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STUDENT REPORT

A scenario analysis of the decarbonisation of the Danish transport sector

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Resumé (Danish abstract)

I december 2019 blev alle Folketingets 13 partier enige om en klimalov, der indeholdt et mål om at nedsætte nationale CO_2 emissioner med 70 pct. inden 2030 i forhold til 1990-niveau. Der blev ikke formuleret sektorspecifikke reduktionsmål og alle sektorer er derfor ikke bundet til at opnå samme reduktion. Analyser på området forventer ikke, at transportsektoren kan bidrage nævneværdigt i opnåelsen af målet og der stilles derfor store krav til den resterende energisektor. I dette speciale, vil det igennem en scenarieanalyse undersøges i hvilken grad CO_2 emissioner fra transportsektoren kan mindskes inden 2030 og hvilke virkemidler, tekniske og planlægningsmæssige, der skal til for at opnå CO_2-neutralitet inden 2050.

Planlægningsparadigmer inden for transportplanlægning har igennem årtier forårsaget en bilafhængighed, og en direkte sammenhæng mellem økonomisk udvikling og et øget trafikarbejde. Denne udvikling har sat præg på transportinfrastrukturen og det har vanskeliggjort en fremtidig udvikling mod mere transport i offentlig transport samt en større andel af ture udført på cykel og gåben. For at overkomme bilafhængigheden og mindske energiforbruget og CO_2 udledningerne fra transportsektoren anvendes i nærværende speciale "Avoid, shift, improve" (ASI) metoden, introduceret i Europa Kommissionen. ASI metoden benyttes til at designe to typer af scenarier; teknologiscenarier og transportbehov scenarier. Der udformes to teknologiscenarier, et realistisk og et optimistisk. De to teknologi scenarier udformes på baggrund af en dybdegående analyse af forventningerne til teknologiudvikling og markedsindtog fra brancheorganisationer og forskere. Transportbehov scenarierne analyseres for at undersøge effekten af at afbøde væksten i transportbehovet. To scenarier sammenlignes med reference scenarier; ét hvor væksten i det årlige trafikarbejde halveres og ét hvor væksten i det årlige trafikarbejde sættes lig nul.

De to teknologiscenarier nedsætter den årlige CO_2 udledning med henholdsvis 24 pct. og 45 pct. i 2030. Det kan således konkluderes, at transportsektoren kan bidrage med markante CO_2 reduktioner inden 2030, hvis teknologiudviklingen tillader det. Fra 2030 til 2050 opnår begge scenarier CO_2-neutralitet, ved hjælp af en omfattende elektrificering og brug af elektrofuels. Nedsættelsen af vækstraten for trafikarbejdet har mindre effekt på det samlede energiforbrug og deraf CO_2 emissioner. I 2030 er det muligt at sænke det årlige energiforbrug i transportsektoren med op til 14 pct., mens det kun er muligt at nedsætte energiforbruget med 4 pct. i 2050 ved at sænke vækstraten for trafikarbejdet. Derimod er det muligt at nedsætte de samlede årlige transport system omkostninger markant ved at sænke vækstraten for trafikarbejdet.

En omfattende elektrificering af transportsektoren og indfasning af elektrofuels vil kræve en udbygning af den vedvarende elproduktionskapacitet. At sænke vækstraten for det samlede trafikarbejde vil kræve omfattende strukturelle ændringer både i transportinfrastrukturen og i opfattelsen hos den enkelte trafikant. Transport er i høj grad præget af vaner og adfærd, som skal ændres for at opnå modal skift fra biler til offentlig transport.

Preface

This Master's Thesis has been carried out at Aalborg University in Copenhagen at the Master's programme Sustainable Cities. The project period ran from February 3rd, 2020 until June 4th, 2020.

This thesis deals with the decarbonisation of the Danish transport sector, through a scenario analysis of technological development and a consideration of planning procedures to limit traffic work growth rates.

I would like to thank my supervisor, Brian Vad Mathiesen, for his helpfulness and constructive critique throughout the project period. His enthusiasm for the project helped me to keep focus in times, when it was needed.

June 4th, 2020

Mikkel Strunge Kany

Contents

1. Introduction

The transport sector represents nearly one quarter of European greenhouse gas emissions. While other sectors have seen a gradual decline in emissions since 1990, the emissions from the transport sector has increased in this period. [1], [2]

In Denmark, the transport sector was accountable for 45 pct. of all national CO_2 emissions in 2018. The tendency of increased CO_2 emissions from the transport sector is apparent in a Danish context too, the emissions has thus increased from 10.9 million tons CO_2 in 1990 to 13.5 million tons in 2018 (outlined in Figure 1). The emissions from the transport sector are emitted primarily from the burning of fossil fuels in combustion engines. The road transport is accountable for the majority of the emissions approximately 70 pct. while international aviation and maritime transport accounts for 27 pct. [3], [4]

In 2019 ambitious targets was formulated by the Danish parliament to reduce total CO_2 emissions by 70 pct. in 2030 compared to 1990 and achieve climate-neutrality by 2050. No sector-specific targets were formulated, hence some sectors may contribute more than others in achieving the target in 2030. [5]

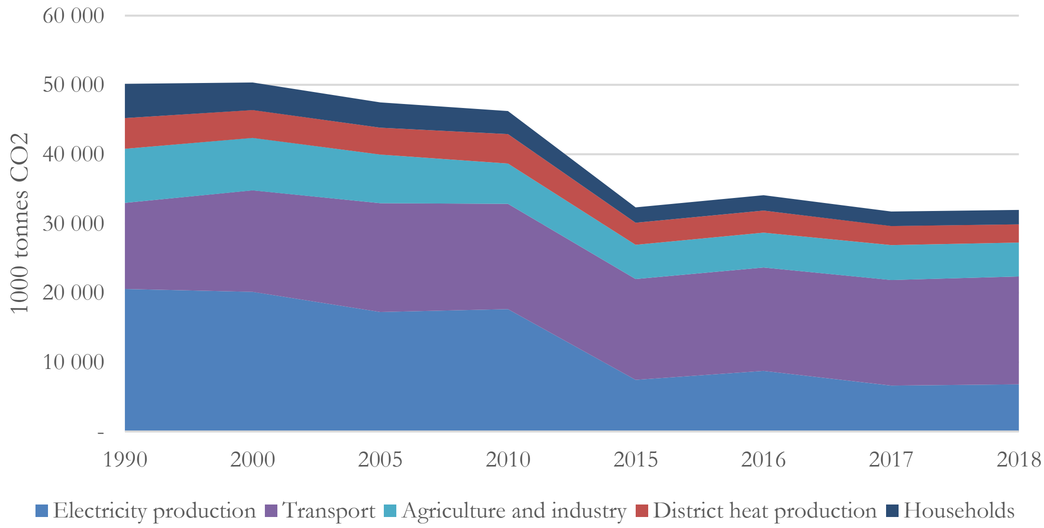

Figure 1. National CO_2 emissions from 1990 to 2018 divided by sector. [3]

Previous studies show that in a renewable energy system transition, the transition of the transport sector implicates the greatest uncertainties. The scale of the sector in terms of energy consumption and CO_2 emissions along with diversity of the sector require innovative solutions, in order to provide a sustainable pathway for a renewable transition. The energy consumption of the Danish transport sector is, together with the energy consumption in households, the single biggest energy consumer in the Danish energy system. The energy consumption in the transport sector has increased approximately 30 pct. from 1990 to 2018. This increase has been observed while the energy efficiency of cars has improved 50 to 60 pct. from 1997 to 2018. The increase in total energy consumption is thus due to a substantial increase in the transport demand. The passenger transport demand (passenger kilometres) has increased 23 pct. from 1990 to 2018. [3], [6], [7]

The transport sector is not expected to contribute noticeably in achieving the targeted CO_2 reduction in 2030. Reports and roadmaps analysing the development of the Danish energy system towards 2030, expects only small contributions from the transport sector, but finds that achieving a 70 pct. reduction is difficult without significant intervention with the energy consumption in the transport sector. [8]–[11]

The transport sector is complex and has been inherently difficult to decarbonize, and most research suggest that it will stay that way in the coming decade. Hence, several studies [12]–[15] have considered a long-term renewable transition of the transport sector, both in a national or European scope, but so far, very few have deliberately analysed the possible CO_2 reductions towards 2030. Fossil fuels, such as petrol and diesel, comprise over 90 pct. of the energy consumption in the transport sector and no single type of fuel is expected to be able to drive the decarbonisation, due to the variety of technologies, transport modes and demands in the sector. [6]

The growth in transport is tightly linked with the growth in gross domestic product (GDP). Reducing transport demand growth may interfere with economic development. A key parameter is to find a solution to decarbonise the transport sector without limiting the possibility for mobility and economic development. Historically, the transport sector has been decoupled from the rest of the energy system, but a renewable transition of the transport sector will require innovative measures and solutions to create valuable synergies between especially the electricity production and grid to implement renewable electricity in the transport sector. [13], [16]

2. Research question and delimitation

To reach the 2030 target of a 70 pct. reduction of Danish CO_2 emissions, the transport sector must contribute. In this work, both the contribution towards the 2030 target and the pathway towards a zero emission transport sector in 2050 are considered. The research question that will form the setting of this thesis is:

How can the Danish transport sector contribute to reduce national CO_2 emissions with 70 pct. in 2030 and pave the way towards a fully renewable transition and a zero emission Danish transport sector in 2050?

A renewable transition will require creations of synergies between the transport sector and the surrounding energy system. Synergies will have implications for the electricity sector especially, where additional capacity may be necessary to power the development.

In this thesis, the development of the transport sector is analysed separately. The implications, that the renewable transition will have on other sectors of the energy system will not be thoroughly analysed. Hence, in the analysis of this report, scenarios for a renewable transition of the transport sector are explored and a complete energy system analysis is omitted. This delimitation will affect the totality of the derived conclusions, but is made to allow for a deep dive into the possible developments within the transport sector. The delimitation is reconsidered in the final parts of the thesis, where the implications of implementing renewable transport scenarios for the development of the entire energy system are considered.

2.1. Report structure

This thesis is divided into 10 chapters. After the introduction of the problem area of consideration and the research question follow the theoretical framework. The theory of wicked problems and the "avoid, shift, improve" paradigm will form the basis of the report. The methodology outlines the strategy with which the research question will be answered and how data collection is conducted.

Following the methodology is the analysis presented. The analysis is split into three parts:

- A review of the development of the Danish transport sector from 1990 to 2017,
- an in-depth analysis of measures to avoid and shift transport demand and technologies to improve energy efficiency and reduce CO_2 emissions of the transport sector and
- a scenario analysis of the implementation of renewable transport technologies and measures to decrease the annual traffic work (km).

Following the analysis, a brief reflection where the implications of the transport scenarios on the entire system is conducted. Subsequent is the possibility of reducing the growth rate of the transport demand discussed and the role of shared mobility is considered. Finally, the conclusion sums up the core findings and results. The report structure is outlined in Figure 2.

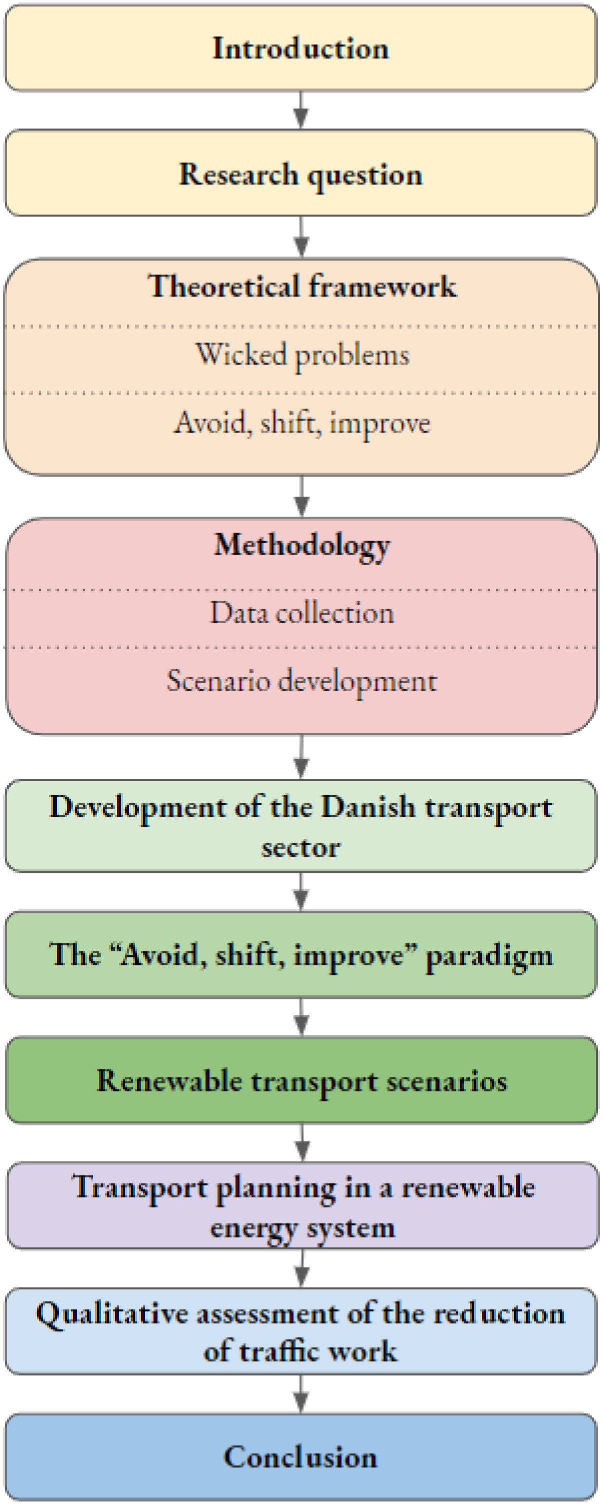

Figure 2. Report structure.

3. Theoretical framework

In the following, the theory of wicked problems is presented and it is argued, why it fits so well with the problems planners face when working on solutions to mitigate climate changes and transition of the transport sector towards 100 pct. renewable energy. The "Avoid, Shift, Improve" paradigm is introduced to serve as an analytical framework to interpret and comprehend the entangled problems in transport planning.

3.1. Wicked problems

Design or planning tasks are regularly considered as wicked problems, where scientific procedures fail to come up with complete solutions. Churchman [17] defines wicked problems as "*problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing.*"

The theory of wicked problems was introduced by Horst Rittel in the 1960's and was conceptualised in 1973 in partnership with Melvin Webber. Rittel and Webber argue that planning tasks are wicked due to the nature of these problems. Wicked problems contrasts with tame problems, which are well-formulated and well-defined problems. Tame problems have precise solutions and known practices to attain these solutions. Examples of tame problems include achieving checkmate in a number of moves, proving mathematical theorems or traversing a maze. [18]

Planning problems are inherently different from archetypal scientific problems. Rittel and Webber discuss that planning problems are wicked when scientific uncertainty coexists with uncertainty of valuation, thus creating a tangled web of conflicting objectives and values, political complexity and multiple stakeholders [18]. Balint et al. [19] formulates in Table 1 the dependency between state of knowledge and agreement on values and determine, how these factors are critical when dealing with planning problems.

	Agreement on values	
State of knowledge	High	Low
Well developed	Routine analysis with periodic stakeholder and expert review. Decisions are easy.	Emphasis on stakeholder deliberation with periodic expert review.
Tentative/gaps/disagreements/research needed	Emphasis on expert deliberation with periodic stakeholder review.	Emphasis on both stakeholder and expert deliberation. Wicked problems!

Table 1. The dependency between state of knowledge and agreement on values regarding decision problems. From tame, easy problems to wicked problems. [19]

The subject of planning become wicked, as the agreement on objective and values may be unclear from the beginning. This is often the case in integrated systems, where many stakeholders have interests at stake. The context of the planning procedure makes it difficult to test solutions before implementation, hence making the decision process even more critical. As a consequence, the method to address wicked problems often become intrinsically political. [20]

Rittel and Webber describe wicked problems with ten properties that illustrate, how wicked problems can be unrestricted and controversial [18]:

1. There is no definitive formulation of a wicked problem
2. Wicked problems have no stopping rule
3. Solutions to wicked problems are not true-or-false, but good-or-bad
4. There is no immediate and no ultimate test of a solution to a wicked problem
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan
7. Every wicked problem is essentially unique
8. Every wicked problem can be considered to be a symptom of another problem
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution
10. The planner has no right to be wrong

Wicked problems are difficult to accurately define, as the problem is often caused by numerous underlying wicked problems. Different stakeholders define the problem differently, and consequently a unique formulation of the problem cannot be made. Hence, it is difficult to produce a satisfying solution. Conflicting objectives and valuation of outcomes are fundamental elements of a wicked problem.

Solutions to wicked problems, Rittel and Webber argue, are "one-shot operations" and a method of trial and error is not a possibility for a planner when faced with a wicked problem. This argument has been challenged by several social scientists, who reason that no wicked problem is solved with a single, one-shot solution. Wicked problems, they argue, are improved by several individual solutions, but are never completely solved, and if they are, new wicked problems will have been created in the wake of the solution process. Rittel and Webber have since proclaimed that wicked problems *"are never solved. At best they are only resolved – over and over again".* [18], [21], [22]

Noticeable from the ten properties of wicked problems is, that one of the difficulties planners face when confronted with wicked problems is identifying the cause-effect relationships. Property one to nine, except property three, essentially describes how there exist no quick fixes to a wicked problem, as the entirety and actual cause of the problem is seldom known to the planner, which makes it inherently difficult to come up with an exhaustive solution that will end the problem. Rittel writes in 1972: *"In order to give exhaustive information ahead of time for a wicked problem you have to anticipate all potential solutions first"* and continues in 1973, that finding the fundamental cause of a wicked problem *"is thus the same thing as finding the solution; the problem can't be defined until the solution has been found".* [18], [21]

A central conclusion to extract from Rittel and Webbers list of ten properties is, that wicked problems are never actually solved. Wicked problems are dynamic and depend on other problems. It is possible that a solution can improve the situation of a wicked problem, but the planner cannot know before the solution is implemented. Tame problems will have no noteworthy costs for failed solutions, while the situation is different for wicked problems, for which solutions have irreversible consequences. Rittel and Webber argue that urban planners might attempt to solve the problem of road congestion in cities by proposing a new freeway, but it is not possible to build the freeway to see if it solves the problem, and tear it down again if it fails. The costs and consequences would be too comprehensive. Solutions to wicked problems are subsequently often reason for specific path dependencies. The example of constructing a new freeway, might cause additional traffic on the roads, thus causing a new problem in years to come with car-dependent infrastructure and extensive environmental effects. This example has been observed by urban planning scientists and supports the arguments made by Rittel and Webber. [18], [21], [23]

3.1.1. Transport planning as a wicked problem

Decarbonizing the Danish transport sector is contributing to the recognized problem at hand of limiting national CO_2-emissions and assisting to mitigate the global climate crisis. The transport sector is a significant contributor to both national and global greenhouse gas emissions. Decarbonisation of the transport sector must then be one of several solutions to limit the effects from climate change and global warming.

To define the problem and hence solutions for the decarbonisation is more difficult. The transport sector is dynamic and the need for transportation is increasing. The demand for transport of passengers and goods have increased manifold in the course of the last centuries, especially since private cars have become common property and international travels an integrated part of many peoples life. Meanwhile, most of the transportation technologies used today have been known for decades. The internal combustion engine have increased its efficiency, but the technology has not changed notably since the commercialisation in the early 20th century. [24]

Traffic and congestion are often a primary focus in transport planning. Traffic and congestion are typical wicked problems, as the cause/effect relationship is inherently difficult to determine. Hendriks [25] summarizes the conflict:

"Does the stream (of cars) fit into the bed? And if not, which of the two should be adjusted?"

Whether the amount of cars on the roads are the essence of the problem or if it is the width of the roads, the problem is wicked, as the problem is not solved by building wider roads for instance. A solution like that may postpone the problem, but not solve it indefinitely. Reducing the amount of cars allowed on the roads, would create collateral problems of people not being able to transport themselves to where they need to be. Solving the wicked problem of traffic and congestion has no stopping rule and is thus never truly solved.

The development of urban planning and the perception of mobility in transport planning has led to an automobile dependency. Newman and Kenworthy outlines three essential developments of the concept of transport in cities [24], [26]:

- Walking cities
- Transit cities
- Automobile cities

Traditionally urban planning focused on accommodating travellers on foot. Walking cities, where the size of cities allowed for walking and essential services where in walking distance of housings and employments. Walking cities were dense in terms of services and households. When trams and trains first entered cities, the new transport technologies allowed for expansions of urban areas and cities grew along the transit lines. This concept of transit cities is observed in the Fingerplan from Copenhagen. The public transit systems allowed people and commuters to travel longer distances and smaller dense sub-urban centres grew around stations. [24], [26], [27] When the private car became a common household property during the 20^{th} century, urban planning changed radically. Cities could grow between railway lines and the car allowed for very little density as people could make the transportation links themselves. Households, employments and essential services were placed farther apart and away from public transit. This urban development in turn created the phenomenon of automobile dependency. The car was no longer a choice but a necessity to reach essential services. The development of automobile cities is present in many parts of the world, most distinct in American metropolitan areas. This development assist in creating a lock-in situation, where the private car is perceived as a necessity and a symbol of freedom. Hence, limiting the transport in cars might be observed as an attack on personal freedom. [24], [26], [27]

Reardon and Wiegmann argue, that the increasing transport demand and steering the demand from governmental level is a wicked problem within the transport sector. Reardon argues that the transport demand in the United Kingdom has increased among other reasons because of the action or inactions from a governmental perspective. By building freeways and expanding the infrastructure for private cars, indirect incentives of encouragements to use the private car are given to the public. [23], [28]

Infrastructure investments in expansions of road capacity or enhanced public transport systems have been the primary mean in a Danish planning context to accommodate the growing need for mobility and avoid traffic congestions. This predict and provide approach has led to an extensive path dependency and induced travel for motorized transport. The predicted growth in transport demand is usually used to justify building new roads. Improved transport conditions and more transport choices will often lead to more travel, as people will have easier access to a larger area. As more road capacity is added to the transport infrastructure the convenience of transportation in personal vehicles increases. This development has consequently aggravated the wicked problem of decarbonizing the transport sector. To overcome the dependency of cars, urban development must be planned in a way that prioritize public transport and active modes of transport, such as walking and bicycling, before cars, to increase the willingness to abandon the cars. [29], [30]

The International Energy Agency (IEA) summarises the measures needed to decarbonise the transport sector under the slogan “Avoid, Shift, Improve” (ASI). These three categories features measures to overcome the growing transport demand and limit the use of fossil fuels. Avoid and Shift entails minimizing the need for transport and limiting the dependence on energy-intensive modes of transport. Improve consists of measures to enhance vehicle efficiencies to decrease the energy consumption while meeting the demand for transport. The three categories are meant to be implemented in prioritised order; the first priority is to avoid an increase in the total transport demand and limit the need for travel. The second is to shift transport demand from high-energy consuming transport modes to low-energy consuming modes and improve overall trip efficiency. The third priority is to improve transport technologies, hence if it is not possible to avoid transport demand growth and promote modal shifts, the high-energy consuming modes of transport must be improved. With the ASI approach, planners and policymakers can easily identify stakeholders and key areas of improvement. [16], [29], [31]

In this thesis it is argued, that transport planning in the context of decarbonisation is a wicked problem. Defining the cause of the problem is difficult. Planning in the transport sector usually involve long term solutions that financially and physically in the built environment often will create a certain path which is difficult to unfollow. Hence, the historic direction of developing the transport sector has created an ever more wicked problem, where the majority of the modes of transport rely on fossil fuels and modal shifts towards public transport is difficult. Transport planning never ends, thus solutions cannot solve the problem but only make it better or worse.

4. Methodology

In this section, the methodology used to analyse the Danish transport sector and develop scenarios towards decarbonisation is described. The general aim is to describe and analyse the potential CO_2 reductions from the Danish transport sector before 2030. In 2030, an objective to decrease the total national emissions with 70 pct. compared to 1990 is agreed upon in the Danish national parliament. A specific objective regarding CO_2 emission reductions for the transport sector has not been formulated. Furthermore, the development and pathway towards a full decarbonisation of the Danish transport sector in a long-term perspective towards 2050 is considered.

The first objective is to establish a detailed profile of the Danish transport sector as of today. This will provide information about where energy is consumed and which areas of the transport sector are important to focus on. Secondly, a method for developing renewable transport scenarios on short-term towards 2030 and long-term towards 2050 is formulated.

The renewable scenarios are developed based on the "Avoid, Shift, Improve" paradigm introduced in section 3. Two types of scenarios are designed; technology scenarios and transport demand scenarios. The technology scenarios focus on the *improve* category and the possibility of implementing renewable fuels and technologies towards 2030 and 2050. The expectations to the rate of implementation are based on an exhaustive review of the development and market uptake of alternative fuels and renewable transport technologies. The results of the technology scenarios alone, will show the implementation rates and technology developments needed to reduce the total CO_2 emissions in 2030 and completely decarbonise the transport sector by 2050.

The transport demand scenarios are developed to evaluate how to support the decarbonisation of the transport sector by reducing the annual transport demand. The transport demand scenarios will not represent solutions that are assessed as "ready to apply", but will represent possible benefits to reduce emissions and transport system costs. The transport demand scenarios are added to the technology scenarios and the corresponding energy consumption, CO_2 emissions and transport system costs of a lower transport demand are estimated. Measures to *avoid* an increase in the transport demand and *shift* from energy intensive modes of transport to less energy intensive modes are investigated and the impact on the technology scenarios is assessed.

When the scenarios are presented the transport scenario tool TransportPLAN is introduced. TransportPLAN is used in this thesis to analyse renewable transport scenarios.

4.1. Analysing and developing the transport sector

To analyse and evaluate the development towards a decarbonisation of the Danish transport sector a detailed breakdown of the sector is necessary. A definition of the different modes of transport and data regarding annual transport demand and energy consumption are required to determine the current state of the Danish transport sector. When the current transport system is mapped in detail, it is possible to identify improvements and recommend implementations of different measures to limit the energy consumption and thus limit greenhouse gas emissions.

In this thesis both passenger and freight transport are considered as well as both national and international transport. All transport inside of Danish borders is considered to be part of the Danish transport sector and its energy demand and emissions are included in the total. All transport outside of Danish borders, which is a consequence of Danish transport demand, such as international flights, trains or busses or export of goods departing from Denmark are also considered part of the Danish transport sector. When interpreting the results of the scenarios it is important to note that international transport is not considered in the 2030 reduction target. Hence, the contributions from the transport sector may be bigger than what is concluded in this work. The decision to include international transport in the analysis was made to accurately describe the emissions that the Danish transport demand is responsible for. In Figure 3 all 20 modes of transport considered are displayed.

Figure 3. Modes of transport considered in the report.

To create a robust foundation to build and develop scenarios from, a range of data is necessary to collect for each mode of transport. The four key parameters inspected to analyse the transport sector are transport demand, energy demand and emissions, fuels and technologies and transport system costs.

Within each parameter a series of subsequent data is collected to increase the level of detail. The parameters are uniform for both passenger and freight transport. The four parameters and the data that is collected are presented in Table 2 and described further below.

