, it will also supplement the bio-methanol/DME as an additional liquid fuel and thus reduce the dependency on biofuels. Since the vehicles used in the *recommendable* scenario are more efficient than those used in the *reference*, there is an overall energy reduction of approximately 118 PJ/year between 2010 and 2050 in the *recommendable* scenario, even though the transport demand is increasing (particularly for freight transport).

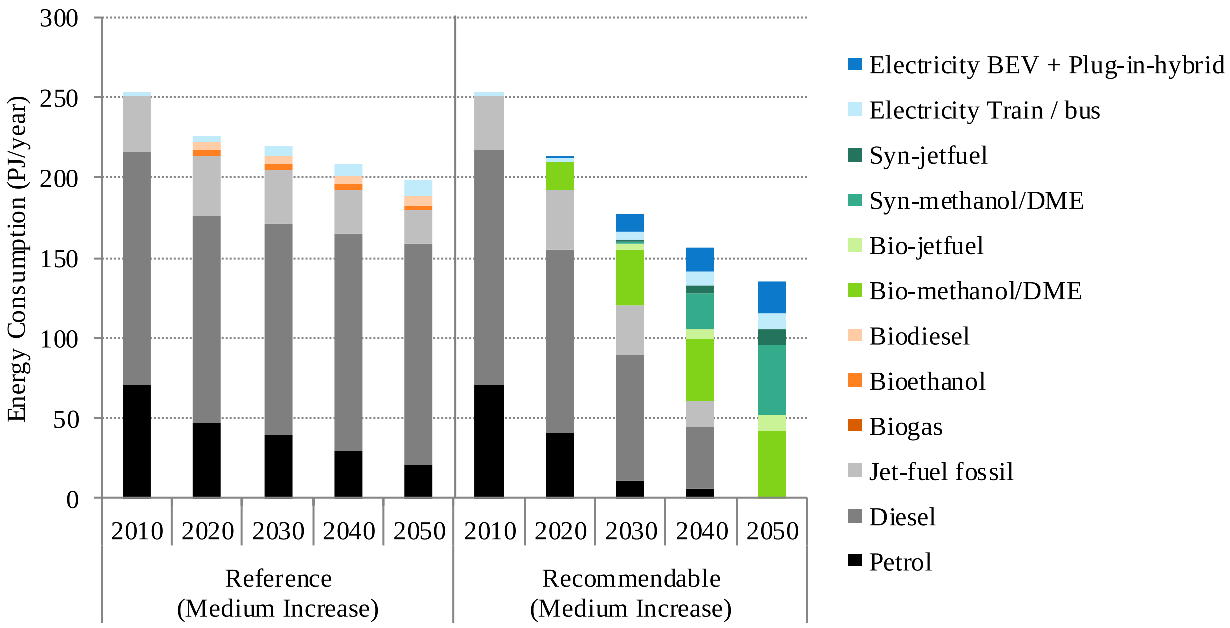

Figure 61: Energy consumed by fuel type for the *reference* and *recommendable* scenarios between 2010 and 2050 for a *medium increase* (CEESA proposal) in the transport demand.

Looking at the energy consumed for passenger transport only, Figure 62 indicates that the energy used for cars is reduced by 78% in the *recommendable* scenario from 92 PJ/year in 2010 to 20 PJ/year in 2050. Although this is primarily facilitated by the direct electrification of 75% of vehicles, 17 PJ of this reduction is also achieved by implementing the new *medium increase* demand. This is evident from the increasing energy demands for rail transport which doubles from 4 PJ/year in 2010 to 8 PJ/year in 2050. It is important to recognise that these changes will not occur naturally and hence they must be encouraged through strong political, regulatory, and financial supports from the Danish government. Moving the transport demand from roads to public transport will only be possible if adequate infrastructure is put in place to support this transition and as displayed in Figure 62, the consequential reduction in fuel demands are very significant. The aviation sector reduces its demand by 35% over the 40-year period, which is primarily related to the 50% energy efficiency improvements forecasted by the industry by 2050: without this single measure alone the demand for passenger aviation would be almost double in 2050 at approximately 43 PJ/year. Reducing the growth in transport demand is also an essential change for passenger aviation, since these measures reduce the energy consumed in the sector by approximately 18 PJ/year. Once again, this demonstrates the importance of strong policy within the transport sector to ensure an energy demand is reached which can be met sustainably. Finally for passenger transport, the marine sector maintains a relatively stable energy demand between 2010 and 2050 of approximately 3 PJ/year.