Parameter	Data collected
Transport demand	Transport demand (pkm/tkm) Traffic work (km) Vehicle capacity Capacity utilisation Trip purpose Trip length
Energy demand and emissions	Annual energy demand Specific energy consumption Fuel and technology specific CO_2 emissions per energy consumed
Fuels and technologies	Types of technologies Market share of technologies Fuel distribution Energy demand by type of fuel Number of vehicles Number of charging stations
Transport system costs	Vehicle investments Vehicle O&M Charging stations Infrastructure investment Infrastructure O&M

Table 2. The key parameters and data collected about the Danish transport sector.

4.1.1. Transport demand

To define and forecast the transport demand several inputs are required. The annual transport demand in passenger kilometres (pkm) for passenger transport and tonnes kilometres (tkm) for freight transport provides insight into the need for transportation. The traffic work (km) is the actual kilometres travelled. Given the transport demand (pkm/tkm) and the traffic work, it is possible to calculate the capacity utilisation. For passenger transport, this is stated as passenger per vehicle (p/vehicle) and for freight transport as tonnes per vehicle (t/vehicle). For some modes of transportation, data about the capacity utilisation can be found in literature, while it is more difficult for others and it must be calculated. To deduce something from the capacity utilisation the total vehicle capacity in passengers or tonnes is also necessary.

The transport demand is further divided by the purpose and length of trip. The purpose of trip is primarily investigated for cars and vans <2t, as the purpose of trip has a significant influence on the capacity utilisation. For both passenger and freight transport, the transport demand is categorised by the length of the journey. This has influence on the fuel efficiency of the transportation technology and provides the opportunity to execute more detailed technology implementations and modal shifts later in the scenarios.

4.1.2. Energy demand and emissions

The annual energy demand for each mode of transport is divided into energy demand by type of fuel. Given the traffic work (km), transport demand (pkm) and annual energy demand it is possible to calculate the specific energy consumption as MJ/km and MJ/pkm or MJ/tkm. The specific energy consumption per kilometres (MJ/km) is the actual efficiency of the fleet of vehicles, trains, ships or planes. The energy consumption per passenger or tonnes kilometres (MJ/pkm or MJ/tkm) provides information about how efficient the transport technology delivers the transport demand, and this makes it possible to easily compare different modes of transport. The comparison of specific energy consumption will provide the basis for modal shifts propositions.

For all technologies and fuels, the CO_2 emissions are calculated based on the energy consumption. The specific CO_2 emissions for each fuel type and technology are found in the Danish Energy Agency's published standard emissions factors. [32]

4.1.3. Transport fuels and technologies

There is a heavy majority of fossil fuels in the present Danish transport sector. The fuels and technologies influence the energy efficiency of the transport sector and thus the energy demand and CO_2 emissions. By identifying the current use of fuel and technologies and evaluating potential renewable alternative technologies, it is possible to transition the transport sector and lower the energy demand by increasing the energy efficiency with an implementation of alternative technologies.

Additionally, the number of vehicles for cars, vans, trucks and busses are calculated and the need for electric vehicle charging stations is estimated. The number of vehicles will correspond with the traffic work. An increase or decrease in the traffic work, will thus relate to an increased or decreased number of vehicles.

4.1.4. Transport system costs

The transport system costs is a key parameter for evaluating and comparing scenarios for alternative developments of the transport sector. The transport system costs considered in this work features the investment and operation and maintenance (O&M) costs related to vehicles. This relates to the investment in passenger vehicles, vans, trucks and busses. The costs associated with investment in trains, ships and aircrafts are not included, as relevant costs data have not been accessible during the time of data collection. All vehicle costs are found in the Danish Energy Agency's "Alternative Drivmidler Model". [33]

Additionally to vehicle investment and O&M costs, the infrastructure costs regarding road, rail and bicycle transport are included. The costs associated with road transport is the costs of expanding the road infrastructure and building new roads, as well as the costs associated with renewal and maintenance of existing roads. The cost data are found via the Danish Road Directorate. To evaluate the costs of future road expansions, historic cost data have been analysed and the average annual investment costs related to the average annual growth in traffic work on roads have been estimated. Given these factors, it is possible to estimate the future road investment costs with alternative projections of the traffic work on roads. [34]

Likewise was it possible to estimate the costs related to investment and maintenance of railway infrastructure. The investment and maintenance costs from 2017 to 2019 was found in Banedanmark's annual reports along with the projected increase in traffic work towards 2032. With the annual investment and maintenance costs and projected growth in traffic work, it was possible to calculate an average cost of growth. With the calculated cost of growth in traffic work on rail, it is possible to estimate the associated investment and maintenance costs for alternative developments of the railway transport. [35], [36] For bicycling infrastructure, data have not been readily available to the same extent, as for road and rail transport. The biking infrastructure costs in Copenhagen from 2009 to 2018 are assumed in this work to be representative of infrastructure costs associated with growth in national bicycling transport. With a total investment in Copenhagen of 2 BDKK over a period of 10 years and an increase in the traffic work for bikes of 2.1 pct. it is possible to calculate the marginal costs of increasing the bicycling transport demand. [37]

4.2. Development of the transport sector

The general objective of the transition of the Danish transport sector is to analyse the potential CO_2 reductions towards 2030 and a complete decarbonisation in long-term by 2050.

The CO_2 emissions from the transport sector depend on the energy consumption and the transport technologies. The energy consumption is reliant on the transport demand and the energy efficiency of the transport technologies. Hence, in this thesis, scenarios with different projections of implementation of transport mode technologies and energy efficiency measures are presented and evaluated. Additionally, scenarios with alternative projections of the transport demand growth are assessed.

All scenarios are built on top of the same *Reference model*. The *Reference* model is based on detailed statistical data of the Danish transport sector from 2017 containing all the data outlined in Table 2 about all modes of transport presented in Figure 3. For some modes of transport, not all of the above data has been available and alternative ways to calculate transport demand, energy demand, fuels and costs have been performed. This is described in detail in the presentation of the *Reference* model in section 5.The scenarios are assessed based on three factors:

- Energy consumption
- CO_2 emissions
- Transport system costs

The scenarios are analysed in the transport scenario tool TransportPLAN. The tool allows the user to modify development rates, and produces the energy consumption divided by mode of transport and fuel and the CO_2 emissions along with the vehicle costs in all modelled years. The tool is described in more detail in section 4.3.

4.2.1. Renewable scenario development

As described above, three parameters have significant influence on the development of the transport sector towards 2030 and 2050:

1. The development of the transport demand
2. The implementation of new technologies
3. Energy efficiency improvements

Following the ASI approach all three parameters are considered, when developing alternative scenarios for the development of the transport sector. In the following, the two types of scenarios considered in this report are presented.

In the development of the renewable scenarios the ASI approach is assessed in reverse. Instead of seeking to avoid an increase in the transport demand and consider shifts between transport modes, measures to improve the transport system are considered at first. This approach entails scenarios that are easily comparable with similar analyses of renewable transitions of the transport system. Measures to decrease transport demand growth rates or promote modal shifts from energy intensive modes of transport to less energy intensive modes are heavily dependent on adequate and available infrastructure, economic incentives and general public opinion. By implementing renewable transport technologies first, it is possible to estimate the need for fuel and vehicle production compared to a *Reference* scenario with identical growth rates.

In the technology scenarios, the transport demand growth is kept constant. The transport demand growth is forecasted based on The Danish Energy Agency's publication "Danish Energy and Climate Outlook 2019" (DECO). The forecast and growth rates are explained in detail, when the *Reference* scenario is outlined in section 5.4.

Three scenarios for the implementation of renewable transport technologies are suggested. The scenarios will differ both in the rate of implementation and in the technologies, which are implemented. The available technologies are inspected and evaluated dependent on maturity and compatibility with the different modes of transport. The scenarios for implementation of renewable transport technologies are:

- Reference scenario
- Reasonable
- Optimistic

In the *Reference* scenario, the short-term rate of implementation of new technologies towards 2030 is slow. At the same time, only well-established, known technologies, i.e. electric vehicles and 2^{nd} generation biofuels are implemented. Renewable technologies are implemented to match the implementation estimated in DECO. From 2030 to 2050, the implementation rates of new technologies are a continuation of the implementation rates from DECO. This entails that no new technologies are implemented other than the ones already implemented between 2017 and 2030 in DECO.

In the *Reasonable* scenario the rate of implementation towards 2030 is faster. Through an exhaustive examination of state-of-the-art transport technologies, it is estimated when renewable alternatives are assumed to be ready to be implemented. Furthermore, an evaluation of the statistics regarding sale of new vehicles will act as background for the proposal of implementation rates. From 2030 to 2050, the objective is to decarbonize the transport sector, with a reasonable implementation of electricity.

In the *Optimistic* scenario, a fast development of currently undeveloped technologies is assumed. Along with a quick maturing process for new renewable technologies, it is assumed that an increased willingness from both politicians, companies and consumers drives the implementation of renewable transport technologies to a fast rate of implementation towards 2030. From 2030 to 2050, the objective is to decarbonize the transport sector, with an optimistic implementation of electricity.

New transport technologies cannot stand alone in the renewable transition of the transport sector. The traffic work and transport energy demand must be decreased to limit the need for fossil fuels and limit the energy consumption in the transport sector. By implementing measures to avoid an increase in the total transport demand and encourage modal shifts, the increase of traffic work will be limited and the transport demand will be moved to modes of transport with higher energy efficiency, and thus decreasing the total transport energy demand.

It is important to note, that the growth in the actual transport demand (pkm/tkm) is not expected to change through the measures proposed in this thesis. It is assumed that the need for transportation of people and goods will increase towards 2050. Instead, the proposals delivered in this work, will focus on limiting the traffic work along with shifting transport demand from low capacity utilisation and energy inefficient modes of transport to high capacity utilisation and energy efficient modes of transport. By doing so, the traffic work (km) and the energy consumption will decrease, while still providing the service of transport to meet the demand. Traffic work is generally used primarily for road transport and is seldom available for modes of transport like rail, sea and air. Hence, in this report the traffic work is calculated using the transport demand (pkm/tkm), the vehicle capacity and the capacity utilisation.

In the development of the transport demand scenarios, measures to avoid an increase in the total traffic work and measures to promote modal shifts are investigated and evaluated. Three scenarios for the development of the traffic work are proposed.

- High growth (*Reference* scenario)
- Medium growth
- Low growth

The *High growth* scenario estimates an annual increase in traffic work across all modes of transport equivalent to a total increase in the traffic work of approximately 26 pct. between 2017 and 2030. The growth rate varies dependent on mode of transport; this is elaborated further in the presentation of the *Reference* scenario. The growth rate in the *High growth* scenario is equivalent to the one anticipated in DECO. From 2030 to 2050, the annual growth rate in the *High growth* scenario is kept constant at the same level as between 2025 and 2030. This results in a total increase of the traffic work of 42 pct. between 2030 and 2050.

In the *Medium growth* scenario, the annual increase in traffic work is reduced by half compared to the *High* growth scenario. This corresponds to an increase in the total traffic work of 13 pct. between 2017 and 2030. From 2030 to 2050, an increase in the total traffic work of 21 pct. is estimated.

In the *Low growth* scenario, a scenario is proposed with a growth rate of the total traffic work between 2017 and 2030 of 0 pct. From 2030 to 2050, the traffic work is assumed to remain stable, with measures implemented to encourage modal shifts and avoid an increase in the total traffic work.

In the *Medium* and *Low* growth scenarios, measures are proposed to avoid an increase in the total traffic work along with measures to promote modal shifts. In the first evaluation the achievability of these measures are not considered, but they are implemented to estimate the impact a reduction of transport demand growth rate will have on energy consumption, CO_2 emissions and transport system costs. As the technology scenarios achieve CO_2 neutrality in 2050, this parameter will not be affected by avoid and shift measures, but limiting the transport demand could lead to reduced transport system costs, thus reducing the costs of a renewable transition. In 2030, reducing the transport demand growth will have an impact on the CO_2 emissions of the transport system too.

In section 9, the achievability of the reduced transport demand scenarios is discussed.

In the following analysis of the scenarios, first, the technology implementation scenarios are applied and secondly the measures to decrease traffic work and are introduced. In Figure 4 the scenarios and structure is displayed.

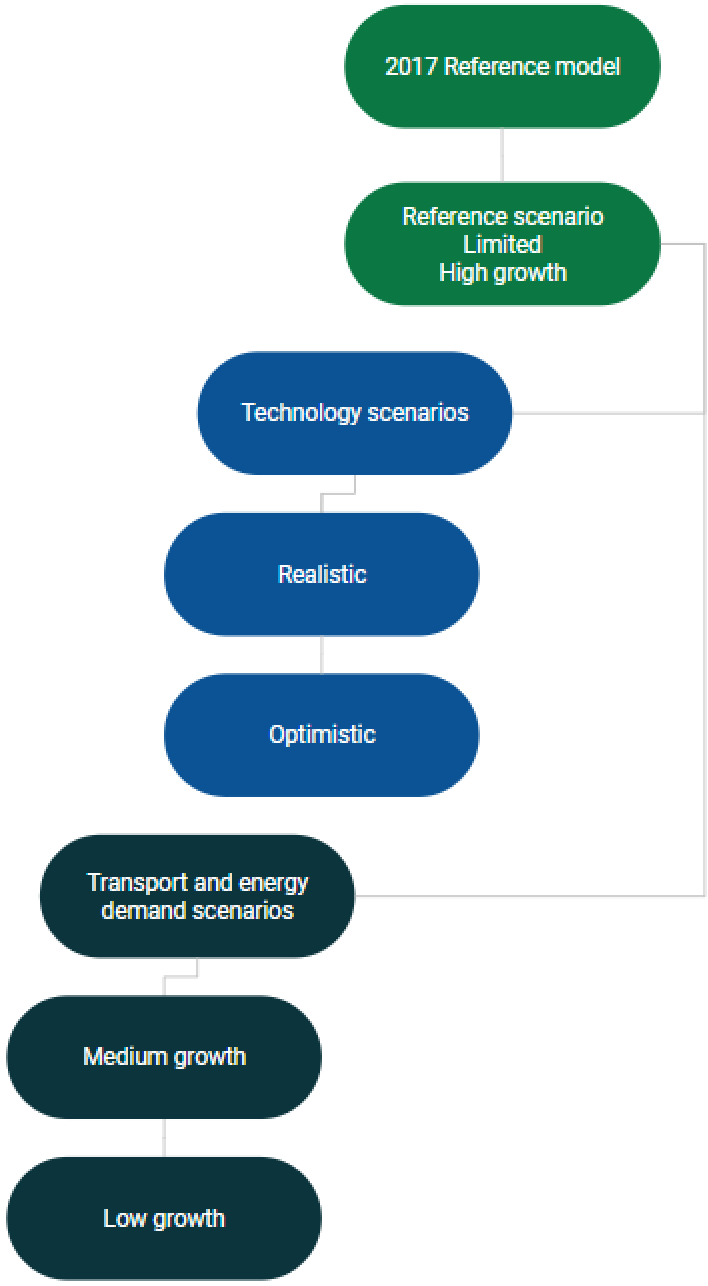

Figure 4. The structure of the scenario analysis. All scenarios take point of departure in the same 2017 *Reference* model. The *Reference* scenario, with a limited implementation of renewable transport technologies and a *High* growth in traffic work, will act a as comparison. Two alternative technology scenarios are analysed along with two different projections of traffic work growth.

4.3. TransportPLAN

The key parameters and data described above are all collected in the Transport Scenario Tool, TransportPLAN. The tool is a transport scenario modelling tool, originally developed as a part of the CEESA project [13]. The tool has been further developed during the writing of this thesis. TransportPLAN allows for the user to create detailed transport scenarios with a three-year interval from 2017 to 2020 and from 2020 to 2050 with five-year intervals.

In TransportPLAN, the *Reference model* of the Danish transport system is a main input. For all modes of transport the transport demand, energy demand, share of fuels and technologies and vehicle and infrastructure costs are found through statistics, models and publications and make up the foundation of the scenario development.

To develop renewable scenarios towards 2030 and 2050, TransportPLAN allows for adjustment of five parameters:

- Annual growth of transport demand
- Market share of renewable technologies
- Modal shifts
- Annual energy efficiency improvements
- Annual capacity utilisation improvement

The parameters enable the user to create alternative scenarios with different forecasts of transport demand, variable rates of implementation of renewable transport technologies, move transport demand between modes of transport, improve energy efficiency of conventional vehicles and improve the capacity utilisation for both passenger and freight transport.

The renewable transport technologies are identified through the exhaustive technology review presented in section 6.2. The efficiencies of alternative technologies derive from the Danish Energy Agency's transport model "Alternative Drivmidler-model". The vehicle costs and costs of charging stations are also found in this model. The costs and efficiencies in the Danish Energy Agency's model are specified for the years 2015, 2020, 2035 and 2050. The costs and efficiencies have been linearly interpolated to find the values needed for all years in TransportPLAN. [33]

The results from the TransportPLAN scenario tool are the annual transport demand in all modelled years, the energy consumption divided by mode of transport and type of fuel and the costs associated with road vehicles, charging stations and infrastructure.

The transport energy consumption divided by fuel type allows for a detailed analysis of the fuel consumption and end-use. These outputs are compatible with a range of energy system analysis tools, for further analysis of the results and the scenarios impact on the entire energy system.

The road vehicle costs and costs of charging stations are calculated in TransportPLAN. The costs are limited to road vehicles, as it has not been possible to obtain cost data for other modes of transport. The number of vehicles is calculated and along with data from the Danish Energy Agency's transport model "Alternative Drivmidler-model" the total investment costs, O&M costs and charging stations investment costs can be calculated. The costs related to infrastructure development are calculated based on the annual increase in traffic work.

5. Development of the Danish transport sector

In the following, an evaluation of the development of the Danish transport sector is presented. First, a general assessment of the passenger and freight transport sectors are presented and general tendencies regarding transport demand, traffic work, energy consumption and CO_2 emissions are reviewed and analysed. Secondly, the transport sector in the year of 2017, which will serve as the point of reference in the following analysis, is presented and a detailed description of the total and the specific energy consumption for each mode of transport is introduced. When the parameters have been evaluated, the 2017 *Reference* model and the *Reference* scenario towards 2030 and 2050 are presented.

The Danish transport sector has been growing steadily from 1990 until today. The transport demand, the traffic work, energy consumption and CO_2 emissions have all increased in this period.

It is well known and documented how the national traffic work is tightly linked with the development of the general wealth of the society and the gross domestic product (GDP). The tendency has been visible since 1990, as the GDP grows our demand for mobility increases. The two factors are co-dependent, hence an increase in the general wealth will enable more people to acquire a vehicle and drive longer distances. Simultaneously, an increase in the potential for mobility will assist the development of the economy as people and companies are connected over longer distances and the deliveries of goods become easier.

The Danish traffic work for road transport has increased 46 pct. from 1990 to 2017. Meanwhile, the Danish GDP has increased 58 pct. In Figure 5, the development is outlined and the tendency is visible.

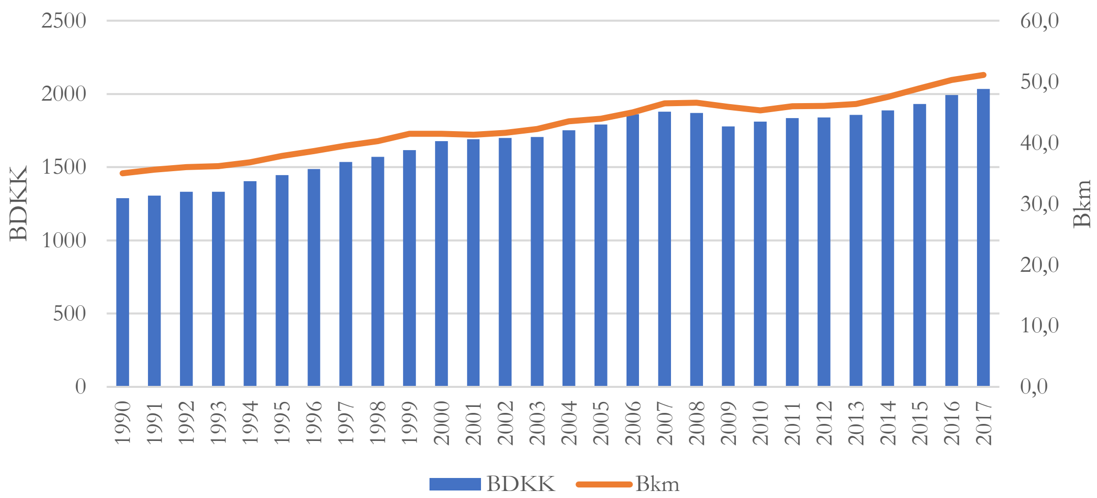

Figure 5. The development of the Danish gross domestic product (GDP) and the traffic work for road transport between 1990 and 2017.

The traffic work is only registered in Danish statistics for road transport, but an identical tendency is eminent for all other modes of transport. [7]

The energy consumption of the Danish transport sector has been increasing gradually from 1990 to today with a total growth of 28 pct., driven primarily by a significant growth in energy consumption in passenger transport. Concurrently, the CO_2 emissions from passenger transport has increased 24 pct. (Figure 6) [3]

The combustion of fossil fuels, such as diesel and petrol, is the primary source of energy consumption and emissions in the transport sector. The use of fossil fuels is a dependency created long before 1990 with exhaustive market uptake and development of the internal combustion engine (ICE). Alternatives have until recently not been considered, hence fossil fuels constitute the majority of the fuels used in the transport sector. Fossil fuels comprised >99 pct. of all fuels in 1990 and still constitute 95 pct. of the share of fuels in 2017. The main contributors are diesel and petrol along with jet fuel. The non-fossil fuels in the transport sector are primarily a mix of biofuels, such as bioethanol and biodiesel and electricity. Since 2010 a mandatory requirement of adding 5.75 pct. of biofuels in all fuels sold for land transport purposes, has driven the implementation of renewable energy in the transport sector. From 2020 onwards, this percentage has been increased to 7.6 pct. [38]

Biofuels can substitute fossil fuels in the existing vehicle engines, thus not creating a need for additional and new infrastructure and vehicles. Hence, biofuels represents a cost-effective way to decarbonize parts of the transport sector. Extensive use of biofuels does entail serious sustainability issues, which will be highlighted in section 6.2. [39]

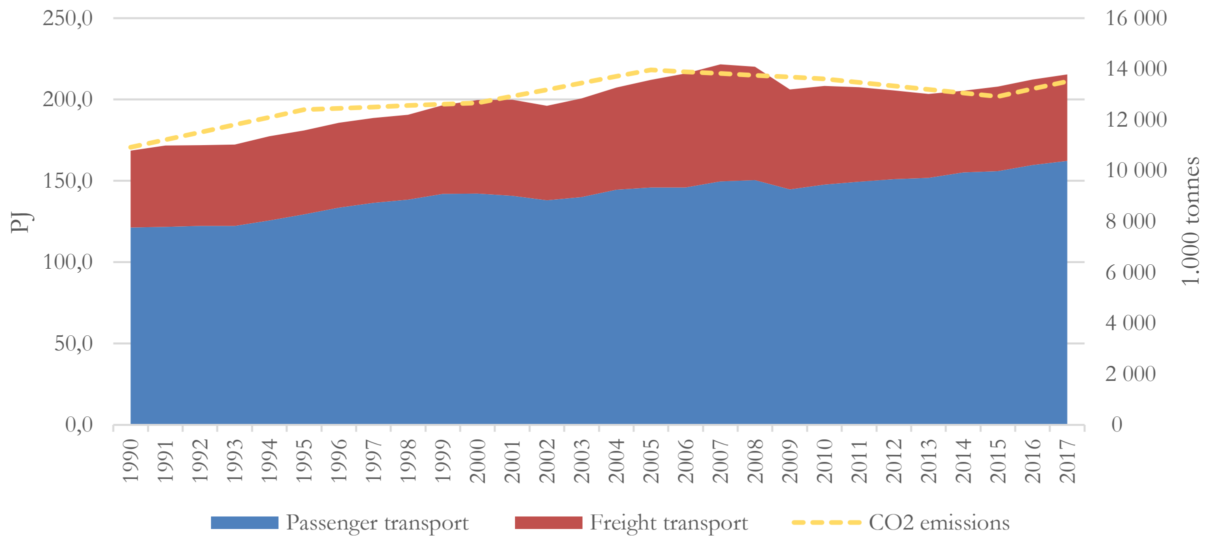

Figure 6. Energy consumption divided by passenger and freight transport. Total greenhouse gas emissions calculated as CO_2 equivalents.

The increase in energy consumption and CO_2 emissions have been limited in recent years and from 2007 to 2017 as the energy consumption and CO_2 emissions have decreased 3 pct. and 2 pct. respectively. The recent decrease is primarily due to regulation implemented at EU level. Regulation and measures implemented at EU level have set boundaries and strict frameworks for vehicle manufacturers and vehicle fleet operators to increase energy efficiency and reduce emission rates. The EU emissions standards has since the 1990's ensured that continuous efficiency improvement requirements minimized the energy consumption and CO_2 emissions from primarily road transport. The standards have apparent effect on the emissions from the transport sector and is considered a significant tool, to reduce the environmental impact of the transport sector in a short-term timeframe. [40], [41]

For aviation and maritime transport, measures to enhance and improve the fuel economy of ships and aircrafts have prompted significant energy and emissions reductions, while increasing the profitability of the industries. The share of renewable energy in the air and sea transport sectors is still absent and improvements have generally concerned energy efficiency and logistics.

5.1. Passenger transport

The passenger transport demand has increased significantly from 1990 to 2017 driven primarily by cars and vans below 2 tons and international flights. The transport demand for busses, rail, sea and national air have remained roughly steady in this period, while the transport demand for cars and vans <2t has increased 28 pct. since 1990. For international air, the transport demand is only registered from 2004 and onwards and since then the transport demand has increased 37 pct. As outlined in Figure 7, the transport demand for all modes of transport, aviation, rail and maritime included has increased 29 pct. from 2004 to 2017.

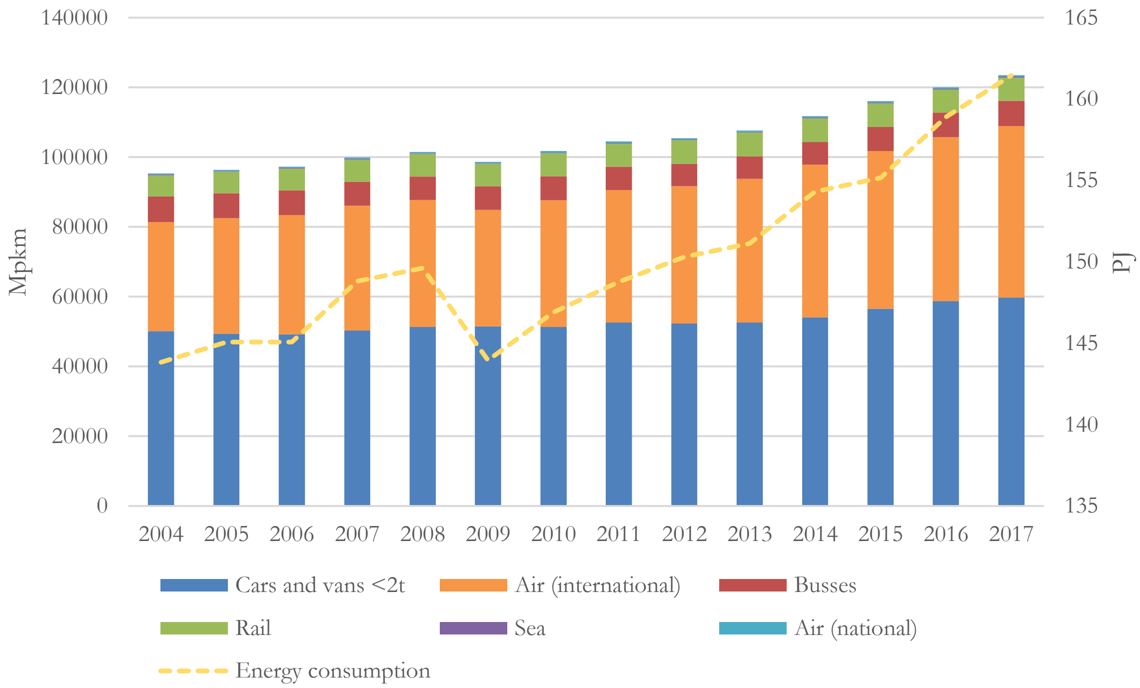

Figure 7. Transport demand divided by modes of transportation and energy consumption in passenger transport.

The increase in the energy consumption of the passenger transport has had a less steep gradient than the increase in transport demand. Energy efficiency improvements of especially cars and vans and international flights have ensured a disengaging between the increase in transport demand and energy consumption.

For passenger road transport in cars, vans and busses a distinct tendency of a declining capacity utilisation has been observable in the period from 2000 to 2017. While the transport demand has increased 16 pct. the traffic work (actual driven kilometres) has increased 28 pct. This explains a tendency, where more and more passengers choose to travel alone, hence increasing the travelled kilometres more rapidly than the demand for transport. The average capacity utilisation of cars and vans has decreased from 1.53 passengers per vehicle in 2002 to 1.42 in 2017. In 2019 the capacity utilisation has declined even further and the average number of passenger per vehicle was down to 1.39.

The car is the preferred mode of transportation for passenger transport in a Danish context. From the annual national Transport Habit Survey (THS) it is evident that 84 pct. of all passenger kilometres (pkm) are travelled by car. The THS does not cover travel by plane or ferries. The share of pkm travelled by car has been increasing in the period from 2010 to 2019. A distinctive shift from public transport, such as busses and trains, towards the car is revealed in the THS. The same trend is present, when the share of trips divided by mode of transport is investigated. The share of trips made by car has remained stable during the past ten years. The share of trips made by bicycle and public transport is declining, while the share of trips accomplished by walking is increasing. The survey indicates that shorter trips are increasingly made by walking, but longer journeys are moving from public transport towards the car. [42]

This tendency has for some time been observed outside of urban areas, but has recently also been visible within the metropolitan areas. Transit oriented development have been neglected and many workplaces are easier accessible by car, than with public transport. This, along with increasing fare prices and low costs of acquiring a personal vehicle, has accelerated the development of increasing traffic work by cars and decreasing for public transport. [42]

This development has significant influence on the total traffic work and energy consumption as the capacity and utilisation of cars is considerably lower than for public transport.

5.2. Freight transport

Data regarding freight transport is not available to the same extent as data for passenger transport, and certain measures have had to be done in order to collect the necessary data for the *Reference* model. Hence, a detailed analysis and evaluation of the development since 1990 is not possible to the same extent as for passenger transport.

Trucks and vans constitute the majority of the energy consumption of freight transport. There is discrepancy in statistics of whether vans should be included in passenger or freight transport. There are almost 400.000 vans registered in Denmark, but the majority of these are not used for freight transport, but are used by artisans of different kinds. In this work, vans below a total weight of 2 tonnes are considered used for passenger transport and vans with a total weight between 2 and 6 tonnes are considered used for freight transport.

The total energy consumption for freight transport has increased 13 pct. since 1990 (Figure 8). The energy consumption has been declining from 2007 to 2017. Especially a drastic decrease in the energy consumption from vans has been the reason for this decline. Data regarding the energy consumption from international freight transport on sea is not available through accessible statistics.

The amount of goods transported have been relatively stable from 2008 to 2017. As data regarding the amount of goods transported does not date further back than 2008, it is not possible to definitely determine whether the amount of transported goods were much higher in 2007. It is assumed, that it was, as there is a clear correlation between the energy consumption and the amount of goods transported from 2008 to 2017. (Figure 9)

The amount of goods transported by vans is not available through accessible statistics.

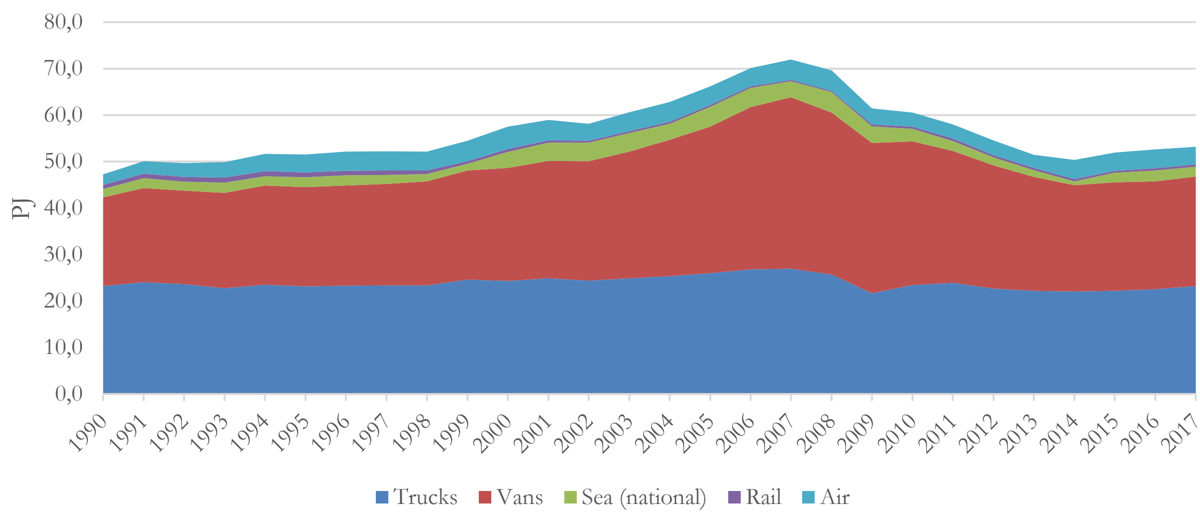

Figure 8. Energy consumption from freight transport divided by mode of transportation.

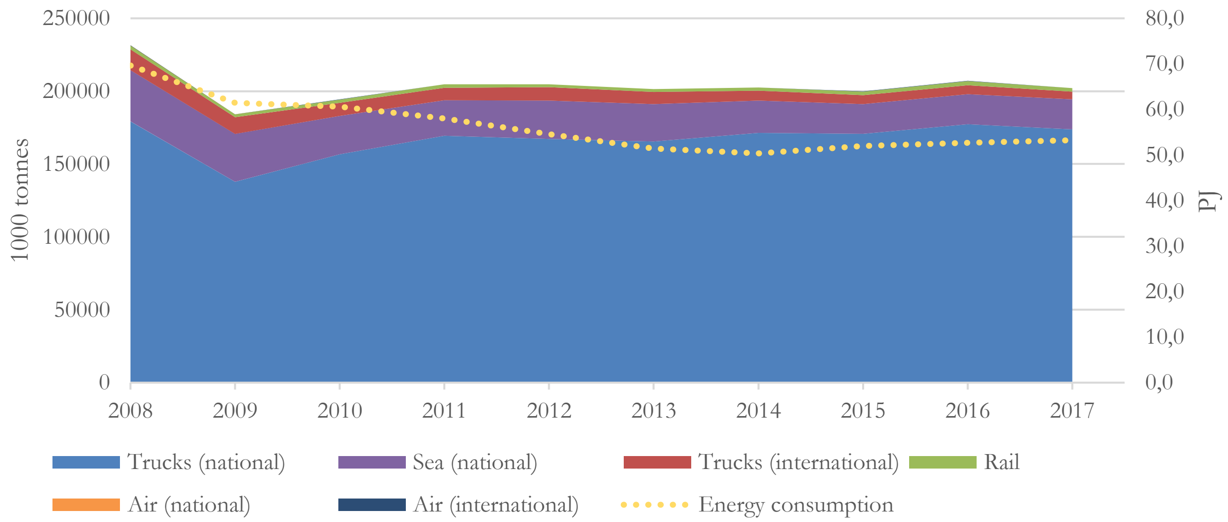

Figure 9. The amount of transported goods divided by mode of transport.

Energy efficiency improvements have been implemented in the freight transport sector in this period and is evident in the development from 2009 to 2017. The amount of goods transported in this period has increased with 8 pct. while the energy consumption has decreased 13 pct. It is unclear, due to lack of sufficient statistical data, whether this development is due solely to energy efficiency improvements, modal shifts, increased capacity utilisation or a combination.

5.3. Reference model 2017

The *Reference* model of the Danish transport sector in 2017 serves as the point of departure of the analyses in this work. The *Reference* model is a detailed, comprehensive overview of the Danish passenger and freight transport.

For each mode of transport, the following data is collected:

1. Transport energy demands (PJ).
2. Traffic work (km).
3. Passenger and freight transport demands (pkm/tkm).
4. Capacity and capacity utilisation.

Due to the complexity of the transport sector, data regarding these parameters are not available for all modes of transport and for some, the necessary data have been calculated differently. This is clarified in the presentation of the individual modes of transport.

In the following, the passenger and freight transport will be presented. A general assessment of the two is executed and the most significant contributors to energy consumption, transport demand and traffic work is identified. In Appendix A, each mode of transport within the categories of passenger and freight transport are described in detail in terms of input in the TransportPLAN model and collection of specific data.

5.3.1. Passenger transport

In passenger transport, cars and vans <2t and international air are responsible for 87 pct. of the transport demand and 86 pct. of the energy consumption (Figure 10). The energy consumption of busses, rail, sea and national aviation constitute merely 14 pct. of the total energy consumption combined.

Cars and vans <2t are accountable for 97 pct. of the total traffic work. The general capacity utilisation of cars and vans is poor, hence the traffic work is significantly higher than for international aviation, which have relatively high capacity utilisation factors.

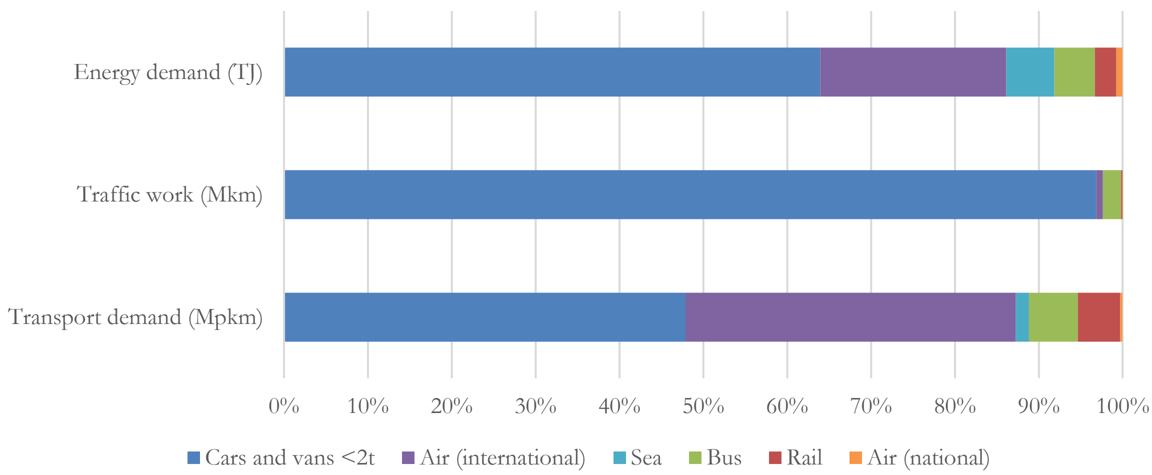

Figure 10. The share of CO_2 emissions, traffic work and transport demand of the passenger transport divided by mode of transport.

It is possible to establish the specific energy consumption for each mode of transport, by combining statistical data regarding transport demand with energy consumption data. As presented in Figure 11 and Figure 12, the specific energy consumption per passenger kilometre across different modes of transport varies significantly. National sea transport is left out of the chart for easier interpretation, as the specific energy consumption is significantly higher than the other modes of transport.

The specific energy consumption for national rail is approximately 2.6 times lower than for cars and vans <2t and the specific energy consumption for international rail is 2.5 times lower than for international flights. Since rail transport only account for a small share of the total passenger transport demand, there is a significant potential in reducing the passenger transport energy consumption by shifting transport from cars, vans and air towards rail.

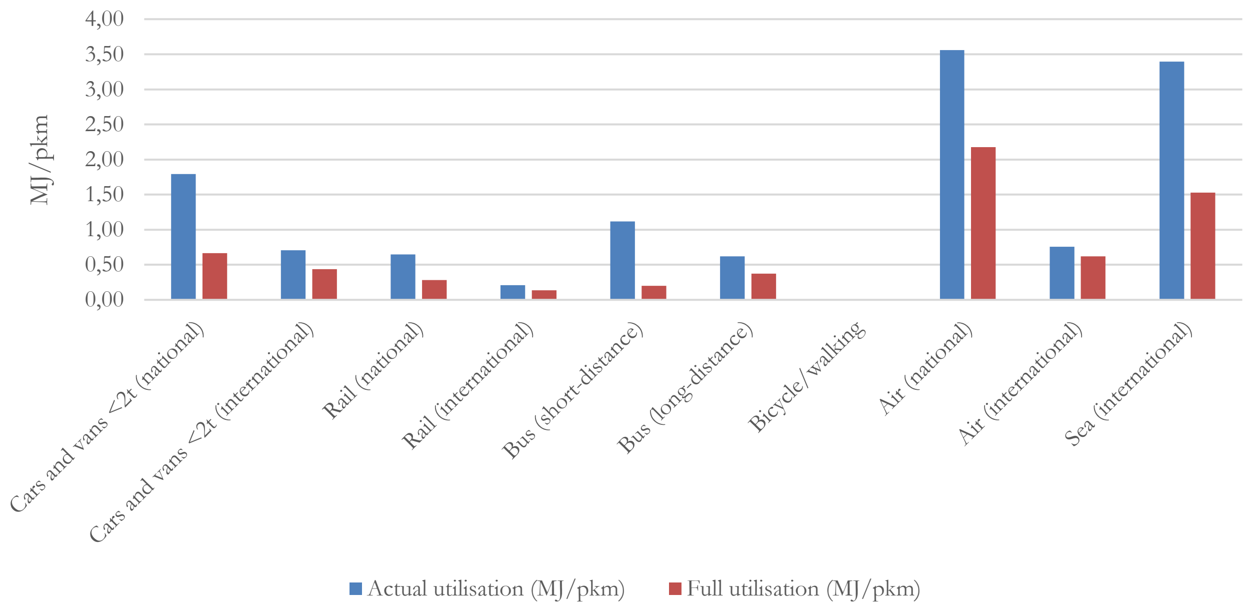

Figure 11. Specific energy consumption per passenger kilometres of the different transport modes. Full utilisation represents the minimum achievable specific energy consumption per passenger kilometre if the capacity utilisation of the vehicle was fully utilised.

Figure 11 also outlines the specific energy consumption in a situation where the full vehicle capacity is utilised for all modes of transport. It is evident from this hypothetical scenario, that especially cars, vans and busses have a significant potential of improving the specific energy consumption if the capacity utilisation is improved.

Figure 12 indicates that maritime, rail and air transport could also improve the energy efficiency. Improvement of the capacity utilisation will be considered when the transport demand scenarios are presented.

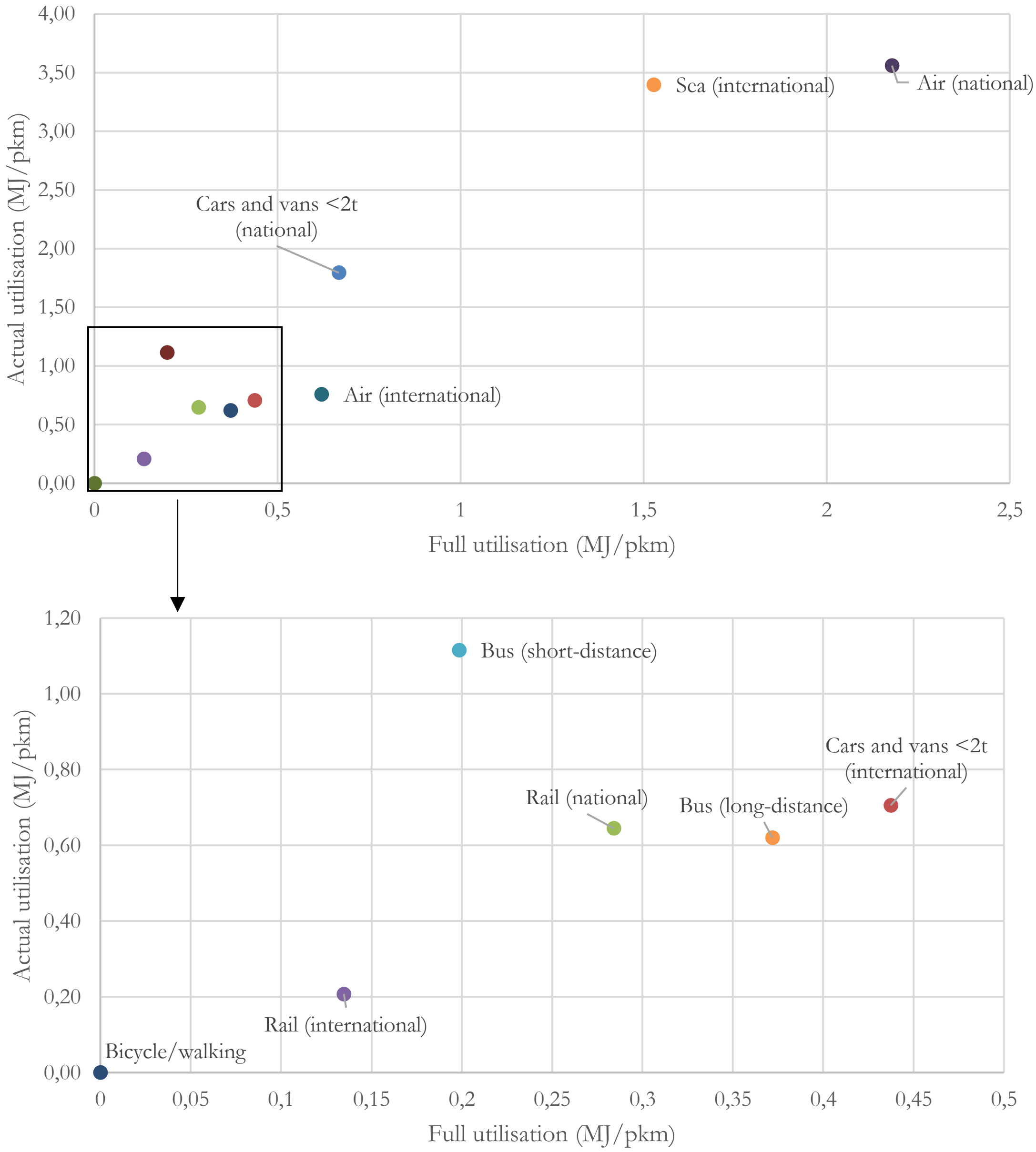

Figure 12. Specific energy consumption per passenger kilometres of the different transport modes. Full utilisation represents the minimum achievable specific energy consumption per passenger kilometre if the capacity utilisation of the vehicle was fully utilised.

5.3.2. Freight transport

In freight transport, the majority of the transport demand is met by sea transport in the *Reference* model. Maritime transport covers over 70 pct. of all freight transport demand, while trucks and vans with 15 pct. and 7.5 pct. respectively cover the remaining predominantly (Figure 13). Regarding traffic work and energy consumption, maritime transport is only responsible for a small share, while trucks and vans comprise the majority. The hauling capacity of freight ships is many thousand tons, and a large transport demand in tonnes kilometres can be met with a minimum need for actual travelled kilometres.

The capacities of trucks and vans are a lot smaller and thus more kilometres will have to be driven to deliver the same amount of goods.

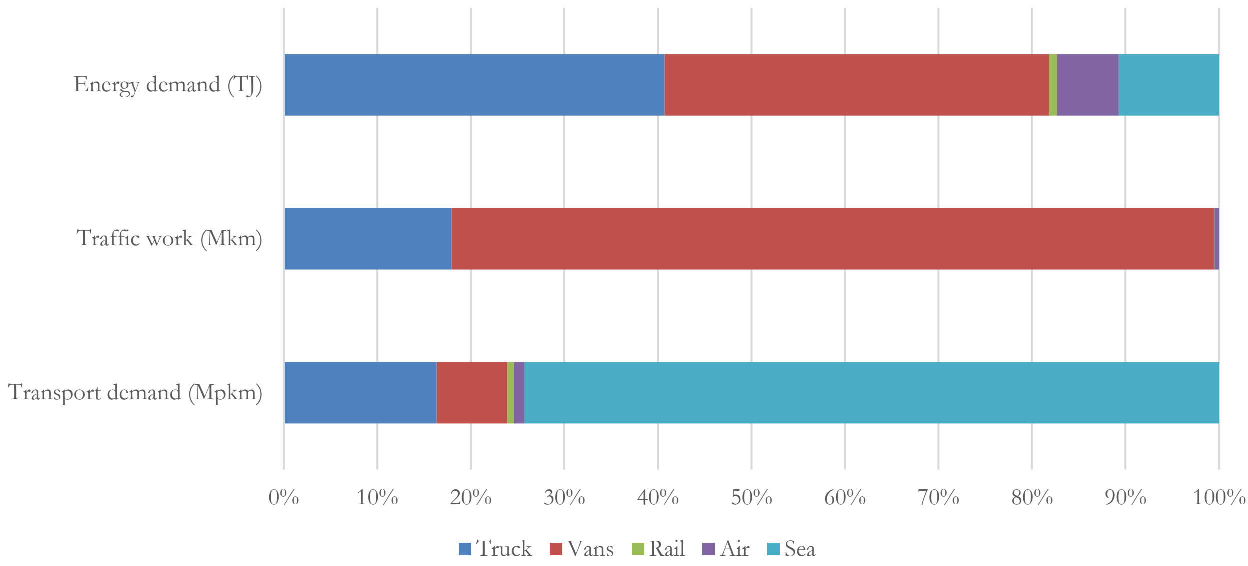

Figure 13. The share of CO_2 emissions, traffic work and transport demand of the freight transport divided by mode of transport.

The low specific energy consumption per tkm for maritime freight transport is the key reason for the overall low impact in the total energy demand from sea transport. While vans and trucks are responsible for only <25 pct. of the transport demand, together they account for over 80 pct. of the energy consumption. Trucks and vans have generally lower capacity utilisation, and thus a higher specific energy consumption.

In Figure 14 and Figure 15, the specific energy consumption per tkm for the different transport modes is outlined. As for passenger transport, the specific energy consumption with actual utilisation is displayed along with the specific energy consumption in a hypothetical scenario with full utilisation.

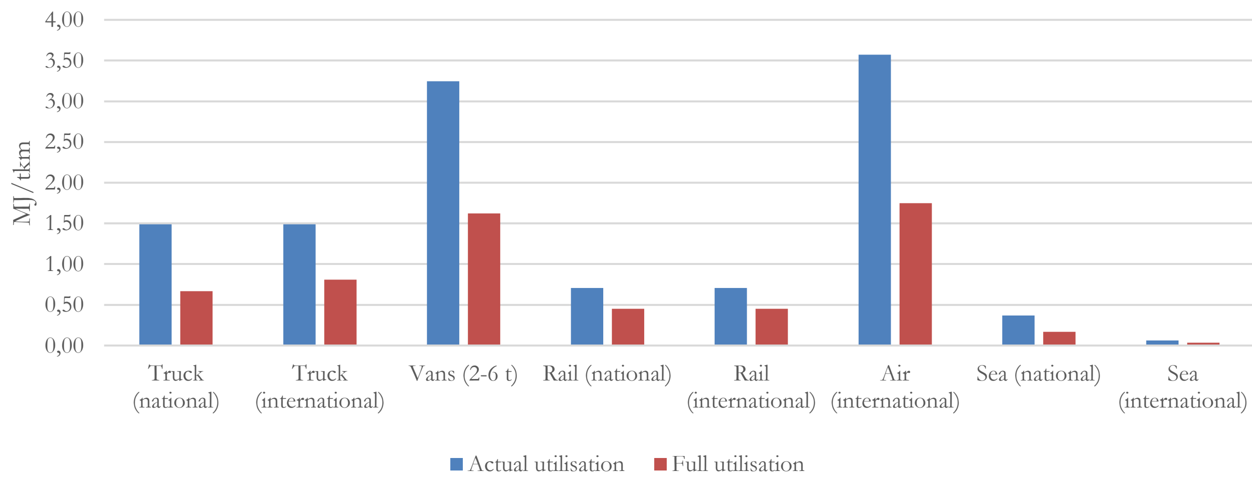

Figure 14. Specific energy consumption per tonnes kilometres of the different transport modes. Full utilisation represents the minimum achievable specific energy consumption per tonnes kilometre if the capacity utilisation of the vehicle was fully utilised.

Even with full utilisation, maritime freight transport is still the most energy efficient way of transporting goods. A large potential for improving the energy efficiency for vans and trucks is evident.

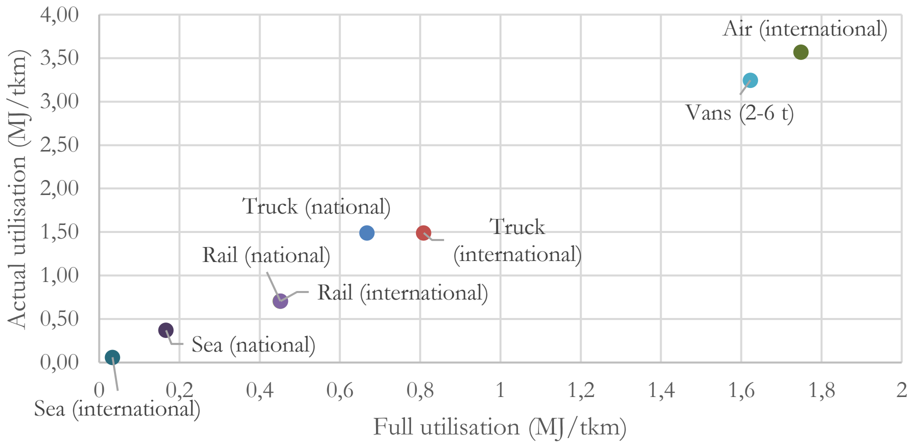

Figure 15. Specific energy consumption per tonnes kilometres of the different transport modes. Full utilisation represents the minimum achievable specific energy consumption per tonnes kilometre if the capacity utilisation of the vehicle was fully utilised.