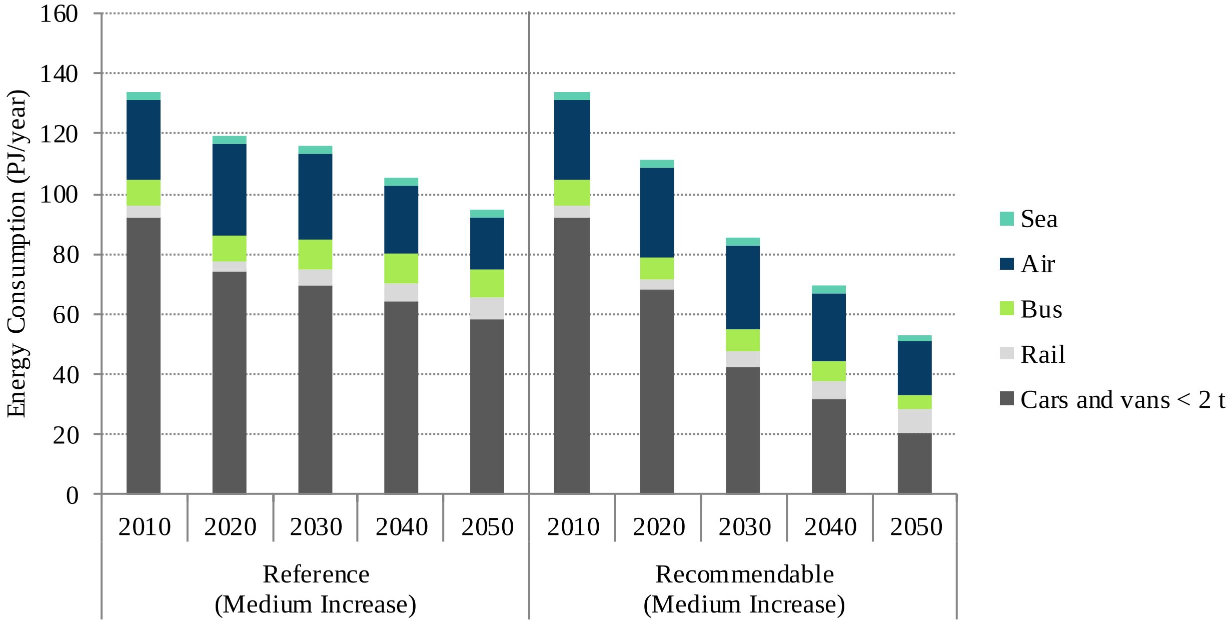

Figure 62: Energy consumed for passenger transport by mode of transport for the *reference* and *recommendable* scenarios between 2010 and 2050 for a *medium increase* (CEESA proposal) in the transport demand.

Even though the overall freight transport demand has not been reduced significantly in the *medium increase* demand forecasts, the energy demand is less in the *recommendable* scenario than in the *reference scenario* since more efficient vehicles are used. By 2050, road transport is still the primary consumer for freight, as it accounts for approximately 69% of the total energy, which is 57 PJ (see Figure 63). Aviation plays a less significant role with a consumption of 4 PJ in 2050 compared to passenger transport where it requires 17 PJ. Ships consume a relatively low amount of energy (5 PJ) considering that they provide approximately 70% of the freight transport demand. Therefore, in the future additional measures could be put in place to reduce the road transport demand for freight, since this has remained a large energy consumer in 2050.