5.4. Development of the reference scenario

The development of the *Reference* scenario towards 2030 is an interpretation of the "Danish Energy and Climate Outlook 2019" (DECO) published by the Danish Energy Agency. DECO is a frozen policy forecast that anticipates the development of the Danish energy system towards 2030 in a scenario, where no new policies are agreed to move the development in a different direction. The development in DECO builds on a comprehensive statistical analysis of the Danish energy system in 2017. In the outlook, the energy consumption, CO_2 emissions and traffic work for all modes of transport is forecasted based on implemented policies and agreed policies regarding energy efficiency improvements. DECO considers only national transport, hence international aviation and maritime transport are not included in the outlook. Data regarding the development of international aviation is available via background reports. [43], [44]

The development of the energy consumption is described in more detail in DECO for road transport, and less thoroughly for rail, aviation and sea transport. DECO anticipates a continuation of the growth rates in traffic work that have been observed in road transportation in recent decades. The growth rates for road transport originates from "Landstrafikmodellen" from Denmark's Technical University (DTU). The growth rates are based on development of the gross domestic product (GDP), population figure, work places etc. Energy efficiency improvements are implemented based on expected developments on behalf of the emissions standards regulated by the European Commission. [43]

The Danish Transport, Construction and Housing Authority forecast the growth rate of the transport demand for rail transport. For sea transport, the growth rate is calculated based on the observed annual energy demand. The aviation transport is forecasted based on an expected development in the number of passengers, GDP, ticket prices etc. [43]

As the purpose of DECO is to forecast energy consumption and CO_2 emissions, a development of bicycling and walking is not incorporated in the calculations and final publication. Hence, in the *Reference* scenario it is estimated that the transport demand for bicycling and walking remain constant throughout the modelled period.

The development of the *Reference* scenario from 2030 to 2050 will be a continuation of the developments from 2017 to 2030. The annual growth rates will be kept constant, while the implementation rate of renewable technologies is expected to increase slightly more rapidly towards 2050. The annual energy efficiency improvements are kept almost identical between 2030 and 2050 as the improvements made between 2017 and 2030. The annual efficiency improvements are assumed to slow down towards 2050, as it is expected that a certain saturation of improvements of fossil technologies will be reached. The implementation of renewable technologies and the energy efficiency improvements are presented in detail for both passenger and freight transport in the following.

5.4.1. Passenger transport

The development of the passenger transport demand in the *Reference* scenario is displayed in Figure 16. In general, the transport demand is expected to increase 66 pct. between 2017 and 2050. In short-term the passenger transport demand increases 21 pct. from 2017 to 2030. This increase is driven primarily by an increase in passenger kilometres for cars and vans <2t (29 pct.), rail (31 pct.) and aviation (13 pct.). In long-term, from 2030 to 2050 the passenger transport increases 38 pct., again driven predominantly by cars, rail and aviation. Between 2030 and 2050, it is anticipated that the passenger kilometres travelled by rail will double.

The composition of the passenger transport demand remains similar in 2030 and 2050. Cars and aviation comprise the majority of the transport demand of approximately 84 pct. in 2017 and 85 pct. in 2050. Public transport covers approximately 12 pct. of the transport, while there is a reduction in the share of passenger kilometres covered by bicycling and walking, as this category is not expected to grow from the basis.

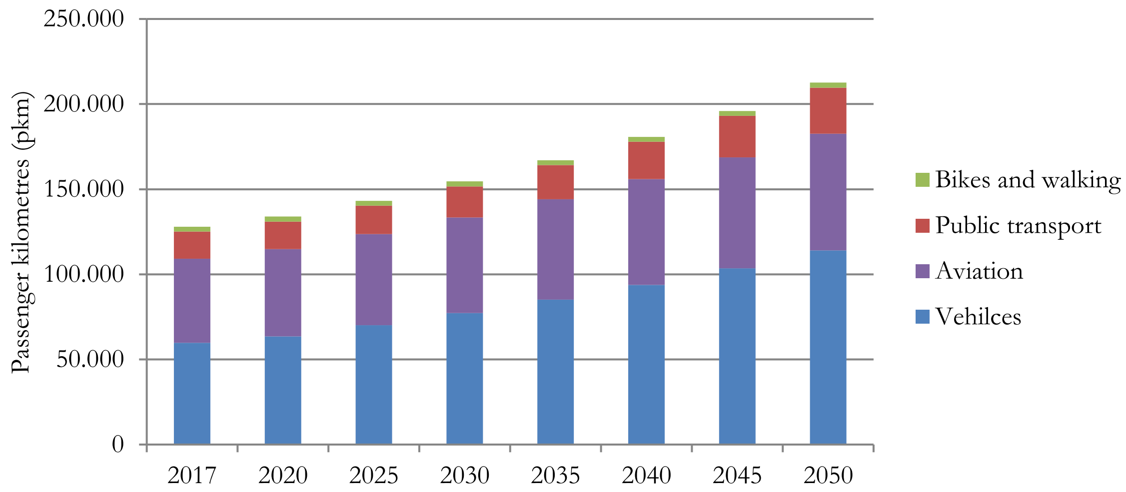

Figure 16. Development of the transport demand (pkm) for passenger transport from 2017 to 2050.

The forecast of the energy consumption is connected to the specific energy consumption outlined for each transport technology. Energy efficiency improvements will affect and decrease the specific energy consumption.

In DECO, an expectation for cars and vans is that the energy efficiency will improve 13 pct. between 2017 and 2030. Busses are expected to improve energy efficiency with 29 pct. in the period, while aviation is expected to improve 5 pct. No improvements are expected for rail and sea transport between 2017 and 2030. From 2030 to 2050, the energy efficiency of cars and vans, busses and aviation is improved 7 pct., 35 pct. and 6 pct. respectively. No improvements are expected for rail and sea transport in long-term either.

The energy efficiency is additionally improved with implementation of new technologies. In DECO, a relatively conservative implementation of renewable transport technologies is executed. As the minimum share of biofuels was increased from 5.75 pct. to 7.5 pct. after the publication of DECO, no increase of the share is anticipated in the *Reference* scenario. Instead implementations of primarily electricity is implemented in cars and vans <2t and busses. For cars and vans <2t, electric vehicles, battery electric vehicles and plug-in hybrid vehicles, will constitute 9 pct. of the share of vehicles in 2030. This corresponds to a share of electric vehicles of newly sold vehicles of 22 pct. In 2050, 50 pct. of all vehicles are expected to be electric, with a higher share of battery electric vehicles relative to plug-in hybrids vehicles.

For busses, both short- and long-distance, it is assumed that 9 pct. will be electric in 2030 and approximately 1 pct. fuelled by hydrogen. In 2050, the share of electric busses increases to 28 pct. and hydrogen busses cover 4 pct. of the transport demand.

For rail, it is assumed, that the electrification project of the Danish railways will be nearly complete in 2030 and electric trains will cover 85 pct. of the traffic work. In 2050, the entire Danish railway infrastructure will be electrified. No alternative fuels are considered for aviation, while 1 pct. of national passenger transport on sea is expected to be electrified in 2030, this is kept constant towards 2050.

As outlined in Figure 17, the energy consumption increases only marginally between 2017 and 2050. The transport demand growth is balanced by the energy efficiency improvements. The energy consumption for passenger transport increases from 167 PJ in 2017 to 176 in 2030. In 2050, the energy consumption for passenger transport has declined to 171 PJ.

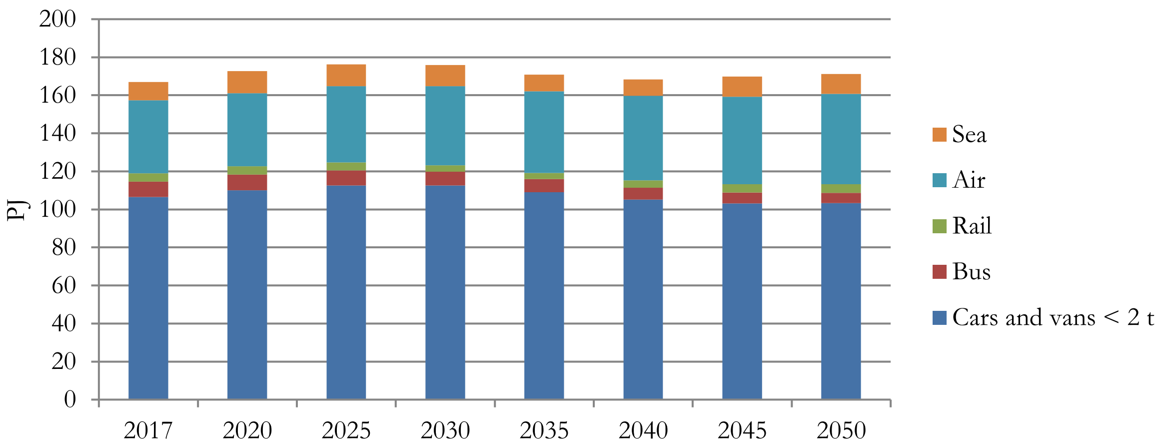

Figure 17. Energy consumption for passenger transport.

5.4.2. Freight transport

The total transport demand is expected to grow considerably between 2017 and 2050. In 2017, the total transport demand is 95.597 tkm and 75 pct. is covered by freight transport on sea and in 2050 the total transport demand has increased to 189.772 tkm. As international maritime freight transport is not considered in DECO, the anticipated growth rate estimated by the International Maritime Organisation (IMO) and the Climate Partnership for maritime transport, is used in the *Reference* scenario. The IMO anticipates the international shipping industry to grow 50 pct. to 250 pct. by 2050. In the *Reference* scenario, it is estimated that the international maritime freight transport demand increases 125 pct. from 2017 to 2050. [45], [46]

In short-term perspective towards 2030, the majority of the transport demand is anticipated to be met by maritime transport, which is expected to increase 34 pct. in the period. The freight transport demand for trucks and vans is expected to grow noticeably as well. The transport demand for trucks and vans increases 19 pct. and 13 pct. respectively. The freight transport demand for rail and aviation are expected to grow identically to the passenger transport demand growth for rail and aviation. This assumption is made as the energy consumption in DECO is not divided between passenger and freight transport, hence the accumulated increase is calculated.

From 2030 to 2050, the same tendencies are evident, as displayed in Figure 18. The transport demand for maritime freight transport comprises 80 pct. of the total transport demand, while the remaining is covered by trucks and vans predominantly. The maritime transport demand increases 60 pct. from 2030 to 2050 while the transport demand for trucks and vans increases 32 pct. and 19 pct. respectively. Rail and aviation freight transport follow the growth rates for passenger transport. This entails, that the market share for maritime freight transport increases, while the market share for rail and road transport demand remains similar.

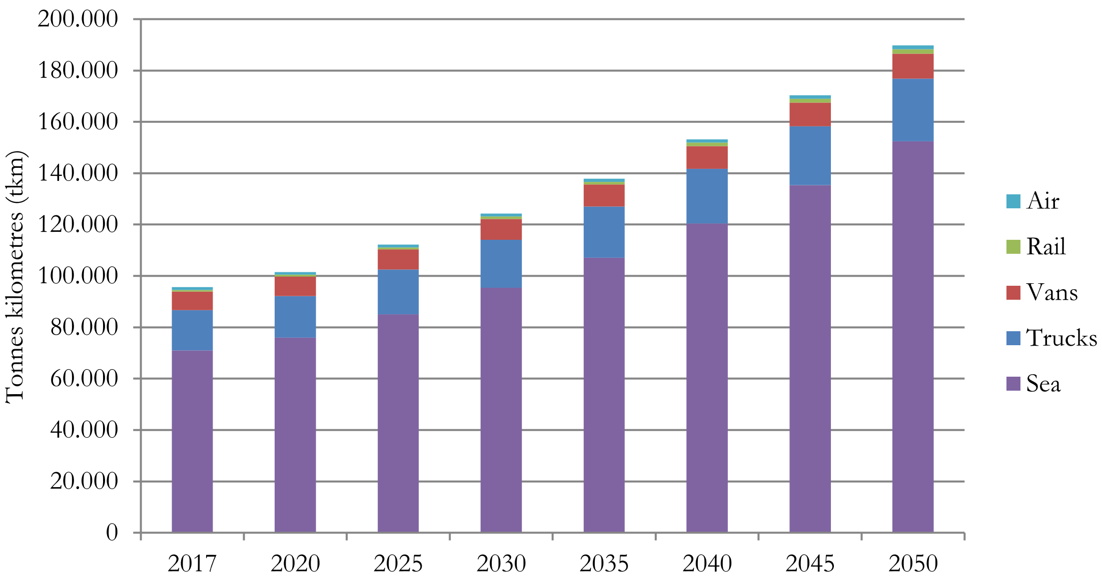

Figure 18. Development of the transport demand (tkm) for freight transport from 2017 to 2050.

The freight transport energy consumption, as outlined in Figure 19 will not increase as significantly as the transport demand. As maritime freight transport is the most energy efficient mode of freight transport, the energy demand only increases marginally even though the transport demand doubles from 2017 to 2050.

The energy efficiency improvements implemented in the *Reference* scenario regarding freight transport considers mainly trucks and vans. Energy efficiency improvements are not expected in rail and maritime transport and will be similar for aviation freight and passenger transport. In a short-term perspective towards 2030, the energy efficiencies of trucks and vans in the *Reference* scenario are expected improve 22 pct. and 7 pct. respectively. From 2030 to 2050, the energy efficiency of trucks improve 13 pct. and improves 2 pct. for vans. The energy efficiency improvements are expected to be conducted primarily on the basis of CO_2 emissions standards from the European Commission.

Implementation of renewable technologies for freight transport in the *Reference* scenario is limited. A share of 0.3 pct. electric trucks and 6 pct. electric vans are implemented by 2030, which increases to 1.6 pct. electric trucks and 37 pct. electric vans in 2050. No renewable technologies are implemented in the sea and aviation transport, while the rail transport follows the same development as for passenger transport.

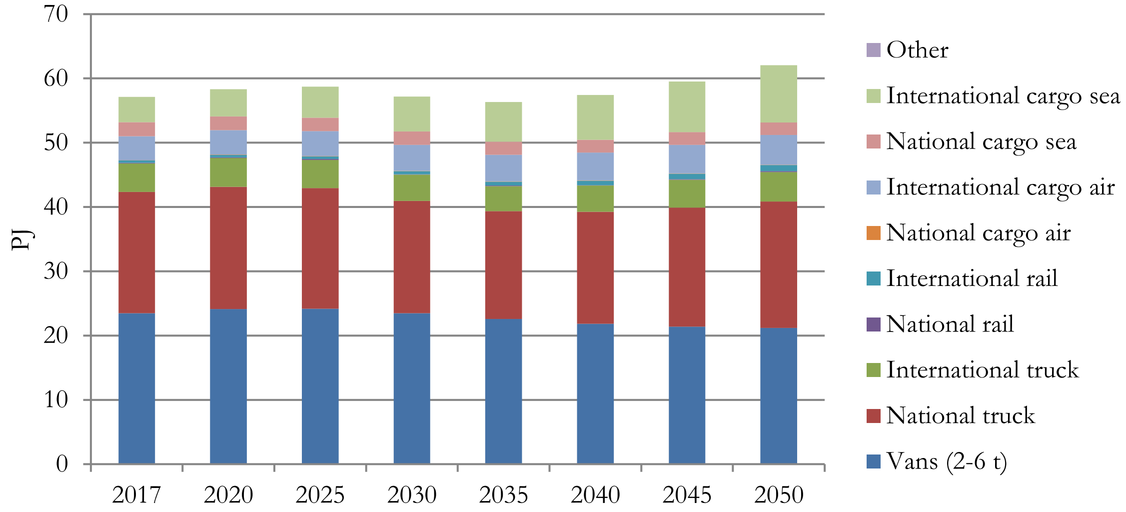

Figure 19. Energy consumption freight transport.

5.4.3. Summary

The final energy consumption of the Danish transport sector in the *Reference* scenario, outlined in Figure 20, increases from 224 PJ in 2017 to 233 PJ in 2030. The implementation of renewable technologies and the transport demand growth rates balance out the energy consumption from 2030 and 2050, hence it remains at 233 PJ. Oil based fuels account for 95 pct. of the fuel consumption in 2017 and 92 pct. in 2030. As renewable technologies are implemented in larger scale towards 2050 the share of oil based fuel in the total consumption decreases to 84 pct. Hence, the *Reference* scenario represents a forecast, where Denmark will remain heavily dependent on fossil fuels towards 2050. Even with significant energy efficiency improvements and implementation of renewable, more energy efficient technologies, the energy consumption will still increase and the fossil fuel dependency will still be substantial.

The CO_2 emissions from the transport sector increases with 1 pct. from 2017 to 2030. The implementation of renewable transport technologies does not make up for the significant growth in transport demand anticipated in the *Reference* scenario. From 2030 to 2050 the CO_2 emissions are reduced with 8 pct.

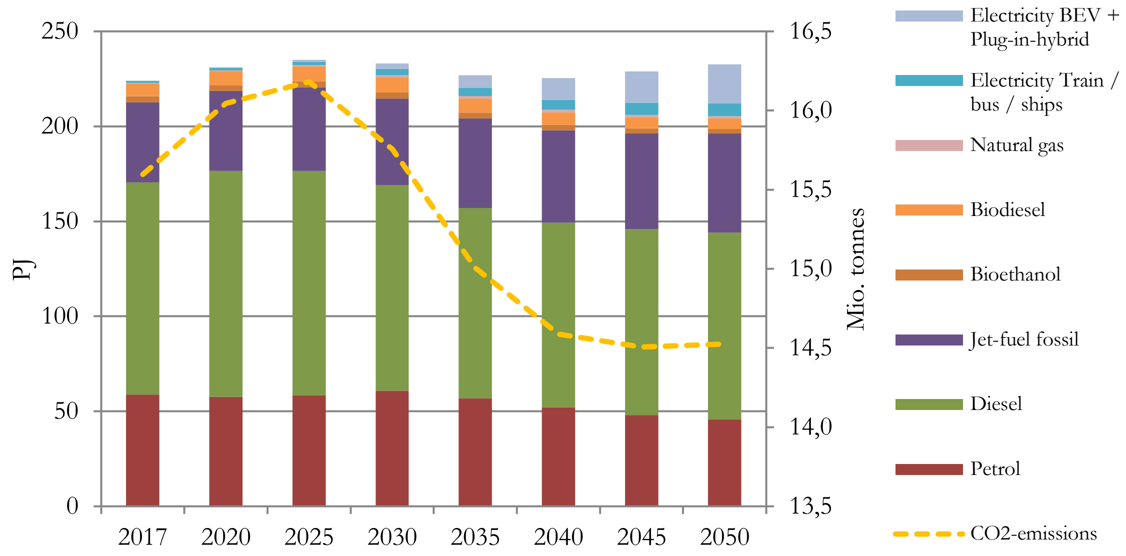

Figure 20. *Reference* scenario energy consumption divided by fuel type and total CO_2 emissions from 2017 to 2050.

The energy system costs of the *Reference* scenario increases noteworthy from 2017 to 2050 (Figure 21). Specifically investment and O&M costs related to new vehicles constitute a major share of the total transport system costs.

The increased traffic work increases the investment costs needed for expanding the Danish road infrastructure, while renewal and maintenance costs related to the railway transport comprise a smaller share the total expenditures. The annual transport system costs increase 32 pct. from 2017 and 2030 and 44 pct. between 2030 and 2050.

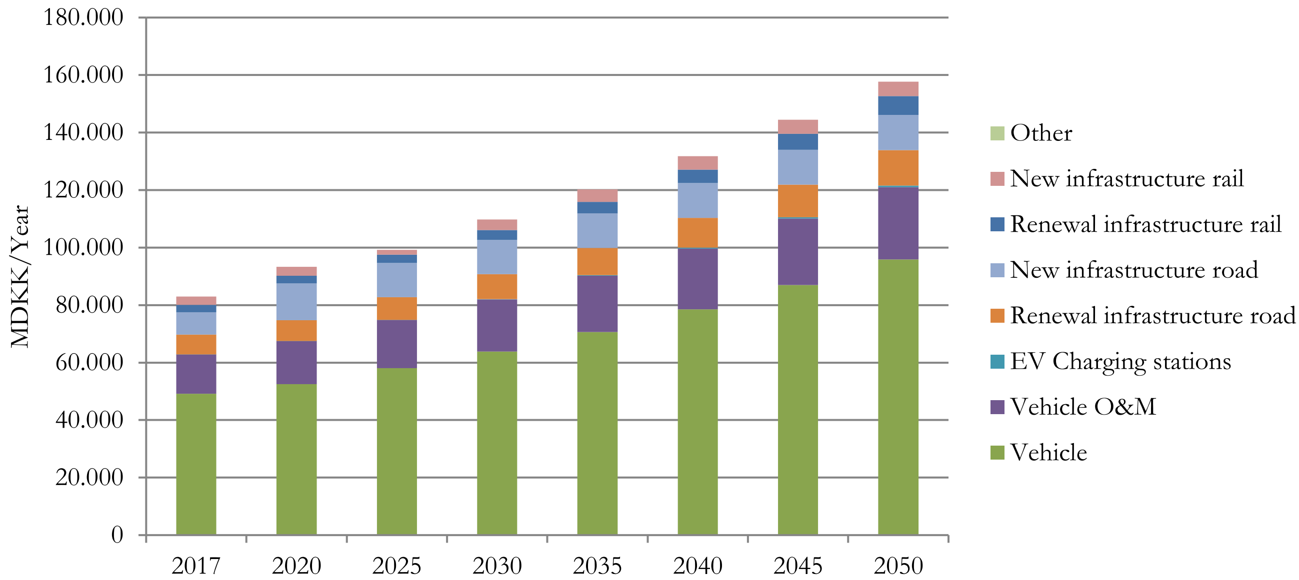

Figure 21. Total transport system costs in the *Reference* scenario from 2017 to 2050.

6. The avoid, shift, improve paradigm

The avoid, shift and improve (ASI) paradigm introduced in section 3, serves as the underlying basis in the development of renewable transport scenarios towards 2030 and 2050. To avoid increasing emissions from the transport sector the ASI approach formulates three fundamental principles to guide planners and decision-makers [29]:

1) avoid rising transport demand and reduce existing demand,
2) shift trips to low-carbon modes, and
3) improve the efficiency of vehicles and fuels.

In the following section, measures to avoid, shift and improve the transport sector are presented and evaluated. Many of the measures investigated will have direct and indirect effects upon all three categories of the ASI paradigm. In an attempt to separate the categories, the measures concerning Avoid and Shift are evaluated together and subsequently measures in the Improve category are analysed.

The measures for avoid and shift are presented as general measures that relates to the entire transport sector, while the improve category will feature a detailed breakdown of the technology developments within each separate mode of transport analysed in this thesis. The technology developments will form the basis of the technology scenarios and the avoid and shift measures will support the design of the transport demand scenarios.

6.1. Avoid and shift

Measures to avoid transport energy consumption and shifting transport demand from energy intensive modes of transport to less energy intensive modes are presented collectively in the following. Achieving motorized transport mitigation or promoting modal shifts will often require comprehensive infrastructure changes at a local level and many of the measures will affect both the avoid and shift category.

It is important to note, that avoiding transportation must not disable or limit the overall mobility. Restraining mobility will have significantly indirect effects on the socio-economic development and the regional and national competitive position. Hence, limiting the amount of driven kilometres must not be accomplished at the expense of the general mobility. [8]

Measures to avoid transport energy consumption will focus primarily on reducing the amount of actual vehicle kilometres driven. Measures to shift transport energy consumption will predominantly include replacing energy intensive modes of transport with less energy intensive modes, such as moving passengers from cars to trains, which have a higher passenger capacity and lower energy consumption per passenger kilometre. For freight transport, a shift from trucks to rail or sea would improve the overall energy efficiency of the transport system.

The population in cities and urban areas is increasing rapidly globally and it is estimated that 70 pct. of the world's population will be living in urban areas by 2050. This urbanization contributes to the growing issue of sustainable transport in cities. Consequently, a lot of research regarding the ASI paradigm is focused on creating sustainable transport solution in urban areas. In an urban context the objective will primarily be to overcome what is known was introduced in section 3 as automobile dependence. Therefore will the measures introduced primarily focus on reducing traffic work in cars for passenger transport. [16], [24] Favouring alternate modes of transport over the transport in personal vehicles is achieved best by developing a well-functioning infrastructure for active modes of transport, such as bicycling and walking as well as improving the public transportation system. Increasing the density of various functions and orienting the urban development in close proximity with the public transport system, will limit the need for transport. In dense mixed-usage areas, the car will seldom be the most convenient mode of transport. Newman and Kenworthy found that the energy consumption per capita is proportionally opposite to the density of a city. [24], [29]

Additionally to enhancing the infrastructure of public transport and active modes of transport to promote a shift away from personal vehicles, increasing the costs of ownership and use is a recognized tool to avoid an increase in the travel in vehicles. [30], [47], [48]

Road charging regulation, congestion charges in urban areas, sustainable fuel pricing and restricted and expensive parking are all measures to restrict car use in general and create incentives to use alternative modes of transport [24], [26]. Congestion charges in Stockholm was introduced in 2006 and immediately reduced the amount of vehicles within the cordon of approximately 20 pct. Commuting trips by car fell 24 pct. and almost all of these trips were shifted to public transit. The observed effects have remained stable over time and statistics show that roads and traffic outside of the charging zone perimeter has remained stable as well. This indicate that congestion charges might be an efficient tool to limit the car traffic in urban areas and initiate modal shifts to public transport. Exemption of the charges for vehicles fuelled by renewables, showed a considerable effect on the sale of these types of vehicles. [49]

Road pricing schemes and sustainable fuel pricing can, if implemented appropriately, support the penetration of all three categories in the ASI paradigm. Road pricing based on time and location as well as vehicle type will create incentives to limit the amount of kilometres travelled and a shift towards public transport. If a personal vehicle is still necessary, road pricing in combination with sustainable fuel pricing, will induce a renewal of the vehicle fleet towards more sustainable fuel types, such as electricity. [29], [50]

Car sharing and ride sharing are two examples of cost-effective measures to limit traffic work. Various studies of car sharing initiatives indicate, that the annual traffic work can be reduced by 30 pct. to 60 pct. Ride sharing can increase the capacity utilisation of vehicles, thus eliminating a significant amount of kilometres driven and need for privately owned vehicles. [51]

Transport infrastructure is crucial for the user's choice of transport mode. Adequate infrastructure for walking, biking or for public transport must be available before a modal shifts can be achieved. Transport infrastructure entails remarkable costs, and are therefore relevant for consideration when promoting modal shifts. The costs associated with increasing the traffic work of road transport heavily outweighs the costs associated with increasing the traffic work of rail transport. Hence, a modal shift from road to rail will benefit the system in terms of reduced traffic work, reduced energy consumption, and decrease the total transport system costs. [7], [12], [34]

For freight transport avoiding unnecessary transport and promoting a shift towards energy efficiency modes of transport, depends, as for passenger transport, heavily on adequate infrastructure. An expansion of the Danish railway infrastructure to encourage a modal shift from freight transport with trucks to trains, would increase the energy efficiency. At EU level, it is expected that the potential of moving transport of goods from roads to rail is approximately 5 pct. In 2011 the European Commission formulated a target that 30 pct. of all freight transport over 300 km on roads should be shifted to other modes of transport, such as rail or maritime transport by 2030 and 50 pct. by 2050. [52]–[54]

6.2. Improve

Improving energy efficiency of conventional transport modes and substituting fossil fuels with renewables are the two primary measures considered to improve both the passenger and freight transport sector.

The implementation of alternative renewable fuels depend on the mode of transport and the technological development of the fuel production. The renewable transport fuels considered in this report contains biofuels, direct electrification via batteries and indirect electrification via electrofuels produced from electrolysis. In literature, there is resilient agreement that as much of the transport sector possible should be converted to electricity. Electric driven vehicles have significantly higher efficiencies and provides a direct path for integration of renewable electricity produces from wind, solar or hydro. The use of biofuels is considered to play a dominant role in the beginning of a renewable transition. The development of biofuels is far along, hence it is estimated that biofuels will comprise a higher share of renewable fuels towards 2030. Biofuels also assist in the renewable transition of the parts of the transport sector that are difficult to electrify. In a long-term perspective towards 2050 biofuels are expected to have a less dominant role, as an overdependence on biofuels would be an unsustainable pathway. Instead of extensive use of biofuels, indirect electrification via electrofuels is expected to deliver the energy dense fuel that are necessary in aviation, maritime and heavy-duty transport. Since biofuels are not anticipated to have a significant influence in a long-term transition, biofuels are not described as thoroughly as electrofuels in the following. [13]–[15], [55], [56]

Direct electrification and indirect electrification via electrofuels are highly dependent on the technological development over the next decades to increase efficiencies and minimize the costs of production. As for direct electrification, the battery costs constitute the majority of the vehicle costs, hence a decreased battery cost would significantly lower the total costs of electric vehicles. The production of electrofuels from renewables via electrolysis is still a novel technology and energy efficiency improvement and costs reductions are necessary to enhance its competitiveness with fossil fuels.

In the following, first an evaluation of the technological development of the production of biofuels and electrofuels is conducted, along with an estimation of market share in 2030 and 2050. The development will have significant influence on the phase-in of renewable energy in the transport sector on short-term towards 2030 and long-term towards 2050. The development of electrofuels and market share of biofuels will affect all modes of transport equally, hence they are presented separately.

Secondly, the development and implementation of battery driven electric vehicles are considered for the following modes of transport along with an estimation of potential for energy efficiency improvements:

- Road transport
- Rail transport
- Maritime transport and aviation

If direct electrification cannot convert all of the transport demand, the anticipations regarding a phase-in of biofuels and electrofuels are considered. The anticipated development, together with the general expected development of batteries, electrofuels and biofuels will form the basis of the technology scenarios.

6.2.1. Biofuels

Until now the integration of renewable energy in the transport sector has primarily been through an admixture of liquid biofuels in petrol and diesel. Biofuels cover a broad term of a variety of different fuel types predominantly produced from biomass. Primary biofuels are unprocessed biomass as wood pellets, firewood and wood chips, which are mainly used in heat and electricity production. Secondary biofuels are modified primary biofuels, which have been treated to the form of liquid or gaseous fuels. Secondary biofuels, such as biodiesel and ethanol can directly replace conventional fossil fuels in the transport sector. [39]

Biofuels, such as bioethanol and biodiesel have successfully replaced a significant share of fossil fuels in the transport sector. In Denmark, 5.75 pct. biofuels have been blended in all fossil fuels since 2010 and this share is increased to 7.6 pct. from 2020 and forward. Blends of 10 pct. to 20 pct. bioethanol in gasoline and even higher in some regions has proven feasible in many European countries. [6], [57]

Gaseous biofuels can replace natural gas in trucks and busses. The market for gaseous fuels especially within heavy-duty transport is growing both in Europe and in Denmark and it is expected that biogas will provide a renewable fuel in the transition towards 2030. [58], [59]

EU have strict regulation regarding the share of biofuels allowed to blend-in with fossil fuels. These regulations are in place due to concern regarding first generation biofuels. Production of first generation biofuels are in direct competition with food production of land use, which could make an extensive production and unregulated blend-in shares an unsustainable solution in many parts of the world. [39], [60]

The market maturity of biofuels is further developed than alternative renewable liquid fuels. Hence biofuels are expected to play a bigger role in the transition of the transport sector towards 2030 and a lesser from 2030 onwards. In long term, replacing fossil fuels directly with biofuels is an unsustainable solution and the extensive use of biomass would create a dependency that will not be available within the domestic resource. The bioenergy resource is scarce and a more efficient utilisation of the bioenergy resource is necessary. [39]

6.2.2. Electrofuels

To meet the fuel demand of the transport sector that is not easily electrified, alternatives to energy-dense hydrocarbons, such as gasoline, diesel and kerosene-type jet fuel, are crucial to identify. Biofuels, as described above, have been substituting fossil fuels in the transport sector in recent decades, but it would be an unsustainable path to create an over-dependency on bioenergy to transition the remaining transport demand. Electrofuels, produced from mixing hydrogen and CO_2, to create gaseous or liquid fuels, such as methane, methanol or DME, provides a renewable pathway for fuel production for the parts of the transport sector that are not readily available for electrification. High blends of methanol in liquid fuels have proven feasible and requires only minor adjustments to the vehicle fleet. Gaseous fuels like methane provides, as well, a feasible integration of renewables in the transport sector. Liquid and compressed natural gas is already a widespread alternative to diesel for heavy-duty trucks, hence the infrastructure for renewable methane is already in place. [16], [61], [62]

The production of electrofuels depend primarily on the development of two processes; electrolysis and chemical or biological synthesis. Hydrogen is produced from electrolysis and hydrogen is then mixed with biomass, biogas or CO_2 from other sources to produce liquid or gaseous fuels. If the CO_2 source is biomass, the biomass is gasified and the syngas is upgraded with the addition of hydrogen. With CO_2 sources from other than biomass, such as carbon capture technologies equipped to power plants, the hydrogen and CO_2 reacts to create a syngas that is then converted into fuels via a synthesis process. The electrolysis technology is well-known and has been developed over the past 200 years. Three types of electrolysis are currently available, alkaline, polymer exchange membrane (PEM) and solid oxide electrolysis cells (SOEC). Alkaline and PEM are commercialised and mature technologies, while SOEC is still in a research and development phase. The alkaline technology has been deployed with plants of several hundred MW capacity. The technology is the cheapest of the three, but operates at the lowest efficiencies. The PEM technology is deployed in single MW scale, while SOEC is still only deployed in kW scale demonstration projects. The SOEC is interesting in future energy systems, as the overall efficiency is significantly higher than for alkaline and PEM electrolysis. [16], [55], [63]

In order to ensure a renewable production of electrofuels, the hydrogen must be produced in electrolysers powered with electricity from renewables. The hydrogen can be used directly in fuel cell vehicles without further upgrades but the energy density is increased significantly when mixed with a source of carbon. This also allows for production of liquid fuels that are easier to store and to implement in the transport sector. In the synthesis process, hydrogen from electrolysis reacts with CO_2 and is converted to gaseous or liquid hydrocarbons. A variety of end fuels are possible to produce and no optimal fuel for the transport sector has been identified. The composition of electrofuels in a future transport system will most likely be a combination of several. In the following analysis, methanol is used to represent electrofuels for road transport. Methanol has higher efficiencies than gaseous fuels and the methanol synthesis has been commercial for decades, although the sustainable methanol synthesis with CO_2 from biomass gasification is still in a development phase and has not been tested in large scale. [16], [63]

The production of different electrofuels will depend on many identical processes, hence whether methanol, DME or methane for instance, are analysed, the same requirements have to be met by the surrounding energy system.

Methanol is not suitable as a fuel for aviation and it is necessary to convert the electrofuel into e-jet fuel via hydrotreating and oligomerization. The technical requirements for jet fuels are strict, and the energy density of synthetic fuels need to be higher than fuels for road transport. Upgrading the electrofuel via chemical synthesis, by Fischer-Tropsch technology, produces e-jet fuels that follow the aviation industry's restrictions for jet fuel. [[16], [63]–[65]

The production of electrofuels in Denmark remains a topic of uncertainty. While some researchers and analyses suggest that the electrolysis capacity could grow significantly during the next five to ten years and the production of electrofuels could provide the transport sector with significant amounts of energy, others do not expect electrofuels to have any major impact until after 2030. Depending on the desired route for production of electrofuels, the technologies are well-known. The primary issue is the costs of production, which is many times higher than for conventional fossil fuels. This can be improved by a technological development of the processes, such as the electrolysis or the synthesis process. In Denmark only small scale implementation of electrolysis and synthesis have been implemented and mainly at demonstration scale. In 2020, plans were announced to increase the Danish electrolysis capacity to 1.3 GW by 2030, with an estimated electrofuel production capacity of 250.000 tons. [63], [66]–[71]

The availability of carbon sources for production of electrofuels towards 2030 are considered in section 8.

6.2.3. Road transport

The electrification of road transport depends heavily on the development of batteries. Battery technology development is substantial for the costs, performance and general competitiveness of electrification of the transport sector. Battery technology is developing quickly as more and more companies and vehicle manufacturers are realizing that the market is significant. Lithium-Ion battery prices dropped 85 pct.

between 2010 and 2018, suggesting that technology development and market demand improve the market competitiveness. [72], [73]

The battery technology for the transport sector is primarily targeted at road transport and passenger vehicles, but developments of larger battery packs for ferries and aircrafts are being developed and implemented.

6.2.3.1. Cars and vans

The desired development regarding passenger transport in cars and freight transport in vans is unified between most stakeholders, an extensive electrification is necessary and is the preferred option for a renewable transition. The development of cars and vans are expected to be very similar, hence the following applies for both cars and vans. [74]–[77]

The implementation of electric vehicles in Denmark in the last decade has been insignificant. The amount of registered electric vehicles in Denmark as of 2020 is 15.000. Recently, the share of battery electric vehicles and plug-in hybrids of newly purchased vehicles have improved and constituted 7 pct., 11 pct. and 9 pct. in February, March and April 2020 respectively [7]. The tendency of increasing sales of electric vehicles is apparent in the rest of Europe as well. In the European market, the share of electric vehicles sold in February 2020 had grown 111 pct. compared to the share sold in February 2019. [78]

In a Danish context there is agreement between researchers and industry associations, that the long term solution for cars and vans is a nearly 100 pct. transition towards battery electric driven vehicles. This is supported by the desire in the Danish parliament to prohibit the sale of conventional fossil fuelled cars from 2030 and beyond. A regulative measure such as prohibiting the sale of conventional cars will indubitably prompt a natural phasing out of fossil fuels and a transition towards electric vehicles. [8], [9], [50], [64], [79]–[81]

The implementation of electric vehicles in passenger transport depends on several parameters including [82]:

- Fossil fuel prices
- Technological development
- Taxes
- Charging infrastructure
- Personal preferences

The costs of electric vehicle batteries are expected to decline substantially in the coming years while the energy density and thus the range of electric vehicles is estimated to improve. The range of a fully charged electrical vehicle varies depending on the model, but the average range is expected to increase to more than 400 kilometres in 2030, hence accommodating the majority of vehicle owner's needs. Inventions to minimize the use of rare materials, which have had a negative impact on the overall life-cycle, are also developing fast and new battery technologies with little or no use of cobalt are being produced. [83]–[87]

The decline of the price of batteries are expected to make the electric vehicles financially competitive with traditional ICE vehicles within the next ten years. The anticipation among researchers and manufacturers is that battery electric vehicles will be competitive with conventional cars during the 2020's. [88]–[90]

Development of charging infrastructure and of high capacity charging stations are improving the overall mobility of electric vehicles. This development is enhancing the convenience of owning an electric car, hence improving the probability that more people and companies will invest. [86], [87]

The effect of electric vehicles in a renewable transition towards 2030 depends on sales share of electric vehicles. To reach an amount of one million electric vehicles (approximately 30 pct. of the total vehicle fleet) in 2030, the Danish Council on Climate Change estimates that the share of electric vehicles needs to reach 100 pct. of all purchased vehicles in 2030. Assuming an exponential growth in the sale share, a fleet of one million could be achieved. Other researchers suggest that there is potential to reach an amount of 1.5 million electric vehicles in 2030. To achieve this, 50 pct. of all new purchased vehicles must be electric in 2024 and almost 90 pct. in 2027. [8], [81]

In Norway, which has the highest share of electric vehicles per capita, financial incentives have been offered to electric vehicle owners since the beginning of the 2000's. Lower road taxes, free parking in selected municipal carparks and sales-tax exemptions have contributed to increase the sale of electric vehicles. Figure 22 outlines how the share of battery electric vehicles and plug-in hybrids have increased from comprising only a few percentages of newly purchased vehicles to constituting almost 70 pct. in April 2020. An extensive development and expansion of charging infrastructure financed in the first place by the government, have supported the market uptake of electric vehicles, as the convenience of charging improved. [91]–[93]

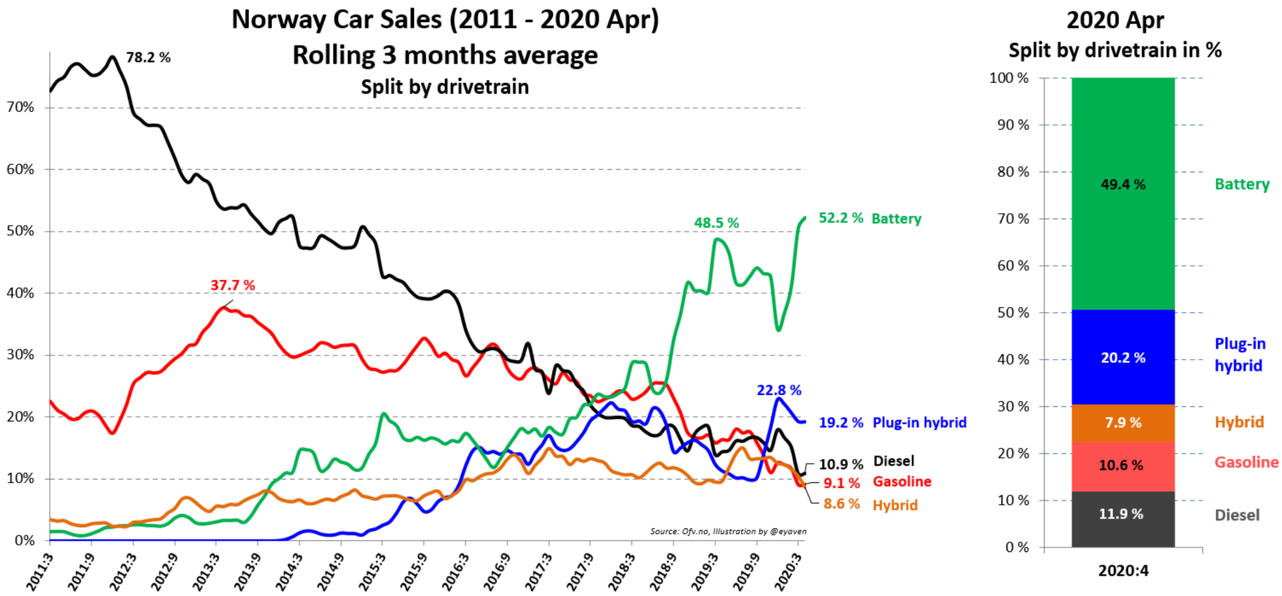

Figure 22. Car sales in Norway from 2011 to April 2020. [93]

The sales share of electric vehicles in Norway grew from approximately 10 pct. in 2013 to 70 pct. in 2020. If it is possible for Denmark to follow the same pattern as Norway, reaching an amount of one million electric vehicles and maybe more in 2030, is realistic.

Additional energy efficiency improvements for cars and vans <2t, other than the ones assumed in the *Reference* scenario, are not considered relevant. Energy efficiency improvements will come primarily from a transition towards electric vehicles.

6.2.3.2. Trucks

The long term target for trucks is, as for cars and vans, to replace the use of fossil fuels with renewables. Whether a full electrification is possible, is still debated, as some analyses suggest that biofuels and electrofuels are necessary to complete a full renewable transition of road freight transport. As of now only very few electric trucks are available on the market, and consists currently of only light-duty trucks. [68]

There are disagreements among researchers and industry associations of when a replacement of conventional diesel trucks with battery electric will happen, as some suggest that battery electric trucks will be financially competitive with conventional diesel trucks during the 2020's, and others believe that electricity as a primary fuel will only have a minor impact on road freight transport before 2030. Trucks typically drive longer distances than passenger vehicles and weighs usually between 3.5 and 50 tonnes. Approximately 60 pct. of all Danish trucks have a total weight of 28 tonnes or more and as the heavy trucks typically drive longer distances, they are responsible for roughly 80 pct. of the total traffic work (km) of all trucks. [68]

The electrification of heavy-duty road transport is highly dependent on decreasing the weight and range of batteries. The range of battery driven vehicles is limited compared to conventional technologies, hence very large and heavy battery packs are needed to deliver the same range. If the weight of batteries can be reduced, the applicability in more areas of the transport sector increases. [94]

The added vehicle weight enhances the performance requirements of batteries, to provide the power necessary and not increase the total weight of the vehicle inexpedient. Lithium-Ion batteries, which are the most common are still expensive compared to fossil fuels and have a high weight compared to the relatively low energy density. This limit the size and the load capacity of the trucks, which worsen the financial calculation, many freight transport companies have to do. The implementation of battery electric trucks will most likely occur faster for urban and regional haul and slower for long haul freight transport. Furthermore the development will emerge more quickly for light- and medium-duty trucks, as the size of the battery is relatively small and slower for heavy-duty. [68], [90], [95], [96]

Of European freight transport, more than 50 pct. of all trips on road are less than 50 kilometres and approximately 75 pct. are less than 150 kilometres. This differs between countries, where the average driving distance for trucks in Finland is 100 kilometres, while it is between 25 and 50 kilometres in Switzerland. In the *Reference* model of the Danish transport system, 50 pct. of the transport demand for national trucks is for trips of less than 200 kilometres while all the transport demand for international trucks is for trips of more than 250 kilometres. The potential for electrification of the road freight transport naturally also varies between countries. In Switzerland, Liimatainen [97] showed that as much of 71 pct. of all freight transport on land was possible to electrify, while the potential would be lower for Finland. Another study notes that 60 pct. of all medium sized commercial vehicles can run on electricity solely. The remaining 40 pct. require too much power. This would entail that a large part of Danish trucks cannot be directly electrified via batteries and alternatives must be considered. The specific potential for electric trucks will depend heavily on the development of battery technologies. [52], [53], [96], [97]

In a short term perspective towards 2030, battery electric trucks are not anticipated to drive the renewable transition of freight transport on land alone. There is general agreement in literature that the transition must be supported by an implementation of biogas trucks. As outlined above, biofuels in general are further developed than alternative renewable fuels, hence biogas can have a quick impact on the emissions and fuel distribution of freight transport. Liquid or compressed biogas trucks can with relative ease replace a large share of the freight transport trips below 200 kilometres. Biogas trucks have already been implemented in Denmark and depending on the development of batteries and electrofuels, could play a significant role in the renewable transition towards 2030. [58], [98]

If a complete electrification of the road freight transport towards 2050 is to be fulfilled, analyses suggest that battery electric trucks alone will be insufficient. As research estimate that long-haul heavy-duty trucks will be difficult to electrify, researchers suggest that either electrofuels or electrical road systems (ERS) could be viable solutions. Electrofuels could directly replace liquid fossil fuels in the trucks that are too large or drive too far to electrify. ERS is a broad concept of various kinds of electric roads and have been developed for a number of years for railway systems and trams. The most developed technology is the conductive charging of vehicles via overhead power lines. The technology is being tested currently in Sweden and Germany, where the system is implemented on short distances of roads. The installation costs of ERS is high and will require a certain coverage of freeway infrastructure in order to be feasible. ERS would provide an alternative to electrofuels as heavy-duty road transport could be equipped with smaller batteries and the total weight would not increase considerably. [68], [99]

In Denmark, over 50 pct. of all cargo is transported on less than 2 pct. of the road network. Hence, only a small share of the road infrastructure would have to be equipped with overhead power lines to electrify a significant share of the road freight transport. Studies have shown that by 2050, 38 pct. of all European highways could have overhead power lines, and in Germany it is estimated that 60 pct. of all truck traffic could be powered by overhead power lines if the potential is fully utilized. The ERS technology is not considered relevant in short term towards 2030, but could prove viable in a long term perspective towards 2050. [8], [52]

In addition to the implementation of renewable fuels, there is a great potential for energy efficiency improvements for trucks. European standards alone are expected to improve the energy efficiency with 22 pct. towards 2030 and are broadly recognized as an effective measure to decrease the energy consumption of road freight transport. Furthermore, systemic improvements, such as optimized logistics and routing, platooning and increased capacity utilisation all possess significant potentials to decrease the energy consumption of road freight transport. [53], [100]–[103]

Improving logistics for freight transport on roads via advanced intelligent transport systems (ITS) and deployment of centralized logistics hubs will increase the general energy efficiency of the freight transport. [16]

6.2.3.3. Busses

The renewable transition of short-distance and long-distance busses will differ in regards of implementation of electricity. The development will most likely be similar to that of trucks, where short-distance busses to a greater extent can be electrified, while long-distance busses will be more dependent on liquid hydrocarbons.

Short-distance urban busses can with relative ease be converted to alternative fuels. In Copenhagen a share of the urban routes have been replaced with both electric and biogas busses. It is expected that electricity and biogas can replace diesel in the majority of urban busses and that the development will be rapid towards 2030. As most urban busses drive relatively short distances and follow the same route every day, charging stations for electric busses can be established at either end of the route and deliver the power needed. With the possibility of planning the driving between charging carefully, the size of the battery can be minimized and thus limit the increase in weight. [9], [81] For long-distance domestic and international busses the development is expected to follow that of trucks. Electricity remains a long-term target, but given the development of battery technologies, the implementation will occur at a slower pace. Hence, biogas is expected to support the transition towards 2030. In a long term perspective towards 2050, the development of long-distance busses is anticipated to move towards electrification, but as for trucks, a certain amount of the transport demand will be difficult to electrify. Therefore are long-distance busses dependent on the development of electrofuels and possibly of ERS.

6.2.4. Rail

The Danish railway infrastructure is expected to be almost completely electrified by 2030. The electrification of the Danish railways is planned and to a large extent financed [35]. No alternative developments within rail transport are considered in this work, as the electrification is anticipated to be the best solution.

6.2.5. Aviation and sea transport

It is considered less likely that electricity will have a significant influence in the decarbonisation of the maritime transport and aviation towards 2030 and 2050. Short-distance ferries can to some extent be electrified, with a high capacity charging station at each destination port. Short ferry distances have been electrified in Denmark, but given the projected development of batteries in terms of energy density and weight, electrification of long distance shipping is not assumed to happen before 2050. [46], [104], [105]

Electrification of aircrafts is a subject of disunity between researchers and the aviation industry. Domestic airlines may be possible to convert to electricity after 2030, but because of the high weight and low energy density of batteries, international flights are not expected to be electrified. Instead a combination of biofuels and electrofuels is anticipated to drive the renewable transition. The same applies for international shipping. [46], [105], [106]

For international aviation secondary biofuels, such as biodiesel or methanol cannot replace jet fuel directly but needs to be upgraded further to form a high energy density liquid hydrocarbon, as outlined above. The high energy density of jet fuel allows for long distance flights because of the low additional weight of fuel. Currently, only one type of renewable alternative to fossil jet fuel, hydro-processed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK) is technically and commercially mature. Up to 50 pct. is allowed for blend in with conventional jet fuel and it is estimated that HEFA-SPK will be the principal renewable fuel to be used towards 2030. Other sustainable aviation fuels are being developed and several researchers anticipates that 10 pct. of the global aviation transport demand could be met with electrofuels in 2030. The main barrier for the implementation of electrofuels is the significant differences in costs. Sustainable aviation fuels, such as e-jet fuel, cost 2 to 7 times more than fossil jet fuel. This creates a barrier for the aviation industry, as the fuel expense is a large part of the total expenses. Technological development and support of renewable fuels are necessary for a significant implementation before 2030. [107]–[110]

Ammonia produced from electrolysis is estimated to drive the renewable transition for maritime transport. The production of ammonia is well-developed and depends on the development of electrolysis in order to become a sustainable and feasible alternative for maritime transport. Ammonia can replace diesel in ships and be used in traditional engines. This allows for an easy transition. Ammonia is produced without a carbon source and can thus relieve the strain on the limited bioenergy resource. [46], [50], [104], [105] For both aviation and maritime transport there are significant potentials to increase energy efficiency. The International Maritime Organisation (IMO) has formulated energy efficiency improvement targets demanding that international sea freight transport must improve energy efficiency with 40 pct. by 2030 compared to 2008. The shipping industry have been particularly good at implementing energy efficiency measures during the last decades, Mærsk for instance has reduced the CO_2 emissions of their fleet with 42 pct. compared to 2008 levels. The University of Maritime Advisory Services estimates several large energy efficiency potentials for maritime transport. Utilization of surplus engine heat, route optimization, bottom paint and propeller optimization have a collective potential of improving energy efficiency with 7 pct. to 35 pct. [46], [111]

For aviation, more efficient engines, reduced total weight of flight and bigger flights are all expected to increase energy efficiency. Along with systematic improvements, such as better logistics planning and less waiting time both in the air and on the ground, the energy efficiency could be improved with up to 31 pct. [106], [109], [112], [113]

7. Renewable transport scenarios

In this chapter the renewable transport scenarios are presented and evaluated. First, the technology scenarios, *Reasonable* and *Optimistic*, are outlined and the development and implementation of renewable transport technologies and fuels along with energy efficiency improvements are described. Secondly, the results regarding energy consumption, CO_2 emissions and transport system costs in the scenarios are presented. The two technology scenarios, *Reasonable* and *Optimistic* are compared with *Reference* scenario in 2030 and 2050. Following the technology scenarios, the transport demand scenarios are presented. The two transport demand scenarios, M*edium* increase and *Low* increase are compared with the *High* increase *Reference* scenario. The scenarios are compared in terms of annual energy consumption and transport system costs.

7.1. Technology scenarios

The technology implementations in the *Reasonable* and *Optimistic* scenarios are based on the comprehensive technology evaluation examined above. The estimation of what is a reasonable technology implementation and what is optimistic is evaluated by the author, based on statements from industry associations, researchers and findings in literature. The core difference between the *Reasonable* and *Optimistic* scenario will be the rate of implementation towards 2030. As outlined in section 6.2, the development of most renewable technologies is assumed to be quite well-established beyond 2030, the disunity regards whether the development will allow for a massive technology implementation before 2030 or not. In each scenario, energy efficiency improvements of conventional technologies are considered as well, and will be outlined when each scenario is presented.

In Table 3 and Table 4 the technology implementations in the two scenarios are presented. Two central points are that the key target for road transport in both scenarios is to convert as much as possible to electricity, and that shipping and aviation will rely on the production of electrofuels and ammonia. Electric vehicles have significantly higher energy efficiencies, so if an electrification is possible, it will greatly benefit the transport system in terms of energy consumption. The forecasts for large scale production of electrofuels are uncertain, hence the implementation towards 2030 differs in the two scenarios.

In the technology scenarios, the annual transport demand growth rates are identical to the *Reference* scenario. Hence, the same transport demand will have to be met in the *Reasonable* and *Optimistic* scenario. By implementing renewable, energy efficient transport technologies along with additional energy efficiency improvements of conventional technologies, the transport energy demand and CO_2 emissions can be reduced towards 2030 and 2050. In both scenarios, it is estimated that carbon neutrality is achieved by 2050.

In the following, the technology scenarios are presented and the implementations are outlined. For both scenarios the potential CO_2 reductions are calculated and they are compared to the *Reference* scenario in terms of annual energy consumption and transport system costs.