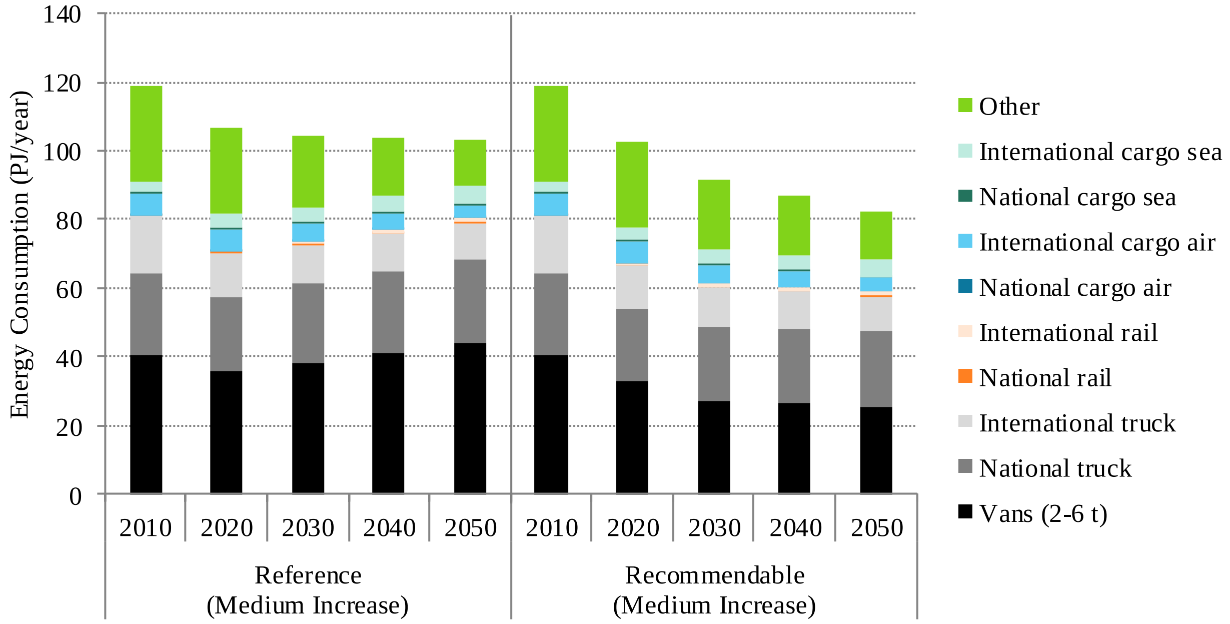

Figure 63: Energy consumed for freight transport by mode of transport for the *reference* and *recommendable* scenarios between 2010 and 2050 for *a medium increase* (CEESA proposal) in the transport demand.

6.2 Transport Sector Costs

Unlike other sectors in the energy system, investments are a more significant proportion of the costs than fuel in the transport sector. Before comparing the costs, it is important to distinguish between two general categories:

- Transport technology costs: these costs include fuel/energy, vehicle, vehicle O&M, and EV charging stations. These costs are different for each transport technology scenario considered i.e. *reference*, *conservative*, *ideal*, and *recommendable*.
- Transport demand costs: these costs include the O&M for road infrastructure, new road infrastructure, O&M for rail, new rail infrastructure, and other. The other category includes the costs for ITS systems, expanding the use of bikes, buses, and training.

Both the *reference scenario* and the *recommendable* scenario in Figure 64 are based on the *medium increase* transport demand. Hence, only the transport technology costs vary in Figure 64 since both contain the same road and rail infrastructure. The results in Figure 64 indicate that the total cost of the *recommendable* transport scenario is very similar as in the *reference* transport scenario. In line with expectations, the *recommendable* scenario has higher vehicle and vehicle O&M costs, but the fuel/energy costs are lower than in the *reference scenario*. As displayed previously in Figure 61, the *reference* only uses approximately 3% biofuel and 5% electricity in 2050, so the highest cost in the *reference* transport system is fuel/energy, which represents 26% of the total. However, as displayed in Table 7 and Table 8, the 2050 *recommendable* scenario has a lot of new and more efficient transport technologies, so the fuel/energy component of the costs is lower compared to the *reference*. This means that the overall demand for energy in the *recommendable* scenario is lower than in the *reference scenario*.