Passenger transport											
Vehicle	Type of technology	Reasonable					Optimistic				
		2017	*2025*	*2030*	*2040*	*2050*	*2017*	*2025*	*2030*	*2040*	*2050*
Cars and vans <2t	Battery electric vehicles	0,5%	10,0%	23,0%	80,0%	100,0%	0,5%	12,0%	32,0%	80,0%	100,0%
	ICE Plug-in hybrid vehicle Diesel	0,4%	5,0%	8,0%	5,0%	-	0,4%	6,0%	14,0%	5,0%	-
	ICE e-methanol	-	-	-	-	-	-	2,0%	10,0%	-	-
Rail	Diesel trains	68,0%	35,0%	8,0%	-	-	68,0%	35,0%	8,0%	-	-
	Electric trains	32,0%	65,0%	92,0%	100,0%	100,0%	32,0%	65,0%	92,0%	100,0%	100,0%
Bus	Battery electric busses	0,5%	15,0%	40,0%	65,0%	75,0%	0,5%	20,0%	50,0%	70,0%	100,0%
	Hydrogen	-	0,1%	0,7%	-	-	-	0,1%	0,7%	-	-
	Natural gas	1,0%	4,8%	-	-	-	1,0%	4,8%	-	-	-
	ICE Biodiesel	-	5,0%	15,0%	20,0%	15,0%	-	7,0%	20,0%	10,0%	-
	ICE e-methanol	-	-	-	1,0%	10,0%	-	2,0%	10,0%	-	-
Air	Electric planes	-	-	-	-	1,0%	-	-	-	-	1,0%
	Gas-turbines Bio-jet fuel	-	-	5,0%	25,0%	49,0%	-	1,0%	9,0%	25,0%	49,0%
	Gas-turbines CO_2-jetfuel	-	-	5,0%	25,0%	50,0%	-	1,0%	9,0%	25,0%	50,0%
Sea	Electricity	-	0,7%	3,0%	5,0%	8,0%	-	0,7%	4,0%	6,0%	8,0%
	e-methanol	-	-	-	5,0%	15,0%	-	-	-	5,0%	15,0%
	Ammonia	-	1,0%	5,0%	20,0%	77,0%	-	1,0%	10,0%	30,0%	77,0%

Table 3. Renewable technology implementations for passenger transport in the *Reasonable* and *Optimistic* scenario from 2017 to 2050.

Freight transport											
Vehicle	Type of technology	Reasonable					Optimistic				
		2017	*2025*	*2030*	*2040*	*2050*	*2017*	*2025*	*2030*	*2040*	*2050*
Trucks	Battery electric vehicles	-	3,0%	10,0%	30,0%	65,0%	-	8,0%	25,0%	55,0%	100,0%
	ICE Biogas	-	3,0%	10,0%	15,0%	15,0%	-	3,0%	10,0%	10,0%	-
	ICE e-methanol	-	-	-	1,0%	20,0%	-	2,0%	10,0%	15,0%	-
Vans	Battery electric vehicles	-	10,0%	23,0%	70,0%	100,0%	-	12,0%	32,0%	80,0%	100,0%
	ICE Plug-in hybrid vehicle Diesel	-	5,0%	8,0%	7,0%	-	-	6,0%	14,0%	5,0%	-
	ICE e-methanol	-	-	-	-	-	-	2,0%	10,0%	-	-
Rail	Diesel trains	68,0%	35,0%	8,0%	-	-	68,0%	35,0%	8,0%	-	-
	Electric trains	32,0%	65,0%	92,0%	100,0%	100,0%	32,0%	65,0%	92,0%	100,0%	100,0%
National air	Electric planes	-	-	-	-	50,0%	-	-	-	10,0%	100,0%
	Gas-turbines Bio-jet fuel	-	-	2,0%	10,0%	25,0%	-	1,0%	9,0%	15,0%	-
	Gas-turbines CO_2-jet fuel	-	-	2,0%	10,0%	25,0%	-	1,0%	9,0%	15,0%	-
International air	Electric planes	-	-	-	-	-	-	-	-	-	-
	Gas-turbines Bio-jet fuel	-	-	2,0%	10,0%	50,0%	-	1,0%	9,0%	25,0%	50,0%
	Gas-turbines CO_2-jet fuel	-	-	2,0%	10,0%	50,0%	-	1,0%	9,0%	25,0%	50,0%
National sea	Electricity	-	-	-	6,0%	15,0%	-	-	1,0%	7,0%	20,0%
	e-methanol	-	-	-	-	-	-	-	-	-	-
	Ammonia	-	-	5,0%	25,0%	85,0%	-	2,0%	10,0%	25,0%	80,0%
International sea	Electricity	-	-	-	-	-	-	-	-	-	-
	e-methanol	-	-	-	1,0%	15,0%	-	-	-	1,0%	15,0%
	Ammonia	-	2,0%	5,0%	25,0%	85,0%	-	2,0%	10,0%	25,0%	85,0%

Table 4. Renewable technology implementations for freight transport in the *Reasonable* and *Optimistic* scenario from 2017 to 2050.

7.1.1. Reasonable scenario

In the *Reasonable* scenario, the energy consumption and CO_2 emission reductions in 2030 are affected primarily by significant implementation of renewables in passenger transport. The amount of electric passenger vehicles increases from approximately 15.000 in 2017 to 1 million in 2030, while 55 pct. of all busses, both short- and long-distance are converted to electricity and biogas. For both national and international passenger air transport, 10 pct. of the fuel consumption is converted to electrofuels which decreases the total CO_2 emissions significantly. For passenger transport on sea 5 pct. is converted to ammonia and 3 pct. to electricity.

Additional to the implementation of renewable transport technologies, an increase of the blend of biofuels in all liquid fuels is implemented. In all liquid fuel for road transport the blend of biofuels is assumed to double from 2020 and onward. An increase of the blend of biofuels is recognized in literature to be an effective measure to implement renewable energy in the transport system.

From 2030 to 2050 the electrification of vehicles and busses continues and all vehicles are electric by 2050. For busses 75 pct. is converted to electricity while the remaining transport demand is met with biofuels and electrofuels. For aviation and maritime passenger transport, the share of electrofuels and ammonia significantly increases and covers almost the entire demand by 2050. The remaining is met by electric planes and ferries. Half of the national aviation is assumed electrified in 2050. The domestic flight distances are short, and could be possible to electrify.

For freight transport the CO_2 reductions towards 2030 are provided primarily by an electrification of trucks and vans. For national trucks especially, approximately 50 pct. of the transport demand is covered by trips under 200 kilometres, thus making it possible to electrify. The implementation of electric trucks is anticipated to be relatively slow and the renewable transition is assisted by an implementation of biogas trucks. The electrification of vans is assumed to follow the pattern of cars. For freight transport by air or sea transport an implementation of electrofuels and ammonia is considered. 4 pct. of the transport demand for aviation is converted to electrofuels and 5 pct. of maritime freight transport is converted to ammonia.

Towards 2050 65 pct. of all trucks are converted to electricity, while the remaining are fuelled by electrofuels and biogas. All vans are electrified similar to the development of cars. The maritime transport and aviation are converted to electrofuels and ammonia. Half of the domestic aviation is converted to electricity.

Energy efficiency improvements are considered for trucks, aviation and maritime transport. In the period from 2017 to 2050 the energy efficiencies are anticipated to improve 35 pct., 5 pct. and 23 pct. for trucks, aviation and maritime transport respectively. Separate assessments of which specific measures that are implemented are not considered, but a combination of the potentials described above are expected to increase energy efficiency.

In Figure 23, the total CO_2 emissions in the *Reasonable* scenario for both passenger and freight transport from 2017 to 2050 are outlined. It is evident that the estimated reductions are more extensive beyond 2030, as many of the renewable transport technologies will not be available for full scale implementation before then. The production costs and efficiency will reduce the speed of the market uptake of novel technologies, hence fossil fuels will still provide the majority of the energy to the transport sector in 2030. The energy consumption is reduced from 224 PJ in 2017 to 198 PJ in 2030. In 2050 the energy consumption is reduced even further to 129 PJ. From Figure 23 it is evident that a reduction of annual

CO_2 emissions of 3.7 million tonnes from 2017 to 2030 is possible. In 2050 the transport sector in the *Reasonable* scenario is CO_2 neutral.

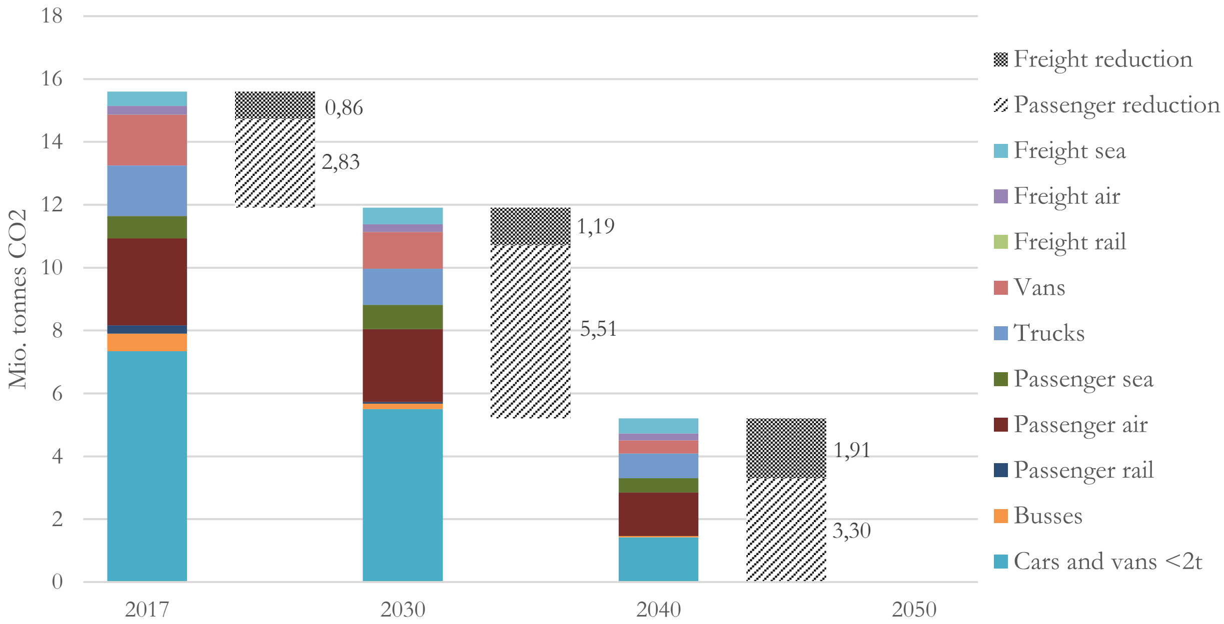

Figure 23. The transport system CO_2 emissions for both passenger and freight transport in the *Reasonable* scenario from 2017 to 2050. The hatched areas represent the reduction for both passenger and freight transport. Next to the hatched area is the actual CO_2 reduction in million tonnes.

The potential of reducing the total CO_2 emissions in 2030 is significant. A total reduction of 24 pct. in 2030 is achieved in the *Reasonable* scenario. There are significant potential CO_2 reductions in increasing the share of biofuels blended with liquid fuels for road transport and increasing the share of electric vehicles for passenger transport. Increasing the share of electric cars to 1 million in 2030 reduces the total CO_2 emissions 11 pct. Doubling the blend in of biofuels reduces the total CO_2 emissions 6 pct. Minor reductions are possible to achieve with the measures implemented for aviation and sea transport that collectively in the *Reasonable* scenario reduces CO_2 emissions with 2.5 pct. Electrifying trucks, vans and busses along with increasing the share of biogas collectively reduces the CO_2 emissions with approximately 5 pct. Energy efficiency improvements implemented for trucks, aviation and maritime transport reduces the total emissions by 3 pct.

7.1.2. Optimistic scenario

In the *Optimistic* scenario, significant CO_2 reductions are expected from 2017 to 2030. In the *Optimistic* scenario, the technology development of batteries and electrofuels is estimated to improve rapidly during the next decade. This is reflected in Figure 24 where significant CO_2 reductions are evident from 2017 to 2030. The production of electrofuels is predicted to reach large scale during the period and 10 pct. electrofuels is blended with all liquid fuels for road transport. A large share of the passenger transport is electrified, led by cars and vans <2t and busses. A total of 1.5 million electric vehicles are implemented in 2030 and 80 pct. of all busses are converted to electricity, biogas and electrofuels. For passenger transport by air and sea 18 pct. and 10 pct. are converted to electrofuels and ammonia.

For freight transport, a conversion to electricity is the first priority for trucks and vans. In 2030, 25 pct. of all trucks are converted to electricity and 32 pct. of all vans. 10 pct. of the transport demand for trucks is converted to biogas. Additionally, as for passenger transport, 10 pct. e-methanol is added to the blend of all liquid for road transport fuels. The development of freight transport by air and sea is projected to follow the same pattern as for passenger transport. For maritime freight transport electrification is not considered possible.

The share of biofuels blended in all liquid fuels is doubled from 2020 and onwards in the *Optimistic* scenario as in the *Reasonable* scenario.

From 2030 to 2050 the electrification of passenger transport limits the need for electrofuels and leaves the electrofuel consumption to aviation and sea transport. All passenger vehicles, busses and national aviation are electrified by 2050. The electrification of vehicles follows the same development as in the *Reasonable* scenario, while the complete electrification of busses will require implementation of ERS. To convert the national air transport to electricity substantial technological development within batteries are necessary. The electrification of short flight routes are considered possible after 2040, and when the technology is available the shift is estimated to happen quickly. International aviation and maritime transport are fuelled by electrofuels and ammonia.

In the *Optimistic* scenario, all trucks and vans are converted to electricity in 2050. To electrify long haul trucks and long-distance busses it is estimated that a retrofitting of the national highways to accommodate electric road systems is necessary. It is estimated that all 1300 kilometres of national highways need to be converted to ERS, to support a full transition of trucks towards electricity. ERS are implemented from 2040 to 2050, when the maximum amount of battery electric trucks are reached. It is estimated that the limit for implementation of battery electric trucks are approximately 65 pct., which is similar to the estimations presented in section 6.2.3. For maritime and air freight transport, the development towards 2050 is similar to the development for air and maritime passenger transport. The national aviation is converted to electricity, while all international is converted to electrofuels. For maritime transport, the majority is converted to ammonia, while the remaining is covered by electrofuels and a share of the national demand is converted to electricity.

Additional to the exhaustive technology implementations, energy efficiency improvements are also considered for trucks, aviation and sea transport. In the *Reference* scenario, the energy efficiency improved 32 pct., 11 pct. and 0 pct., for trucks, aviation and maritime transport respectively. In the *Optimistic* scenario, this is anticipated to increase to 37 pct., 29 pct. and 10 pct. due to enhanced logistics planning, improved fuel economy and more efficient engines. The energy efficiency of conventional cars and busses is not expected to increase further than what is expected in the *Reference* scenario.

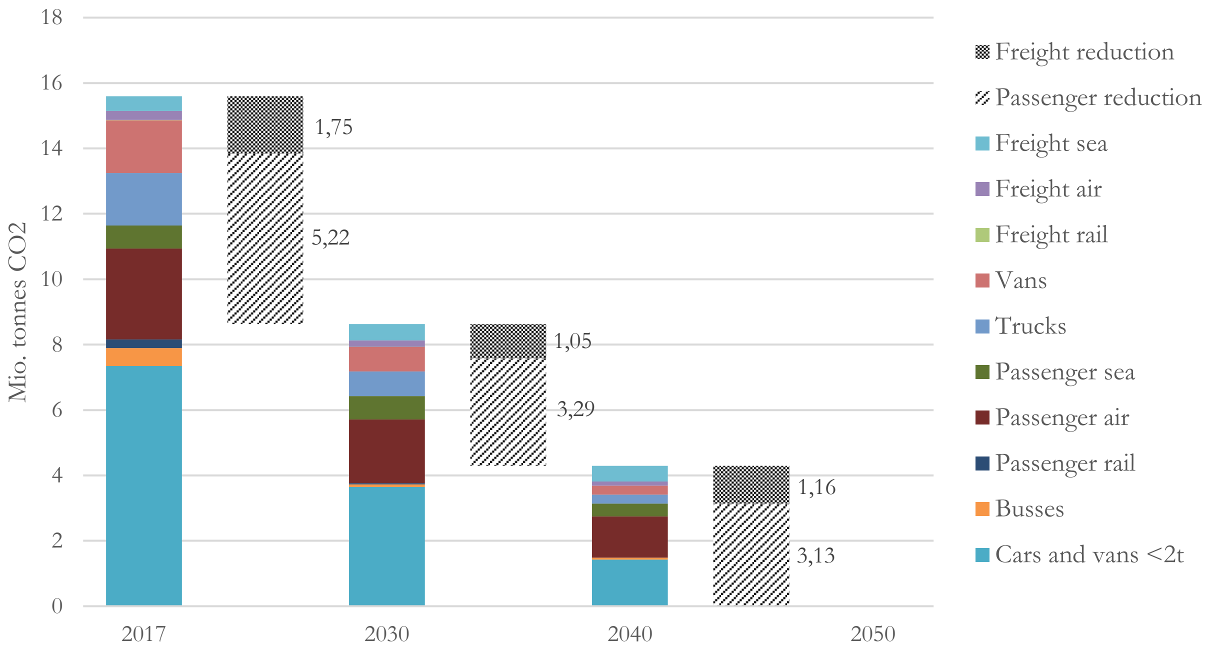

Figure 24. The transport system CO_2 emissions for both passenger and freight transport in the *Optimistic* scenario from 2017 to 2050. The hatched areas represent the reduction for both passenger and freight transport. Next to the hatched area is the actual CO_2 reduction in million tonnes.

The total potential for reduction in CO_2 emissions in the *Optimistic* scenario in 2030 is 45 pct. Increasing the share of electric vehicles and doubling the blend in of biofuels for road transport have, as in the *Reasonable* scenario, a significant impact on the CO_2 emissions from the transport system. Increasing the share of electric vehicles to 1.5 million in 2030 reduces the total CO_2 emissions by 18.5 pct. Doubling the share of biofuel blend reduces emissions 6 pct. A rapid development and implementation of electrofuels will have a significant impact on emissions as well, adding a share of 10 pct. electrofuels in all liquid fuels for road transport will reduce total CO_2 emissions in 2030 by 7.5 pct. The measures implemented for aviation and maritime transport reduces CO_2 emissions with 5 pct., while electrification and increasing the share of biogas for trucks, vans and busses collectively reduces emissions with 9 pct. The energy efficiency improvements suggested for maritime transport, trucks and aviation reduces emissions with 5 pct.

7.1.3. Summary

The *Reasonable* and *Optimistic* scenarios both reduces the energy consumption and CO_2 emissions considerably compared to the *Reference* scenario. The energy consumption in the *Reference* scenario is 233 PJ in 2030 and remains the same in 2050. The *Reasonable* scenario reduces the energy consumption to 198 PJ in 2030 and 129 PJ in 2050. The CO_2 emissions are reduced with 24 pct. in 2030 and 100 pct. in 2050 compared to 2017 emissions. The *Optimistic* scenario reduces the annual energy consumption to 172 PJ in 2030 and 116 PJ in 2050. The CO_2 emissions are reduced with 45 pct. in 2030 and 100 pct. in 2050 compared to 2017 emissions.

In Figure 25 the energy consumption of the three scenarios are compared in 2017, 2030 and 2050 divided by fuel type. The *Optimistic* scenario has a lower annual energy consumption than the *Reasonable* in 2050 due to a more comprehensive electrification.

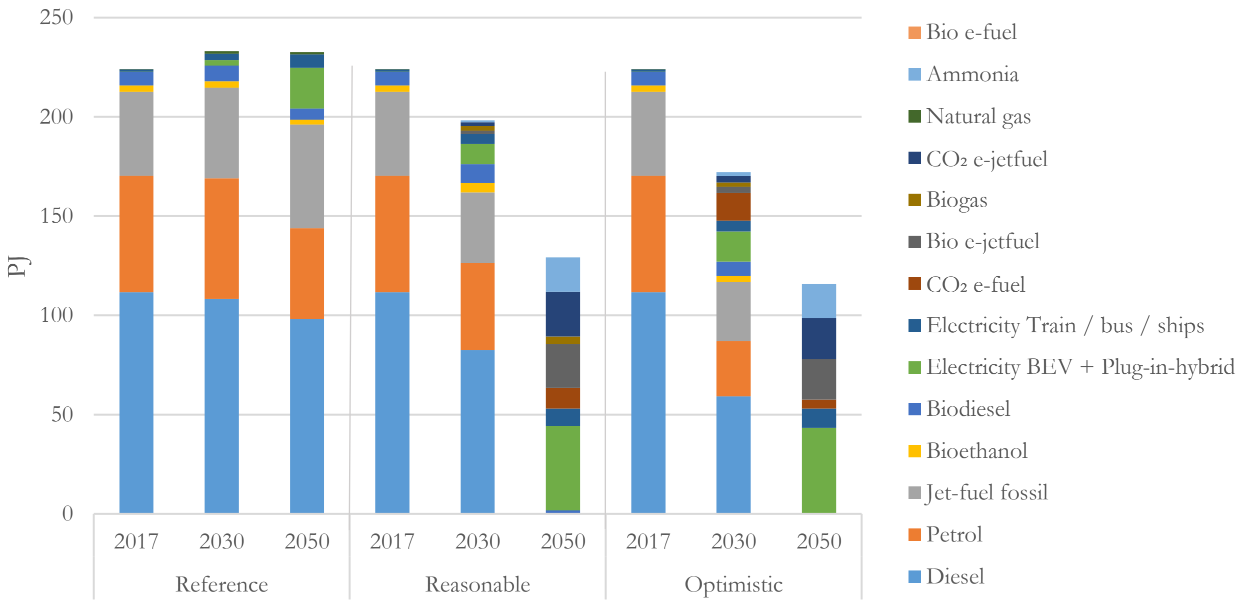

Figure 25. Energy consumption in the *Reference*, *Reasonable* and *Optimistic* scenario in 2017, 2030 and 2050.

To achieve substantial reductions of CO_2 emissions in 2030, it is essential that as much of the road transport possible is electrified. Especially electrification and cars and vans <2t have significant impact on the total CO_2 reductions. Increasing the blend in of biofuels towards 2030 have a noteworthy impact on reducing emissions, as well as an early implementation of electrofuels would have. Decent reductions in emissions are possible to achieve by focusing on energy efficiency improvements for aviation, maritime transport and trucks.

The annual transport system costs in the *Reference*, *Reasonable* and *Optimistic* scenarios are outlined in Figure 26. The annual transport system costs are comprised primarily by the costs associated with investment and O&M costs related to vehicles. As the fleet of vehicle grows at the same rate as the transport demand, the annual costs are increasing significantly from 2017 to 2030 and 2050. The number of cars in the scenarios increase from 2.5 million in 2017 to 3.3 million in 2030 and 4.8 million in 2050. The vehicle expenditures constitute approximately 75 pct. of the total annual costs in all scenarios. Costs associated with infrastructure expansions and electric vehicle charging stations comprise the remaining 25 pct. The annual costs of the *Reasonable* and *Optimistic* scenario are marginally higher than in the *Reference* scenario, as the costs of electric vehicles is expected to be slightly higher than conventional vehicles. The costs of implementation of ERS in the *Optimistic* scenario is included in the road infrastructure costs and only constitute a small share of the total transport system costs.

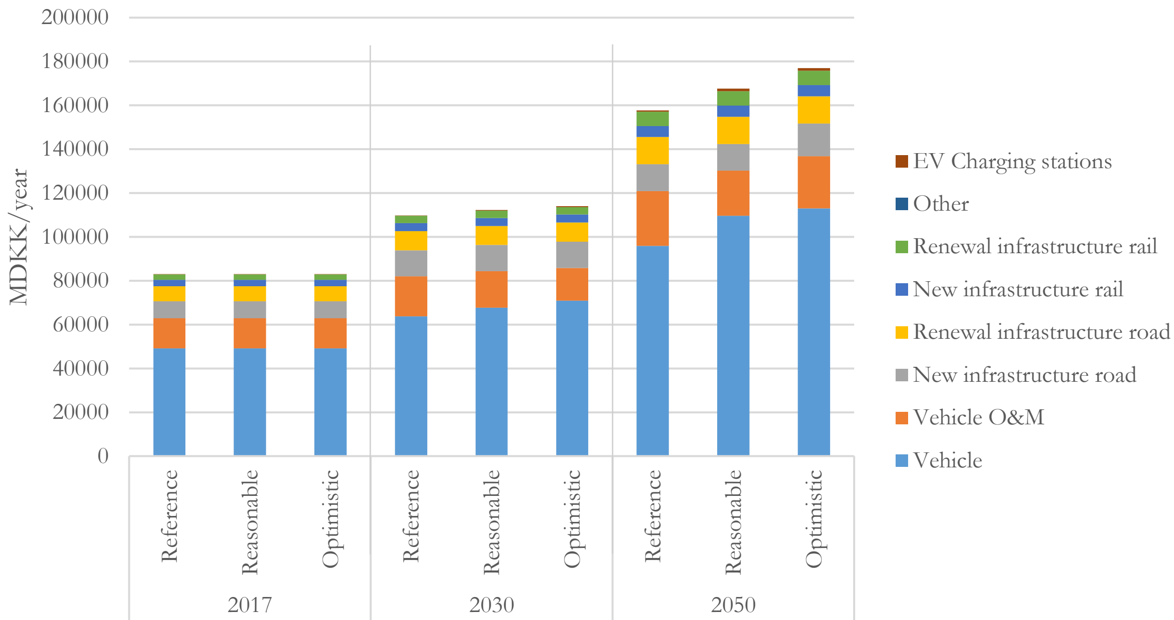

Figure 26. Annual transport system costs in 2017, 2030 and 2050 in the *Reference*, *Reasonable* and *Optimistic* scenario.

7.2. Transport demand scenarios

The transport demand scenarios depicts different developments of the transport system, where the transport demand (pkm and tkm) grows identical to the *Reference* scenario but the traffic work (km) develops differently. This is accomplished by avoiding an increase in the transport demand for modes of transport with low capacity utilisation, promoting modal shifts and implementing measures to increase capacity utilisation factors.

As the growth in transport demand remains the same as in the *Reference* scenario, the transport system model TransportPLAN, provides two ways to limit the traffic work:

- Modal shifts
- Capacity utilisation improvements

Achieving modal shifts from high energy intensive modes of transport with low capacity utilisation, such as cars, to low energy intensive modes, such as trains, bicycling and walking, suitable infrastructure and financial incentives must be in place, as outlined in section 6.1. Improving capacity utilisation of primarily cars and vans <2t and trucks will require financial incentives predominantly. The transport system costs associated with modal shifts entails infrastructure expansions for bicycling, walking and railways. The costs of improving capacity utilisation are outside of the scope of this work and the energy savings therefore appear to be cost-free in the analysis. To demonstrate the economic concerns regarded to limit the growth in traffic work, the majority of the measures implemented will be modal shifts. Some capacity utilisation improvements are included, but they will only limit the growth in traffic work slightly.

In the following, the suggested modal shifts and capacity utilisation improvements implemented in TransportPLAN are defined and the results regarding energy consumption and transport system costs are evaluated. The scenarios are not meant to be "ready-to-apply" solutions, but are used to describe how limiting the growth in traffic work could simplify the renewable transition of the transport sector and limit the total costs. Hence, the modal shifts will not be described in detail, but are used to represent a potential scenario to limit the growth in traffic work.