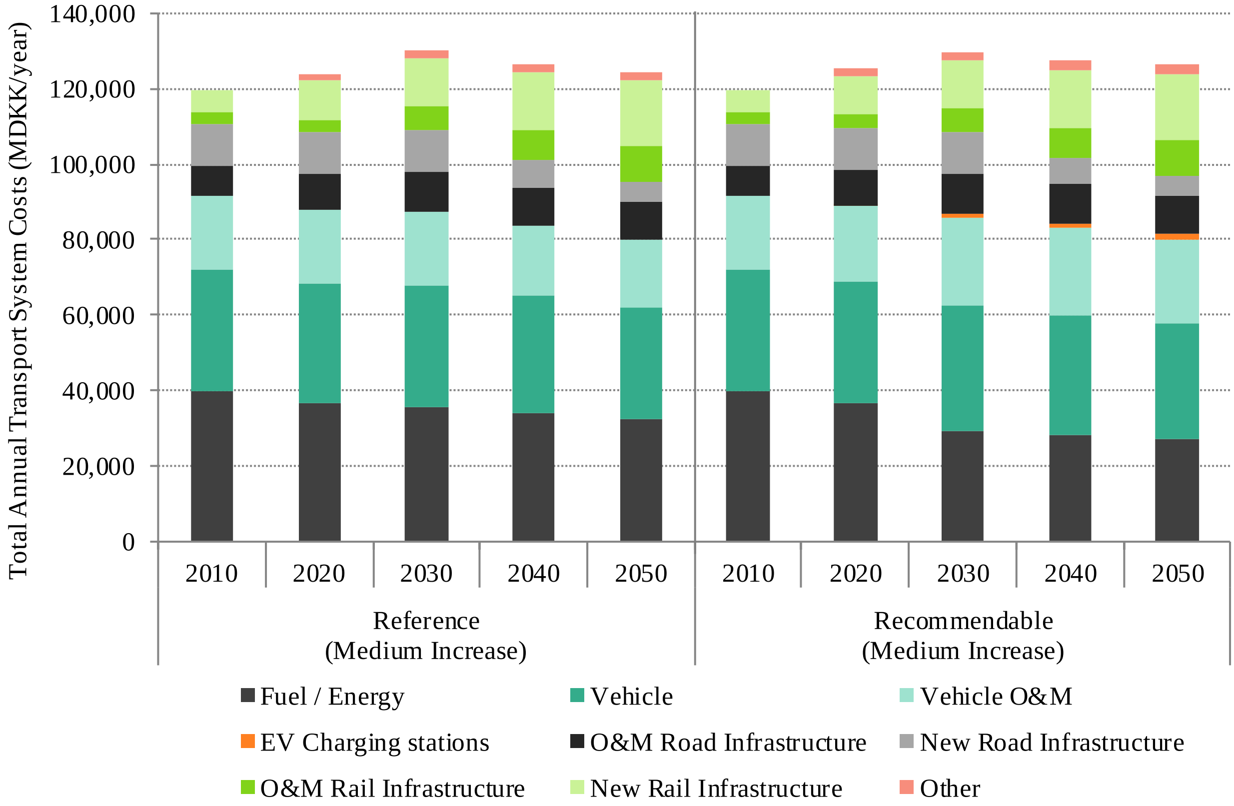

Figure 64: Total annual transport system costs for the *reference* and *recommendable* scenarios between 2010 and 2050 for a *medium increase* (CEESA proposal) in the transport demand.

Since the fuel costs are quite different in the two scenarios, it is important to recognise how they are calculated. As outlined in Figure 65, the fuel/energy costs are made up of four key components: fuel, CO_2, O&M, and investment costs. To calculate the energy costs relating to transport, the total cost of the fuels and technologies required to meet the transport demand are calculated under each of these headings. For example, in the 2050 *recommendable* scenario, the fuel/energy component contained a very large amount of investments, since a large proportion of the *recommendable* transport demand is met by electricity from wind turbines and electrolysers (see Figure 61).