Two alternative transport demand developments are analysed and compared to the *Reference* scenario referred to as the *High* growth scenario. A M*edium* growth and a *Low* growth scenario. In the M*edium* growth scenario measures are implemented to limit the increase in the traffic work to half of the increase observed in the *Reference* scenario. In the *Low* growth scenario measures are implemented to stop the growth in traffic work completely.

In the *Reference* scenario the traffic work for passenger transport increased 27 pct. from 2017 to 2030 and 45 pct. between 2030 and 2050. For freight transport the traffic work increased 14 pct. from 2017 to 2030 and 21 pct. between 2030 and 2050.

7.2.1. Scenario implementations

The modal shifts implemented in the M*edium* growth scenario for both passenger and freight transport are presented in Table 5 and Table 6.

Passenger transport	**Average annual modal shift**
All car trips to biking/walking	0.5 pct.
Car trips >50km to train or bus	0.7 pct.
Bus trips to biking/walking	0.4 pct.
Air travel to train	0.3 pct.

Table 5. M*edium* growth scenarios passenger transport

Freight transport	**Average annual modal shift**
All trucks to train	0.8 pct.

Table 6. M*edium* growth scenarios freight transport.

In the M*edium* growth scenario, the capacity utilisation of passenger cars and vans is not improved. As explained in section 5, the average capacity utilisation of vehicles has been decreasing over the last decade, and it seems difficult to improve. For both national and international trucks the capacity utilisation is improved 12 pct. from 2017 to 2030 and remains constant from 2030 to 2050. This increases the average amount of tonnes per vehicle for national trucks, regardless of trip length, from 9 tonnes/vehicle in 2017 to 10.2 tonnes/vehicle in 2030. For international trucks the average amount of tonnes per vehicle increases from 16.3 tonnes/vehicle in 2017 to 18.3 tonnes/vehicle in 2030. The capacity utilisation is improved from 45 pct. for national trucks and 54 pct. for international trucks to 51 pct. and 61 pct. respectively. This improvement seems more achievable, as it is an area of focus and interests of both the freight transport industry and transport researchers. [100]

In the *Low* growth scenario more significant modal shifts from road transport and aviation towards rail, walking and bicycling are necessary to stabilise the traffic work while the transport demand grows. The implemented modal shifts for both passenger and freight transport are outlined in Table 7 and Table 8.

Passenger transport	**Average annual modal shift**
All car trips to biking/walking	0.8 pct.
Car trips >50km to train or bus	0.9 pct.
Bus trips to biking/walking	0.6 pct.
Air travel to train	0.5 pct.

Table 7. *Low* growth scenarios passenger transport.

Freight transport	Average annual modal shift
All trucks to train	1.0 pct.

Table 8. *Low* growth scenarios freight transport.

In the *Low* growth scenario, the capacity utilisation of passenger cars and vans is improved 6 pct. from 2017 to 2030 and 10 pct. from 2030 to 2050. That increases the average number of passengers in vehicles, regardless of trip length and purpose, from 1.49 passenger/vehicle in 2017 to 1.59 passenger/vehicle in 2030 and 1.76 passenger/vehicle in 2050. The capacity utilisation of both national and international trucks is improved 49 pct. from 2017 to 2030 and remains constant from 2030 to 2050. That increases the average amount of tonnes per vehicle for national trucks, regardless of trip length, from 9 tonnes/vehicle in 2017 to 16.8 tonnes/vehicle in 2030. For international trucks the average amount of tonnes per vehicle increases from 16.3 tonnes/vehicle in 2017 to 26 tonnes/vehicle in 2030. The capacity utilisation of national trucks is improved from 45 pct. to 84 pct. and from 54 pct. to 87 pct. for international trucks.

7.2.2. Transport energy consumption

In 2030, there are noteworthy energy savings from reducing the growth in traffic work. By promoting modal shifts and improving capacity utilisation it is possible to reduce the annual energy consumption, presented in Figure 27. The energy consumption in the *Reference*, *Reasonable* and *Optimistic* scenarios in 2030 are reduced with 5 pct. to 7 pct. in the *Medium* growth scenario and 12 pct. to 14 pct. in the *Low* growth scenario. The reduction is slightly larger in the *Reference* scenario as the benefits of moving transport demand from cars to trains, walking and bicycling are greater in a scenario with a larger share of conventional cars and vans. The efficiency of electric vehicles is significantly higher than for conventional vehicles, hence the energy savings from moving transport demand from cars to trains are greater if a larger share of the vehicle fleet is not electrified. This tendency is more distinct in 2050, where all cars are electric.

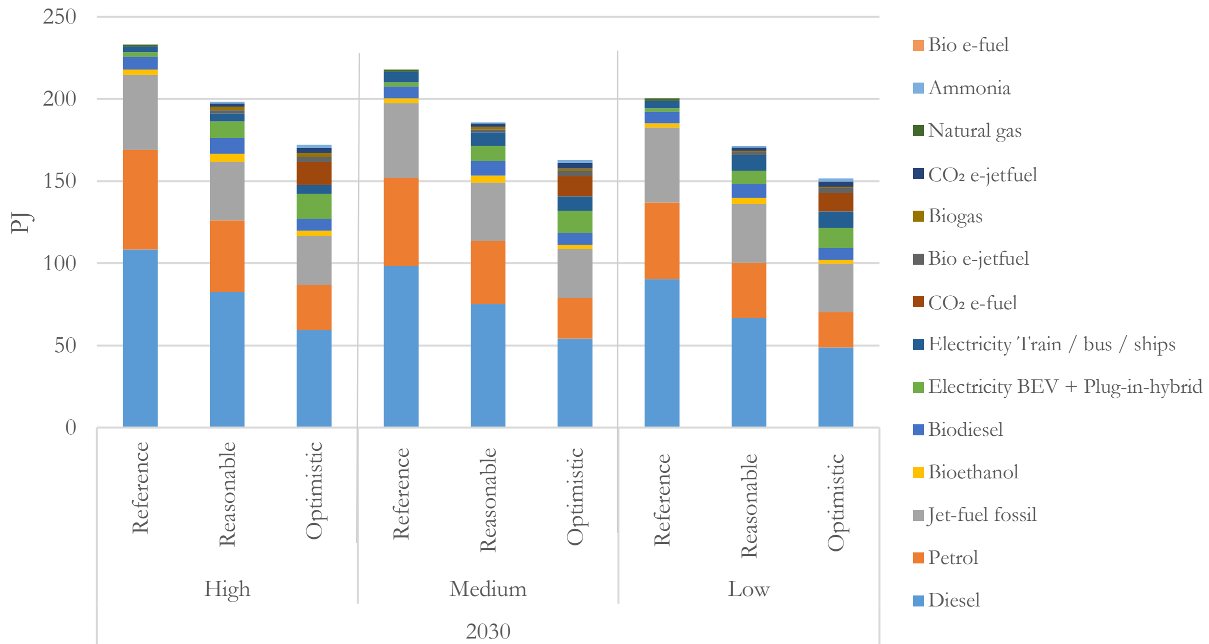

Figure 27. Annual energy consumption in 2030 in the *Reference*, *Reasonable* and *Optimistic* scenario with a *High*, *Medium* and *Low* increase in traffic work.

In 2050, displayed in Figure 28, the energy consumption is affected only minimally from reducing the growth in traffic work in the *Reasonable* and *Optimistic* scenario. The energy consumption in the *Reference* scenario is reduced between 12 pct. and 24 pct. in the M*edium* and *Low* growth scenarios, while it is only reduced between 0 pct. and 4 pct. in the *Reasonable* and *Optimistic* scenarios.

As the entire fleet of cars and the majority of the trucks are electric in the technology scenarios in 2050, the energy consumption per passenger and ton kilometre is close to similar and the potential energy savings in modal shifts are therefore insignificant.

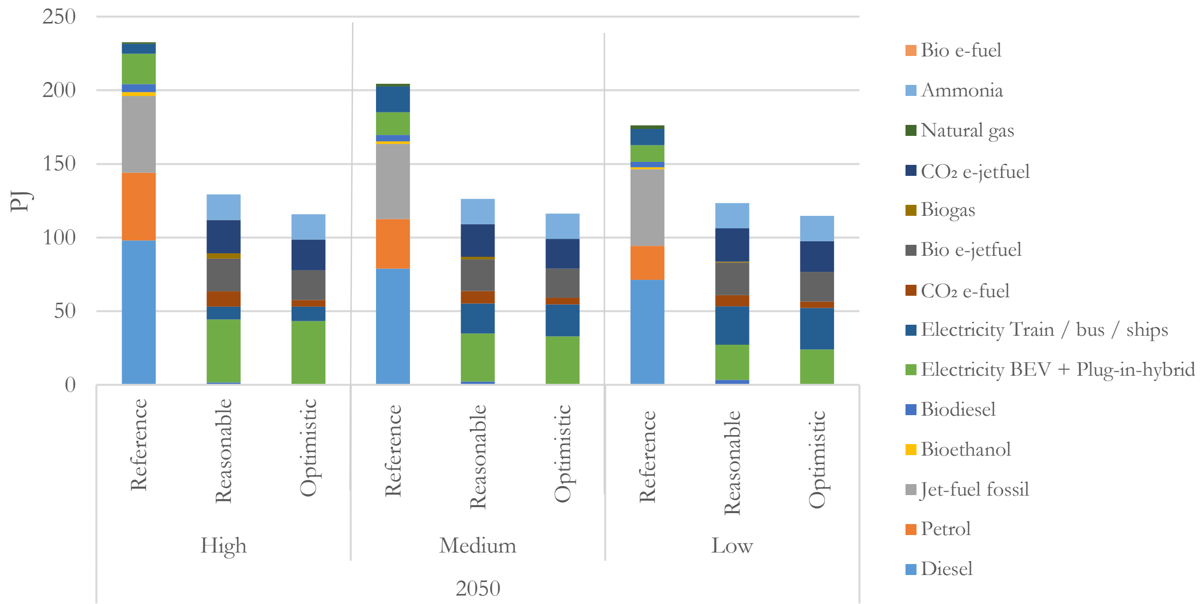

Figure 28. Annual energy consumption in 2050 in the *Reference*, *Reasonable* and *Optimistic* scenario with a *High*, M*edium* and *Low* increase in traffic work.

7.2.3. Transport system costs

While reducing the growth in traffic work only have a minor impact on the transport system energy consumption and thus CO_2 emissions, reducing the growth will have significant impact on the costs of the renewable transition. As analysed in the technology scenarios in section 7.1, the vehicle investment and O&M costs comprise the majority of the transport system costs. If the growth in traffic work is reduced predominantly by moving transport demand from road vehicles to rail, walking and bicycling, the number of vehicles needed decreases drastically. In Figure 29 and Figure 30 the transport system costs in 2030 and 2050 are outlined.

In 2030, a reduction in the growth of the traffic work from 26 pct. to 13 pct. reduces the annual transport system costs by 6 pct. in all scenarios. If the traffic work can be contained stable at the level as of 2017 the transport system costs can be reduced by 20 pct. in 2030. From Figure 29 it is evident that the costs associated with investment and O&M for vehicles drops significantly, while the investment in rail infrastructure increases. The costs included in "Other" are expansions of bus infrastructure and infrastructure for bicycling and walking. Whereas the costs for rail, bicycling and walking infrastructure increases, the costs for expanding and renewal of roads decreases. The cost of expanding the road infrastructure are many times higher than expanding railway, walking and bicycling infrastructure, hence the savings heavily outweighs the added costs.

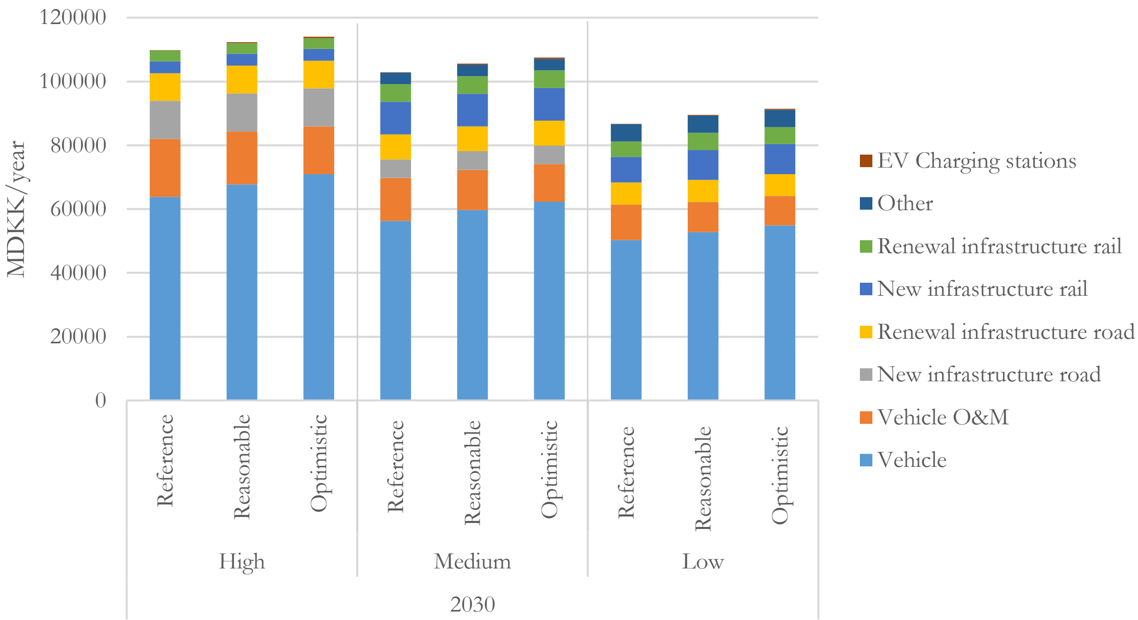

Figure 29. The transport system costs in 2030 in the *Reference*, *Reasonable* and *Optimistic* scenario, with a *High*, *Medium* and *Low* growth in the traffic work.

In 2050, the possible savings are even greater as the amount of vehicles is reduced significantly in the *Medium* and *Low* growth scenarios compared to the *High* growth scenario. The savings in annual transport system costs in 2050 are 20 pct. and 40 pct. in the *Medium* and *Low* growth scenario respectively compared to the *High* growth scenario. As for the costs in 2030, reducing the traffic work for road vehicles creates significant savings, while the added infrastructure costs in railway, bicycling and walking infrastructure are outweighed by the reduced costs of road infrastructure.

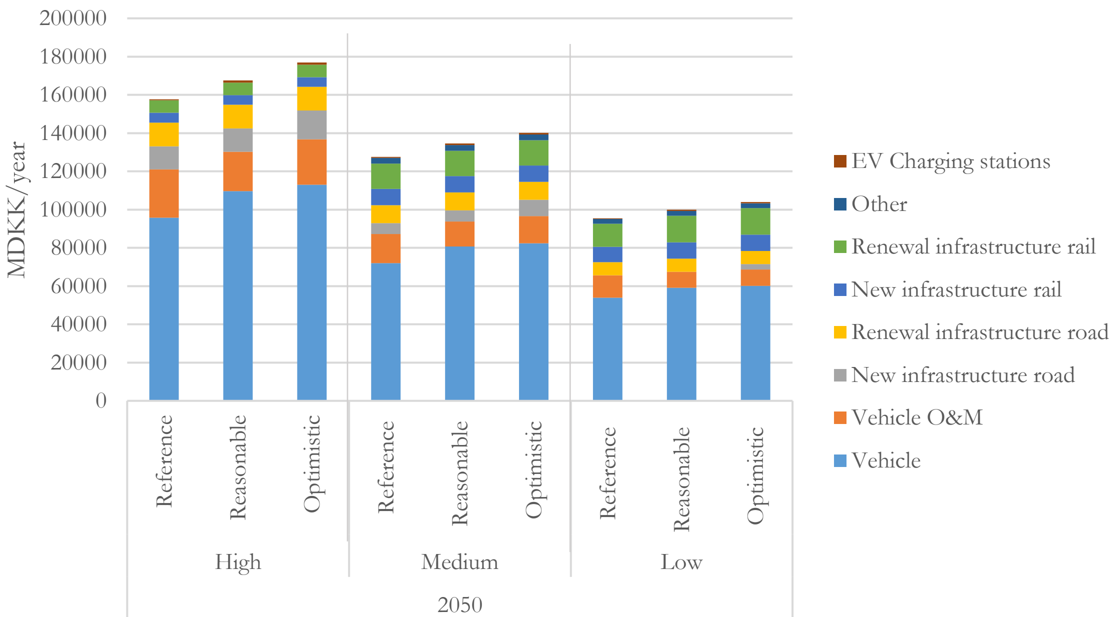

Figure 30. The transport system costs in 2050 in the *Reference*, *Reasonable* and *Optimistic* scenario, with a *High*, *Medium* and *Low* growth in the traffic work.

Reducing the traffic work will reduce the energy consumption in 2030 and support the reduction of the CO_2 emissions from the transport sector. In long-term, towards 2050, the measures implemented to reduce the traffic work, do not have a significant impact on the transport system energy consumption. Instead the associated costs of the renewable transition benefits greatly from the reduction of the growth in traffic work and the costs of decarbonising the transport sector can be reduced with up to 20 pct. in 2030 and 40 pct. in 2050.

8. Transport planning in a renewable energy system

The methodological decision to analyse the transport sector without analysing the entire energy system is considered in the following. Many of the renewable transport technologies and fuel proposed in the scenarios above depend on a renewable expansion of the entire Danish energy system. A renewable transition of the transport sector poses requirement to the energy system in regards of delivering the electricity and biofuels necessary. In this section, the electricity production necessary for a substantial electrification of the transport sector and production of electrofuels is analysed. Electrofuels refer in the following to all fuels produced from electrolysis, hence both electrofuels to road transport, e-jet fuels and ammonia for maritime transport. Methanol will refer to electrofuels for road and maritime transport.

The transport system today is predominantly decoupled from the rest of the energy system. There are hardly any conversion technologies between fuel and demand, as for heating and electricity. In a renewable transport system, the transport sector will be interconnected with the surrounding energy system. One of the reasons, why decarbonizing the transport is a wicked problem, is that creating a solution will affect not only the transport sector but the entire energy system.

The extensive electrification of the transport sector, suggested in this work, requires a substantial expansion of the renewable power production capacity. The production of electrofuels for road, maritime and air transport will require considerable amounts of electricity along with a large source of carbon. In the following, the additional electricity production needed to provide for the *Reasonable* and *Optimistic* scenario is illustrated. Additionally, the carbon resource required for electrofuel production in 2030 and 2050 is estimated.

The Danish Energy Agency expects, in DECO, an electricity production in 2030 of 53.6 TWh. This is primarily produced from onshore and offshore wind and solar photovoltaics (PV). The offshore wind capacity is expected to increase from 1.3 GW to 4.9 GW, while the onshore capacity increases from 4.2 GW to 5.3 GW. The solar PV capacity increases from 0.9 GW to 4.9 GW. The electricity production from renewables exceed the domestic energy consumption of 47.5 TWh in 2030 and an electricity export of 6.2 TWh is anticipated. The electricity demand from the transport sector, which is exemplified in the *Reference* scenario in this report, is included in the total domestic electricity consumption of 47.5 TWh in 2030. [43]

The electricity and electrofuel demand in 2030 is outlined for all three scenarios in Table 9. To calculate the electricity needed for electrofuel production an average efficiency of 60 pct. is estimated for methanol production, 60 pct. for ammonia production and 50 pct. for the production of e-jet fuels. The efficiency will depend heavily on the efficiency of the electrolysis. The total energy efficiency will be higher if the SOEC technology is available and lower if alkaline electrolysis is utilized. [114]

		2030	
[PJ]	*Reference*	*Reasonable*	*Optimistic*
Electric vehicles and trains	6.1	15.1	20.6
Methanol	0.0	0.0	13.9
Ammonia	0.0	0.9	1.9
E-jet fuels	0.0	3.7	6.4

Table 9. Electricity and electrofuel demand in the *Reference*, *Reasonable* and *Optimistic* scenario in 2030.

Given the conversion efficiencies of power to methanol, ammonia and e-jet fuel, it is possible to estimate the additional electricity demand in the *Reasonable* and *Optimistic* scenario compared to the *Reference* scenario.

In the *Reasonable* scenario in 2030 15.1 PJ of electricity is consumed by electric vehicles and trains. 1.6 PJ of electricity is consumed to produce ammonia and 7.5 PJ of electricity is used to produce e-jet fuel. In total, an additional electricity demand of 18 PJ (5 TWh) compared to *Reference* scenario.

In the *Optimistic* scenario in 2030 20.6 PJ of electricity is consumed by electric vehicles and trains. The production of methanol require 23.1 PJ, while 3.1 PJ of electricity is consumed to produce ammonia and 12.8 PJ of electricity is used to produce e-jet fuel. In total, an additional electricity demand of 53.5 PJ (14.7 TWh) compared to *Reference* scenario.

The additional electricity demand in the *Reasonable* scenario may be accommodated by the anticipated excess production of 6.2 TWh, assumed in DECO. In the *Optimistic* scenario, an annual electricity demand of 8.5 TWh cannot be met with domestic electricity production. Either a considerable electricity import is necessary or an expansion of the renewable production capacity. If the renewable capacity is expanded as offshore wind farms, approximately 2 GW of additional capacity is required by 2030 to meet the demand of the *Optimistic* scenario. [115]

In 2050, the electricity demand in the *Reference* scenario is 27 PJ, while there is no consumption of electrofuels. In the *Reasonable* and *Optimistic* scenario, the electricity and electrofuel consumption have increased significantly (Table 10).

		2050	
[PJ]	*Reference*	*Reasonable*	*Optimistic*
Electric vehicles and trains	27.0	51.0	53.0
Methanol	0.0	10.4	4.5
Ammonia	0.0	17.3	17.2
E-jet fuels	0.0	44.8	41.0

Table 10. Electricity and electrofuel demand in the *Reference*, *Reasonable* and *Optimistic* scenario in 2050.

The additional electricity demand in the *Reasonable* and *Optimistic* scenario compared to the *Reference* scenario is calculated in the same way in 2050 as in 2030. Conversion efficiencies remains the same.

In 2050, the *Reasonable* scenario will have an additional energy demand compared to the *Reference* scenario of 159 PJ (44 TWh). The *Optimistic* scenario will have an additional energy demand compared to the *Reference* scenario of 144 PJ (40 TWh). This is equivalent to a required renewal production capacity expansion of 10.3 GW and 9.4 GW in the *Reasonable* and *Optimistic* scenario, respectively.

In the first draft of a national climate plan the Danish government have proposed the construction of two energy islands with an offshore wind capacity of 4 GW installed before 2030 and possibility of increasing capacity of an additional 8 GW. [116]

The production of electrofuels requires both electricity for the production of hydrogen and a source of CO_2 in the synthesis process. The ratio of hydrogen and CO_2 differ according to the source of CO_2. In this work, no distinction has been made between sources of CO_2, and conversion efficiencies might not be completely accurate. For the production of methanol approximately 1.4 tons of CO_2 is necessary to produce 1 ton of methanol. Methanol has an energy content of 22.9 MJ/kg. For the production of e-jet fuel approximately 3.9 tons of CO_2 is necessary for producing 1 ton of e-jet fuel. E-jet fuel has an energy content of 42.8 MJ/kg. With these ratios, approximately 0.34 million tons of CO_2 is needed for electrofuel production in 2030 and 4.7 million tons in 2050 in the *Reasonable* scenario. In the *Optimistic* scenario circa 1.4 million tons of CO_2 is needed for electrofuel production in 2030, and 4 million tons in 2050. [114], [117], [118]

The Danish Council on Climate Change estimates 4.5 million tons of CO_2 will be available for capture and used for electrofuel production from biogas plants, biomass powered CHP plants, waste incineration plants and at industrial sites in 2030. [8]

9. Qualitative assessment of the reduction of traffic work

In this section, the achievability of the reduction of transport demand is discussed. Reducing the transport demand is a key parameter to reducing the costs associated with a renewable transition. The discussion will feature a qualitative assessment of the potential benefits a reduction in traffic work can have.

As stated in the ASI paradigm, avoiding an increase in transport demand and promoting shifts to low-carbon transport modes, should be first and second priority, when dealing with the wicked problem of decarbonising the transport sector. Road transport is responsible for the majority of the traffic work and energy consumption in the Danish transport sector. Hence, avoiding road transport and shifting from individual cars and vans to active modes of transport and public transport and from trucks to rail are key parameters to analyse.

Following the arguments presented in section 3, the development of the Danish transport system has created a path dependency on motorised road transport and a mobility system that is highly dependent on the ownership of a car. In the following, the measures introduced in section 6.1 to avoid and shift transport demand are elaborated further, and it is discussed whether it is realistic to witness a reduction in traffic work, while maintaining and covering a growing transport demand.

From the results of the scenarios, it is evident that reducing the growth in traffic work will not have a significant influence on the energy consumption, but will have substantial impact on the transport system costs. The energy consumption is affected more in 2030 than in 2050, as the electric vehicles are more efficient and the benefits from moving from cars to trains are not as apparent. Reducing the growth in traffic work was done in TransportPLAN by increasing vehicle capacity utilisation and enforcing modal shifts, primarily from road transport to rail, bicycling and walking. In section 6.1 it was argued that improving alternatives to cars and creating disincentives for car-usage were central parameters to limit the traffic work of cars. As reasoned, investments in adequate infrastructure for public transport and active modes of transport have substantial effect on the development of modal shifts. Increasing comfort and accessibility will increase the likelihood of modal shifts without limiting mobility. Promoting modal shifts will also be more effective if the transport in cars is made less convenient and perhaps more expensive.

The number of cars in the 2017 *Reference* model is 2.55 million. The number of privately owned cars in Denmark has grown 22 pct. from 2007 to 2017 exactly as the growth in traffic work. It shows that Danes drive more every year and purchase more vehicles. In TransportPLAN, this correlation between growth in traffic work and growth in the number of vehicles is assumed to continue. Hence the number of cars in 2030 in the *High* growth scenario increases to 3.3 million, which rises to 4.86 million cars in 2050. In the M*edium* growth scenario the number of cars is 2.9 million in 2030 and 3.5 million in 2050. In the *Low* growth scenario the number of cars remains stable and even decreases slightly as the average number of passengers per vehicle increases.

The number of cars significantly affect the annual transport system costs, but also affect a number of externalities. Negative impacts of cars in urban or populated areas are among others [26]:

- Air and noise pollution
- Infrastructure and time costs
- Land utilisation
- Use of resources
- Road accidents

Air pollution and road accidents represent significant annual financial expenses. In Denmark air pollution is responsible for an average of 4000 premature deaths annually which corresponds to a socio-economic expense of 75 BDKK. If a clear correlation is found between the number of cars and air pollution and road accidents, extensive annual costs may be overlooked in the analysis of transport system costs. Likewise, substantial annual savings, from reducing the growth in traffic work might not be considered either. [119], [120]

Infrastructure costs for road expansions and renewal are significant as highlighted in the transport demand scenarios, but time spent in traffic and congestion is also a relevant measure to consider when planning for transport infrastructure, as time is valuable and reduced travel times can increase productivity. Travel time can possibly be utilised more efficiently in public transport, as the passengers do not have responsibility of driving and instead can use the travel time for work.