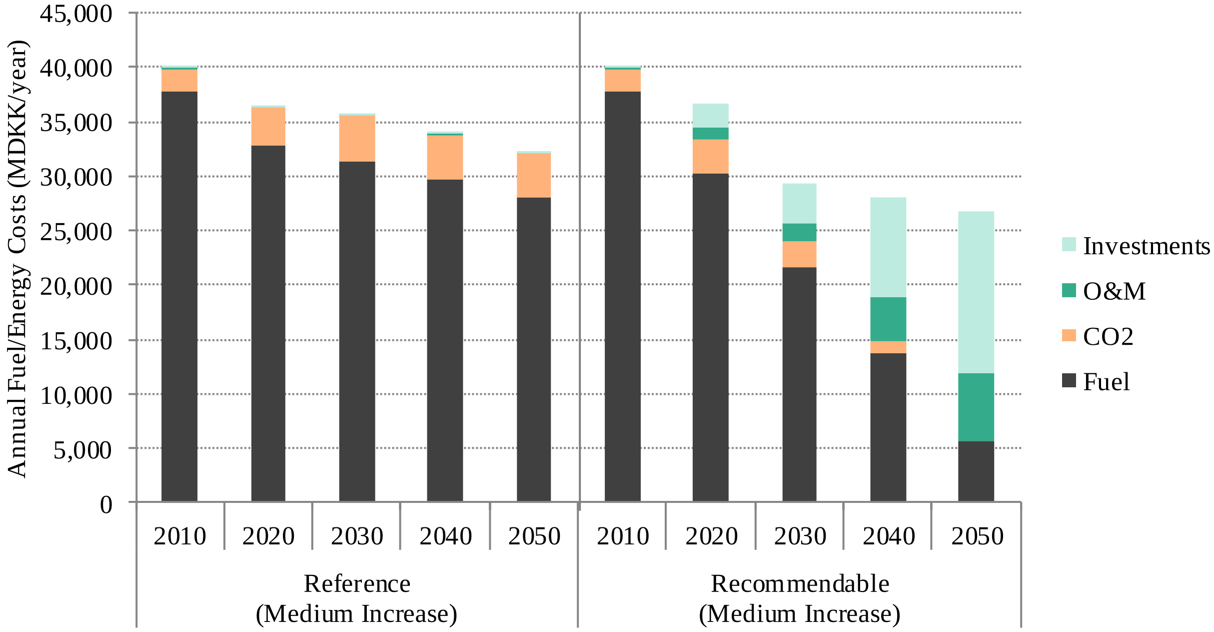

Figure 65: Annual fuel/energy costs for the *reference* and *recommendable* scenarios between 2010 and 2050 for a *medium increase* (CEESA proposal) in the transport demand.

7 Conclusions

An 'optimum' technology cannot be defined based on one single metric, but consists of many quantitative and qualitative assessments. As already described in this report, the metrics included here are land use, resource availability, efficiencies, costs, and overall energy system integration. Based on these metrics, it is concluded that electricity should be utilised wherever possible in the transport sector. In other areas, where electricity is not suitable, bioenergy (bio) or CO_2 (syn) based fuels which are boosted by hydrogen from steam electrolysis should be utilised (i.e. electrofuels). It is still unclear how the share between bio and CO_2-electrofuels will develop: bio-based liquid fuel is limited by the resource available, while CO_2-based liquid electrofuel is relatively expensive and some of the technologies required are still at the early stages of development. Hence, in the *recommendable* scenario, there is an equal share of both bio-based fuels and electrofuels where direct electrification is not possible. However, even with these dramatic technological developments, there is still an overreliance on the Danish bioenergy resource.

To further reduce bioenergy consumption, an alternative transport demand is constructed called the *medium increase*. The transport demand reductions are achieved by modal shifts (primarily from road to rail), increased public transport shares, and improvement the energy efficiency of vehicles. By combining the measures in the *medium increase* demand scenario, with the technologies in the *recommendable* scenario, a final solution is proposed from the CEESA project. More research will be necessary to create more certainty in the *recommendable* scenario, but based on the results in this report, it is possible to make the following conclusions:

- **The methodology utilised in this report is subject to many uncertainties and only reflects what we know today.**
  Any forecast of the future is always subject to many uncertainties and this research is no different. This is particularly true when assessing radical technological change over a 40-year period. However, due to the lifetime of the infrastructure in the energy system, decisions taken now will affect how the energy system in 2050 functions. Based on existing literature, expert group meetings, and interviews with many industrial representatives, the *recommendable* scenario has been constructed in CEESA to represent the most realistic projection of how the Danish transport sector can become sustainable by 2050. Naturally, as new research is completed, this will change and evolve, but even now it is still possible to make a number of concrete conclusions. This is particularly true for the transport sector, since the bio (i.e. biomass hydrogenation) and syn (i.e. CO_2 hydrogenation) also provide indicative results for similar technologies which may in the end develop faster (i.e. fermentation and co-electrolysis respectively).

- **The transport demands in Denmark should not be allowed to increase as much as currently forecasted.**
  These growth rates can be reduced by a variety of actions such as:
    - Building new infrastructure for electric rail and biking, to get passengers and freight transport off the roads and onto more sustainable modes
    - Creating economic incentives which could be road pricing, congestion charging, removing travel subsidies for private cars, restructuring car tax to reflect the distance travelled and the efficiency of the vehicle used, reducing the subsidy on company cars, introducing a CO_2 tax, and reducing taxes on public transport
    - Introducing new regulations which could be long-term spatial planning, energy efficiency improvement regulations for vehicles, information technology systems

which provide consumers with more information, and regulations which encourage local production of goods.

- **Direct electrification should be utilised as much as possible, then biomass hydrogenation is recommended to the point where the residual bioenergy resource is utilised and finally, CO_2 hydrogenation is recommended to supply any shortfalls.**
  The most efficient and sustainable fuel identified here for the transport sector is electricity and so it should be utilised as much as possible. However, since electricity cannot be stored and transported at high energy densities, it is not possible to use electricity for all applications such as trucks, aeroplanes, and ships. To support electricity, some form of energy-dense fuel is necessary. Based on existing knowledge, it is very difficult to identify the 'optimal' fuel to do this, especially due to the complex matrix of issues that need to be considered. For example, it is not just about the efficiency of creating the fuel, but also the sustainability of the resources utilised and the uncertainties related to the technologies required. However, after considering these based on existing knowledge and forecasts, this study concluded that biomass hydrogenation seems like the most sustainable method to create methanol or DME in a 100% renewable energy system, until there is no more residual bioenergy available. After this point, steam electrolysis and carbon capture technologies will most likely be required to create CO_2 electrofuels (CO_2-methanol/DME). In this way, the most efficient pathway (i.e. biomass hydrogenation) is used as much as possible without becoming unsustainable.

- **Improving the process of creating electrofuels should be the focus in the short-term rather than defining the exact type of electrofuel to produce.**
  There are many different options to both produce and supply electrofuels [13]. Ultimately they **require** some form of carbon and hydrogen, which can then be combined in different ratios to **produce** many different types of fuels. In this study, some key distinctions were developed on both sides of this balance. As discussed in the previous point, in terms of their 'requirements', electrofuel pathways were defined for two different types of carbon sources: bioenergy and CO_2. In relation to the hydrogen, this was always produced from electricity in the scenarios proposed here, with intermittent electricity production prioritised where possible. On the opposite side, it is assumed in the final scenarios of CEESA, that the electrofuel produced is methanol. The well-to-wheel efficiency of methanol is very similar to dimethyl ether (DME): although methanol is more efficient to produce, DME compensates for this since it can be used in more efficient diesel-engines. Therefore, the pathways produced here represent both methanol and DME. It is important to emphasise that methanol/DME is only chosen here to represent one potential method of producing electrofuel. For example, the transport sector could potentially more towards more gas-based technologies and in this case, methane may be a more suitable electrofuel. Although a brief comparison was carried out here between methanol/DME and methane, there is still too much uncertainty to fully conclude which electrofuel will be 'optimal' in the future. In any case, the electrofuel pathways share so much common infrastructure, such as biomass gasification, carbon capture, and electrolysis, that the key focus in the short-term should be on developing these components rather than defining the exact fuel that will be necessary at the end of the transition.

- **A 100% renewable energy transport sector is technically possible and economically feasible.**
  If the 100% renewable *recommendable* scenario from CEESA is implemented, it will cost approximately the same (within +/-5%) as the business-as-usual *reference scenario* which is dependent on fossil fuels. The type of costs will be very different since the *recommendable* scenario requires a lot of investments in local transport and energy infrastructure, whereas the

primary cost in the *reference scenario* is imported oil. Furthermore, the *recommendable* scenario is a 100% renewable scenario so it does not have any carbon dioxide emissions. Therefore, considering the costs are the same, the CEESA *recommendable* scenario should be implemented.

- **It is possible to recommend a number of specific actions for the Danish transport sector between now and 2020.**
  These recommendations relate to both technologies and demand reductions. These are:
    - The growth in transport demands should be reduced by using some of the suggested techniques above i.e. the infrastructural, economic, and regulatory changes.
    - Direct electrification should be promoted as much as possible. For example, electric vehicles, urban electric rail, and intercity high-speed electric rail should be facilitated to move both passengers and freight from road to rail transport.
    - Biomass gasification is a key technological bottleneck in the biomass hydrogenation pathway (as well as for other sectors in the energy system). The development of this technology should be prioritised to begin producing bio-methanol/DME from residual biomass resources.
    - Carbon capture and electrolysers are key technologies which need further development to produce CO_2-methanol/DME. Although these should also be supported, the development of biomass gasification is more important in the short term.

Finally, the transport scenarios constructed here are also utilised in the CEESA-WP1 report to investigate their impact on the complete energy system [1].

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9 Appendices

A. TransportPLAN

B. Reference Model 2010

C. Reference Scenario 2010-2050

D. Technology Data Sheets for Vehicles and Infrastructure

E. Vehicle Energy Consumption

F. Considerations Regarding Future Aviation