Travelling in cars is an inefficient use of land as cars take up many times more space than public transport, walking or bicycling to deliver the same transport demand. Hence, increasing the numbers of vehicles will require more space to build roads and consequently less space for everything else. Researchers have previously debated about a 'peak-car' situation, referring to the situation where the amount of privately owned cars has reached a saturation point and the increase in cars would stabilise. This has proven not to be the case. The 'predict and provide' approach to transport planning has assisted in the creation of concrete jungles and helped push the path dependency. [121]

Reducing the traffic work in cars will most likely prove to be a difficult task. As argued in section 3, the approach to mobility and transport planning have over an extensive period of time created a lock-in situation, where mobility is equal to accessibility for cars and other motorised vehicles and the car has become an integrated part and a necessity of most people's life. This path dependency makes it inherently difficult to continue the positive development of the economy and reduce the traffic work from road transport.

Investments in public transport and walking and bicycling infrastructure will not ensure a reduction in traffic and promote modal shifts alone. Many cities have well-functioning, well-priced transit systems, but almost all still experiences traffic congestions on the roads. The ministry of Transport and Housing [89] and Mathiesen et al. [50] suggest that road pricing can be an effective measure to limit the amount of kilometres driving in cars and possibly promote modal shifts or increase the appeal of car sharing and ride sharing arrangements. Road pricing based on vehicle type, location and time could also reduce congestion in dense populated areas and thus save time spent in traffic. Globally, car sharing, ride sharing and shared mobility services are gaining a foothold in the market and companies such as Über and Lyft are experiencing noticeable growth in recent years. Statistics show that the average car is parked 95 pct. of the time, hence there seem to be a considerable potential for car sharing systems. Car sharing would have to brake with the imbedded culture surrounding the ownership of cars. The ownership of a car is connected to human perception of norms and status, and breaking with this dogma requires exhaustive interventions to the concept of mobility. [122]–[126]

The psychology of car travel and owning cars provides more than just the convenience of being able to transport from A to B. Gössling [121] describes the car to have an inherently symbolic value in communicating social status. The development of automobile cities have made the perception of a car even stronger, and the choice of travelling in a car instead of public transport is more complex, than deciding between the costs of travel. Transportation and mobility is, to a certain degree, determined by behaviour and the perception of freedom. Hence, road pricing is often mentioned as a measure to limit road transport, but it is rarely practiced. The problem of road pricing seems to be the perception, that what is perceived as public property, such as roads, now becomes private and it is charged to use road space. The interference from government in the publics perceived mobility, have ensured that very few politicians wants to promote the idea of road pricing schemes. As the political agenda in the last decades have been to build new roads to accommodate growing transport demand, many people and commuters are dependent on their car for daily travel and to reach essential services. Hence, a road pricing scheme would not move transport demand from cars to public transport, but instead only increase the costs related to travel, for the individuals with no other option than driving in a car. Road pricing may affect sections of the population differently, and could end up being an economic strain to citizens outside of urban areas, where public transport and other alternatives to travel in cars are scarce. [121], [127], [128]

The taxation of private vehicles is oriented primarily at the ownership. Several researchers and organisations suggest that this is changed to focus on driving, as this is what causes emissions and environmental effects. No one has yet to come up white a taxation scheme that ensures the same tax payments to the national treasury and does not limit the availability of affordable mobility for all citizens. [127], [129]

Neither road pricing schemes or investment in infrastructure alternatives can alone relieve the outspoken dependency on cars, suggesting that there is no quick fix to change transport habits and reduce traffic work. A complete, holistic solution is necessary to improve the transport sector.

Transport behaviour is to a noteworthy degree based on habits. In a situation, where alternatives to the car is available, it is possible to successfully implemented road pricing schemes. Congestion and road charging schemes have proven effectively in shifting transport from cars to public transport and has reduced car numbers. If the alternative to cars is available, the biggest issue is to change the travel habits of travellers and convince them that the car is not a necessity. Public acceptability is observed to change regarded to road pricing schemes. The public perception changes and the acceptability increases with familiarity. In Stockholm, the perception towards congestion charges were negative to begin with, but changed over time as commuters' habits changed. The implementation of new transport cultures will undeniably cause resistance and pervasive driver-vehicle bonds will have to be dissolved. [49], [121]

Campaigns targeted at behavioural change have proven to have a positive effect on traffic work reduction. National or local campaigns have proven effective in shifting commuters towards bicycling. [130], [131]

Growing attention is being brought to shared mobility (SM) concepts and Mobility as a Service (MaaS). Both SM and MaaS are concepts that are still evolving, but several researchers suggest that such schemes could gain acceptance and broader recognition, if the transport in vehicles would become more expensive due to road charges for instance. It is argued that shared mobility could, if implemented smart, provide the missing link and overcome the dependency of private vehicles and increase the usage of public transport. [122], [123]

Shared mobility is a broad term covering both car sharing, ride sharing and public transport systems. As outlined, ride sharing and car sharing can both significantly assist to reduce the traffic work and thus the need for cars. In shared mobility systems, multimodal transport is encouraged and the car will provide the linkage between housing and employment areas, and public transport in areas where this is not within walking or cycling distance. Systematic road charging schemes will ensure that cars are only used for certain parts of the journey, and well-functioning public transport systems will offer a comfortable and affordable alternative to purchasing a private vehicle. Shared mobility will enable more passengers to be connected to public transport systems, hence enhancing the convenience of low-carbon modes of transport and limiting the need of personal vehicles.

Shared mobility services, such as Über, have seen strong social and political opposition. Shared mobility services disrupt existing mobility services and transport businesses and operates on the border of the transport regulation. The idea of revolutionising the transport sector, will indisputably meet opposition from the established transport sector. A comprehensive implementation of shared mobility services would have to face the same challenges as road pricing schemes, as shared mobility would entail that private vehicles were to be replaced. The car, as reasoned above, is a symbol of status and to break with this interpretation, will require extensive measures. Shared mobility systems must provide a costs-competitive alternative to owning a private vehicle, in order to promote a shift, but campaigns and additional financial incentives may be necessary to experience a true disruption of the transport system.

An extensive implementation of shared mobility systems are anticipated to be tightly connected with the development of autonomous vehicles. Autonomous vehicles could possibly revolutionise the transport sector, and if implemented intelligently reduce the amount of vehicles and traffic work. In the following, the impact of autonomous vehicles and the relevance for implementation of shared mobility solutions are considered.

9.1.1. Development of autonomous vehicles

Autonomous or self-driving vehicles is a rapidly developing technology within road transport. Automation is already wide-spread in other parts of the transport sector, for instance in aviation, where large part of the travel is accomplished with auto-pilot. A pilot still has to be present, but the level of automation is notably higher than for other modes of transport, such as road transport.

Automation of vehicles is defined by The Society of Automotive Engineers (SAE) in five levels; level 1 offers simple driving assistance, while level 5 is full automation with no human driver needed. Level 1 to 3, which assist the driver with lane keeping assistance, brake and acceleration support and blind spot warnings, are widespread in many vehicles, but private consumers have yet to be presented with fully autonomous vehicles of level 4 and 5. The introduction of level 4 and 5 vehicles depends on both technological development and regulative recognition. The development of fully autonomous vehicles is retained by regulation, such as the Vienna Convention on Road Traffic, that requires every moving vehicle to have a driver that is in control at all times. Other regulative and ethical barriers are as well withholding the market uptake of self-driving autonomous vehicles. If technical and regulative barriers are possible to overcome, some research suggest that autonomous vehicles may already have an impact on the transport system within the next decade. In a Danish context the Danish Road Directorate expects autonomous vehicles to comprise 30 pct. of the Danish fleet of vehicles in 2045. [124], [132]–[135]

The influence of autonomous vehicles is heavily debated, and there is inconsistency when evaluating whether self-driving vehicles will lead to an increase in traffic work or a decrease. Some researchers suggest that autonomous vehicles will have a negative effect on the transport demand, as autonomous vehicles will increase the comfort of driving, and possibly connect people with cars that otherwise would not have chosen the car as their preferred mode of transport. The costs of travel could be drastically reduced by autonomous vehicles and consecutively increase the traffic work. As a driver is no longer necessary young people, kids and adults without a driving license would have the opportunity to drive alone in a car. The number of vehicles can be drastically reduced but the traffic work might be increased. Others, estimate that the introduction of autonomous vehicles could decrease traffic work from vehicles by up to 30 pct. [51], [89], [133], [136]–[141]

In a shared mobility environment, autonomous vehicles could prove to be the missing link that connects the automobile city with the public transport system. In automotive cities public transportation systems are facing the problem of providing the users with the first/last mile. Shared autonomous vehicles could provide this and connect more users with public transportation. Autonomous vehicles could improve the average utilisation of cars and overcome the issue of vehicles being parked 95 pct. of the time. [51]

Transport researchers from University of California suggest, that a renewable transition of the transport sector will require revolutions to the way we look at transportation today. They suggest that only if urban transportation become shared and automated along with an extensive electrification the decarbonisation of the transport sector can be satisfied. Shared Autonomous Electric Vehicles (SAEVs) will according to this research reduce the need for privately owned vehicles and induce a drastically reduced amount of vehicles. This will assist in an easier transition of the transport sector towards renewables, as the fleet of vehicles will be reduced. Additionally electric vehicles will be preferable, as a large fleet of electric vehicles that are operated by the same authority can provide significant ancillary services to the electricity grid, which will improve the general business case for the transport service provider. [74], [142], [143]

The development and statements from the automotive industry suggest that autonomous vehicles will be part of the transport sector in the future. Whether the introduction will transform the transport sector and provide the missing link for shared mobility services or it will induce the traffic work even more, is still unclear.

10. Conclusion

The aim of this thesis is to analyse the possible contribution from the transport sector to achieve the national target of reducing the total Danish CO_2 emissions with 70 pct. in 2030 compared to 1990. The contributions are estimated to come primarily from substituting conventional transport technologies and fossil fuels with renewable technologies and alternative fuels. Additionally, the effects of reducing the growth in traffic work is considered.

The energy consumption and CO_2 emissions from the Danish transport sector has steadily increased from 1990 to today. While almost all other sectors have achieved reductions in emissions the opposite is true for the transport sector. While there has been energy efficiency improvements and EU standards have assisted in reducing emissions factors of vehicles, the growing transport demand have outweighed the improvements. Road transport is responsible for the majority of the Danish transport demand and traffic work. For passenger transport, cars and vans <2t cover 47 pct. of the transport demand and 90 pct. of the traffic work. For freight transport, 24 pct. of the transport demand and 97 pct. of the traffic work is covered by trucks and vans. Hence, road transport is consequently responsible for the majority of the energy consumption and CO_2 emissions.

Decarbonising the transport sector is argued to be a wicked problem. A wicked problem is defined as an ill-formulated problem with many conflicting objectives, that is difficult solve. Identifying the cause-effect relationships of wicked problems is inherently difficult, hence solutions might cause other wicked problems and the problem is never actually solved. It is argued, that transport planning faces wicked problems, when dealing with issues of increasing CO_2 emissions and road congestions. It is argued, that the development of urban planning and the perception of mobility has created an automobile dependence, which makes the decarbonisation of the transport sector increasingly more challenging.

In order to reduce the energy consumption and CO_2 emissions from the transport sector, the concept of "Avoid, shift, improve" (ASI), recognised by the European Commission, is applied as a methodological framework. The ASI approach formulates three fundamental principles to guide planners and decision-makers to limit energy consumption and emissions from the transport system:

1) avoid rising transport demand and reduce existing demand,
2) shift trips to low-carbon modes, and
3) improve the efficiency of vehicles and fuels.

This approach was applied in the design of renewable transport scenarios. The order of the ASI concept is considered in reverse in the design of the scenarios, hence scenarios with renewable technology implementations to improve the overall efficiency and reduce emissions are considered first and secondly, scenarios with alternative development of the transport demand is considered. The scenarios are meant to describe potential routes for partial decarbonisation towards 2030 and a full decarbonisation in 2050. The technology scenarios are based on an exhaustive review of researchers' and industry associations' expectations to renewable technology development and market uptake. Two scenarios are considered, one considering a reasonable development of renewable transport technologies towards 2030 and a relatively slow market uptake and one optimistic scenario, where expectations to technology development towards 2030 are high and a fast market uptake is achieved. In both scenarios carbon neutrality is achieved by 2050.

There is broad consensus in literature and in the industry, that an extensive electrification of the transport system is preferable. Integration of electricity will provide a valuable synergy between the transport sector and the renewable electricity production. Furthermore, integration of electricity will significantly improve the overall energy efficiency. For the parts of the transport sector where electrification is not an available option with the current technology development, biofuels and electrofuels are estimated to replace fossil fuels. Electrofuels provide a renewable alternative to modes of transport where high energy-dense hydrocarbons are necessary, such as aviation, maritime transport and heavy-duty road transport.

Towards 2030, biofuels will have a more significant role, while it is anticipated that electrofuels will constitute the majority of liquid renewable fuels towards 2050. The market share for electrofuels will depend on technological development in terms of improving efficiencies and reducing production costs.

The technology implementations in the *Reasonable* and *Optimistic* scenarios had significant impacts in terms of reducing the transport system CO_2 emissions. Towards 2030, implementation of electric vehicles for passenger transport poses the most significant potential for reducing emissions. Implementing 1 million electric vehicles in 2030 reduces CO_2 emissions with 11 pct., while an implementation of 1.5 million electric vehicles reduces emissions with 18.5 pct. All renewable transport technologies implemented by 2030 reduced total emissions with 24 pct. in the *Reasonable* scenario and with 45 pct. in the *Optimistic* scenario. Hence, there is a significant potential for CO_2 reductions in the transport sector before 2030.

From 2030 to 2050 an extensive electrification of all cars and vans is anticipated in both technology scenarios. For aviation, maritime transport and heavy-duty road transport electrofuels are estimated to cover the majority of the energy consumption in the *Reasonable* scenario. In the *Optimistic* scenario all heavy-duty road transport is electrified by an implementation of electric road systems covering 1300 kilometres of national freeways. All national aviation is electrified, while international aviation and sea transport is converted to electrofuels and ammonia.

The costs related to cars and vans <2t constitute the majority of the total transport system costs. The vast amount of vehicles necessary to meet the growth in transport demand comprises 75 pct. of the annual transport costs in all scenarios in both 2030 and 2050. The transport system costs are marginally higher in the technology scenarios compared to the *Reference* scenario, as the costs of electric vehicles is slightly higher than for conventional vehicles.

Considering the implications, that the renewable transport scenarios will have on the surrounding energy system, it is estimated that in order to accommodate the increase in electricity demand both for direct electrification and indirect via electrofuels, additional renewable production capacity equivalent to 2 GW offshore wind farms is necessary in 2030 in the *Optimistic* scenario. The additional electricity demand in the *Reasonable* scenario can be covered by estimated excess production. In 2050, the additional renewable production capacity needed to accommodate the electrification and production of electrofuels is equivalent to 10.3 GW offshore wind capacity in the *Reasonable* scenario and 9.4 GW offshore capacity in the *Optimistic* scenario.

Reducing the growth in traffic work were analysed by implementing measures to increase capacity utilisation of trucks and cars and shifting transport demand from energy-dense modes of transport to low energy-dense modes of transport. Reducing the growth in traffic work compared to the growth rate in *Reference* scenario showed a potential reduction in the transport energy consumption of between 5 pct. and 14 pct. in 2030. In 2050 the potential energy consumption reductions were less significant and only a 0 pct. to 4 pct. reduction was achieved from reducing the growth in traffic work. Instead, reducing growth in traffic work considerably reduces annual transport system costs. Reducing the growth in traffic work can reduce the transport system costs with up to 20 pct. in 2030 and 40 pct. in 2050.

Finally, it is argued that reducing traffic work and overcoming automobile dependence require systematic changes and interventions with the public perception of transport and mobility. Improving public transport systems or introducing road pricing schemes will not singlehandedly avoid an increase in traffic work or promote modal shifts. A combination and an individual assessment of the area and transport demands is necessary. Growing concepts like shared mobility and technology developments within autonomous driving could assist in reducing traffic work, but have yet to be seen implemented in large scale.

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Appendix A

Passenger transport

Cars and vans

As outlined in section 5, the transport demand for cars and vans has increased in recent decades, contemporary with a decline of the capacity utilisation. This has increased the traffic work of cars and vans.

In the 2017 *Reference* model the transport demand for cars and vans <2t is 59.736 Mpkm. The traffic work is 40.181 Mkm and the corresponding energy consumption is 106.450 TJ.

From the THS data and data in [13] it was possible divide the transport demand and capacity utilisation between leisure, work and international related trips, along with a segregation of the transport demand between the length of trip. It was found that 59 pct. of all trips in cars and vans <2t in the *Reference* model are related to leisure, 40 pct. to work and 1 pct. to international transport. Approximately half of the transport demand is for trips longer than 50 kilometres. The capacity utilisation varies depending on whether the purpose is leisure, work or international transport. For work related trips, the average number of passengers per vehicle is 1.14. For leisure related trips, the average number of passengers is 1.86, while it for international trips is an average of 2.48. In Table 11, the transport demand of capacity utilisation is outlined.

It is estimated that the specific energy consumption for cars and vans is related to the length of the trip. As longer driving trip will typically involve driving on highways and less driving in urban areas, the fuel economy is expected to be improved, hence it is estimated that the specific energy consumption of trips over 50 kilometres is reduced with 50 pct. compared to trips under 50 kilometres [144]. Given this estimate, it is possible to calculate the specific energy consumption for cars and vans to be 3.5 MJ/km for trips under 50 kilometre and 1.75 MJ/km for trips over 50 kilometre. In Table 11 the specific energy consumption per kilometre and per passenger kilometre is displayed. As the capacity utilisation is higher for leisure and international trips, the specific energy consumption per passenger kilometres is lower.

Cars and vans <2t	Transport demand	Capacity utilisation	Specific energy consumption	
	Mpkm	p/vehicle	MJ/pkm	MJ/km
Leisure	**59%**	**1,86**		
<5km	*5%*		1,88	3,50
5-25km	*29%*		1,88	3,50
25-50km	*20%*		1,88	3,50
>50km	*46%*		0,94	1,75
Work	**40%**	**1,14**		
<5km	*2%*		3,07	3,50
5-25km	*23%*		3,07	3,50
25-50km	*27%*		3,07	3,50
>50km	*48%*		1,54	1,75
International	**1%**	**2,48**	**0,71**	**1,75**

Table 11. Distribution of leisure, work and international related transport demand and the capacity utilisation.

Cars and vans <2t in 2017 are primarily fuelled by petrol and diesel. 56 pct. and 43 pct. are fuelled by petrol and diesel respectively. Thus, battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) comprise only 1 pct. of the vehicle fleet. As of the Danish regulation in 2017 a mix of at least 5.75 pct. biofuels must be added in the petrol or diesel available at Danish fuel stations. Hence, biofuels constitute the majority of renewables in the Danish transport sector. The share of renewable transport technologies have been increasing in recent years, but BEVs and PHEVs still only made up less than 1 pct. of newly sold vehicles in 2017. [7]

Busses

The transport demand for busses in the 2017 *Reference* model is 7300 Mpkm. The traffic work is 648 Mkm and the corresponding energy consumption is 8210 TJ. The energy consumption of busses in Denmark are split evenly between urban short-distance busses and regional and national long-distance busses.

A detailed segregation of data regarding the transport demand and length of trip has not been accessible during the data collection process of this work and it is therefore assumed that approximately 20 pct. of the transport demand in busses is met by trips under 25 kilometres and 80 pct. by trips over 25 kilometres. Of the trips over 25 kilometres it is assumed that approximately half of them are over 50 kilometres. As for the specific energy consumption, the same assumption applies for busses as for cars and vans, hence the specific energy consumption per kilometre is assumed to be reduced 50 pct. compared to trips under 50 kilometres.

The average capacity of both urban short-distance busses and regional and national long-distance busses is 45 passengers. The capacity utilisation of urban short-distance busses is on average 18 pct., while it for long-distance busses is on average 60 pct. [145]

The busses are fuelled primarily by diesel, which contains 5.75 pct. biodiesel as for cars and vans.

Rail

The passenger transport on rail covers both national and international travel. The total passenger transport demand for rail in the *Reference* model is 6620 Mpkm, whereof 342 Mpkm are international. The corresponding energy consumption is 4270 TJ.

The electrification of the Danish railway infrastructure has been developing in recent years and electric trains meet approximately 30 pct. of the transport demand on rail. The remaining 70 pct. is fuelled met by diesel fuelled trains. It is assumed that all international trains are powered by electricity.

Electric trains are more energy efficient than traditional diesel trains. According to EcoTransIT electric trains have an average energy efficiency of 2.7 times that of diesel trains. In the following analysis electric trains will only have an energy efficiency of 1.7 times that of diesel trains. There is an obvious discrepancy between this estimation and the estimation found in the literature, but the Danish Energy Agency anticipates that electric trains are 1.7 times more energy efficient than conventional diesel trains in their publication DECO and as that publication will form the basis of the *Reference* scenario, this estimate has been adopted. [43], [146], [147]

The electrification of the railway infrastructure still remains a cornerstone in the improvement of rail transport. As more of the railway infrastructure is electrified, the specific energy consumption will decrease, thus improving the energy efficiency of railway transport.

The average capacity of both national and international trains are 245 passengers. The capacity utilisation for national trains is 43 pct. and 65 pct. for international trains. [145], [148]

Air

Passenger transport in flights are divided by domestic and international travel. The international share is more than 99 pct. of the total transport demand for aviation. National passenger transport by air has a transport demand of 354 Mpkm in the *Reference* model and international transport 49161 Mpkm. The total energy consumption is 38490 TJ.

For national flights route between Copenhagen airport and Aalborg airport is used a representative of all flights. The average passenger capacity on this route is 89 passengers and the average capacity utilisation is 61 pct. [145]

The international transport is subdivided by the length of the flight. The length of the flight has influence on the energy efficiency, as the fuel consumption is highest during landing, take-off and ground movement. Long distance flights have a better fuel economy as the take-off and landing constitute a smaller share of the total journey. [13]

For international transport the average passenger capacity is 184 and the average capacity utilisation is 82 pct. [149]

The specific energy consumption per kilometre for national aviation is 3.6 MJ/pkm and for international aviation the specific energy consumption is 0.9 MJ/pkm for trips under 1000 kilometres and 0.7 for trips longer than 1000 kilometres. It is assumed that long-distance flights are 25 pct. more energy efficient than short-distance flights.

Sea

Maritime passenger transport is divided between national and international transport. The national transport demand in the *Reference* model is 297 Mpkm and the international transport demand is 1629 Mpkm. The energy consumption for sea transport is only available through accessible statistics for the domestic share. The energy consumption in the *Reference* model is 4030 TJ. For international travel, the energy consumption is calculated by assuming that the specific energy consumption for national and international transport is identical.

To calculate an average capacity and capacity utilisation for national transport the route between Zealand and Aarhus is chosen to be representative. 71 pct. of the domestic passenger transport demand is on this connection. The capacity of the ferry on this route is 1100 passengers and the average capacity utilisation is 19 pct.

For international sea transport the average capacity and capacity utilisation are found in [13]. The capacity is 1900 passengers and the average capacity utilisation is 45 pct.

Freight transport

Trucks

The transport demand for trucks is divided into a national and international demand. In 2017, the national transport demand is 12.651 Mtkm, while the international is 2958 Mtkm. The traffic work and energy consumption were only available for all trucks collectively, hence it had to be calculated for national and international trucks separately. It was estimated that the energy efficiency of national and international trucks were similar, hence the energy consumption and traffic work could be calculated based on the divided share of transport demand. The traffic work and energy consumption in the 2017 *Reference* model for national trucks, thus is 1.412 Mkm and 18.852 TJ. [3], [7]

The transport demand of both national and international trucks is divided by the length of trip. For national trucks approximately 50 pct. of the transport demand is covered by trips under 200 kilometres, while the other half is longer than 200 kilometres. For international trucks only 5 pct. of trips are under 250 kilometres while approximately 50 pct. are under 1000 kilometres and 45 pct. are longer than 1000 kilometres. [7]

The average capacity utilisation is generally higher for international trucks than for national trucks. For international trucks the average capacity utilisation in 34 pct. for trips under 250 kilometres, 54 pct. for trips between 250 and 1000 kilometres and 60 pct. for trips longer than 1000 kilometres. For national trucks the average capacity utilisation is 41 pct. for trips below 50 kilometres and 45 pct. for all trips longer than 50 kilometres. The average capacity (ton) of national trucks is 20 ton and 30 ton for international trucks. The specific energy consumption (MJ/km) is estimated to be 2.8 times for trips below 50 kilometres. It is estimated that the majority of these trips will take place in urban areas, which will affect the fuel economy. [7], [13]

Both national and international trucks are fuelled by diesel with a blend in of 5.75 pct. biodiesel.

Vans

The transport demand for vans is not available through published statistics and have to be calculated from the traffic work and capacity utilisation. The traffic work for vans in the 2017 *Reference* model is 7240 Mkm and with an average load capacity of 2 tons and average capacity utilisation of 50 pct. the transport demand is 7240 Mtkm. The energy consumption for vans is 23.500 TJ. [3], [7], [145]

It is estimated that 34 pct. of the transport demand is by trips under 50 kilometres and 66 pct. for trips over 50 kilometres. This estimation is based on the estimations in [13]. As for cars the specific energy consumption is expected to be reduced by 50 pct. for trips over 50 kilometres compared to trips under 50 kilometres. [144]

93 pct. of all vans are fuelled by diesel while the rest is fuelled with petrol. A blend of 5.75 pct. biofuels are added in both.

Rail

The transport demand for national and international rail freight transport is 163 Mtkm and 529 Mtkm respectively. The distribution of national transport between electric and diesel trains is the same as for passenger transport. The average load capacity of national trains is 750 tons, while it is 1000 tons for international trains. The average capacity utilisation is 64 pct., assumed for both national and international trains. The energy demand for national trains is 115 TJ and 375 TJ for international trains. [3], [7], [13], [145] The assumption made for specific energy consumption of electric trains for passenger transport also applies for freight transport, hence electric trains are estimated to be 1.7 times more energy efficient.

Air and sea

For freight transport by air or sea transport the available data about transport is in tonnage of freight handled by ports or airports. To calculate the transport demand in Mtkm an average travel distance is therefore necessary. For national freight transport it is estimated that the route between Copenhagen and Aalborg is representative. It is estimated that the distance is 230 kilometres by air transport and 300 kilometres by sea. The average travel distance for international freight by sea and air are estimated to be 1.737 km by sea and 8.000 km by air. [7], [13]

The calculated transport demand for national and international air is 0.7 Mtkm and 1.044 Mtkm respectively. For sea the national transport demand is 5.887 Mtkm and the international is 65.151 Mtkm. The average load capacity of national and international aviation is 25 tons and 50 tons. The average capacity utilisation is 60 pct. for national air and 49 pct. for international. For maritime freight transport the average capacity is 15.000 tons for national and 75.000 tons for international. The average capacity utilisation is 45 pct. for national sea transport and 55 pct. for international. [13], [149]

The energy demand for national and international air freight transport in 2017 is 42 TJ and 3.727 TJ. For maritime freight transport the energy demand is 2.180 TJ for national transport and 3.950 TJ for international transport. [3]